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Design and Implementation of a Bluetooth Low Energy-Based Local Area Network for Fall Detection †

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Abstract: Falls are harmful to the elderly; therefore, fall detection technologies have been developed by many researchers to help detecting these incidents. The research presented here investigates a Bluetooth Low Energy-based local area network for fall detection. One of the major concerns is not only the detection of a fall incident but also the location where this incident occurred. This research utilizes a fall detection network with three different types of network nodes: alarm node, relay node, and center node. Alarm nodes are worn by the elderly for fall detection; relay nodes are fixed in the target area for receiving the signal from alarm nodes; and the center node is the hub of the detection network. When a fall incident occurs, the alarm node will send out alarm signals which will be passed towards the center node by the relay nodes. The center node forwards the alarm to any iMessage capable device.

Keywords: wearable fall detector; Bluetooth low energy; accelerometer; fall detection algorithm

1. Introduction

Falls are dangerous to people, especially to the elderly. One of the main reasons for these accidents is ageing, which brings people many adverse effects, such as frailty and osteoarthritis which reduce their mobility and make them react slower to environment changes. Furthermore, cardiovascular disease and medications can cause dizziness for people and make them imbalanced [1], which could lead to fall.

Among the elderly, falls are the leading injury-related hospitalization cause, which is four times more than other injuries [2,3]. Statistically, the fall accidents rate increases with age [4]. Vellas, Cayla [5] study shows that nearly 80 percent old people who fell cannot get up unaided. The complications from the long-time lying on the floor are even more harmful than the fall impact, such as pressure sores, dehydration, hypothermia, and pneumonia [6]. Compared with the fall victims who can get up unaided, the fall victims who cannot get up unaided were more likely to die or to be hospitalized and their ability to perform daily activities is more likely to reduce [7,8]. Therefore, the emergency aid is important for fall victims. Fall detection technology can let fall victims get helped quickly by identifying a fall accident and sending out alarm signals to other people.

Fall detection is important for the elderly even if they do not live alone because half-hour's aid delay in fall accident might be vital for fall victims. In all kinds of fall detection approaches, the wearable fall detectors need to send out an alarm signal wirelessly to another device immediately after detecting a fall accident. The wearable fall detectors are usually designed for regular home users. In a large environment, such as a retirement apartment or public areas, it's more difficult to locate the accident as the elderly may fall anywhere. In this case, the ordinary fall detectors may send an alarm signal to other people, however, they would not know the place where the fall victim is located.

In this paper, wearable Bluetooth Low Energy devices are designed and configured as internal and external network nodes for a building in order to detect and locate fall accidents.

2. Fall Detection Approaches

To detect a fall accident, the target's activities such as acceleration signals, images, or pressure signals, are usually being monitored. The data will be processed with a fall detection algorithm; with the most of the fall detection algorithms being based on analytical models, and some being based on machine learning [9]. Fall detection approaches have two main categories, namely context-aware systems and wearable devices [10].

The context-aware systems deploy sensors such as cameras, floor sensors, infrared sensors, microphones and pressure sensors in the environment to monitor the target(s)'s activities. For example, Sixsmith and Johnson [11] used an infrared thermal-imaging sensor array mounted on the wall to monitor the target's activities; Rougier, Meunier [12] used wall mounted cameras to track the trajectory of the target's head in 3D. The main advantage of context-aware systems is that the targets are not required to wear any special device. However, the valid detection area is limited by the sensor's measuring range. Additionally, they are bound to privacy concerns, especially for video-based technologies [10].

Most of the wearable fall detectors use accelerometer sensors and some studies also involve gyroscope [10]. Those devices collect target's acceleration data by using one or more independent tri-axial accelerometers attached to the certain part of the body [10]. Typically, the device is attached to the waist area, because the waist is close to the body center mass [13]. The main advantage of wearable devices is the low cost and large coverage area. There are also some hybrid fall detection approaches, for example, Kepski and Kwolek [14] used both time-of-flight camera mounted on the ceiling and a wearable accelerometer attached to the lumbar region to detect fall accidents.

For all the fall detection approaches, their main objective is to distinguish the fall accidents from the daily activities [10]. There are four possible results [9]:

1. True Positive (TP)—a fall occurred and the detector reported a fall accident.
2. False Positive (FP)—a fall did not occur but the detector reported a fall accident.
3. False Negative (FN)—a fall occurred but the detector did not report any fall accident.
4. True Negative (TN)—a fall did not occur and the detector did not report any fall accident.

The performance of a fall detection system is measured by its sensitivity which is calculated as $TP/(TP + FN)$ and specificity that is calculated as $TN/(TN + FP)$.

High sensitivity and specificity are usually achieved in experimental environments, however, in real life, the performance is smaller. These are due to the fact that in most cases the simulated falls in the experimental situation are done by young people rather than old people [10]. The wearable fall detector as introduced by Bourke et al. [13] is adopted as the basis technique to detect fall accidents and extended the communication part with distributed mesh-network.

3. Design

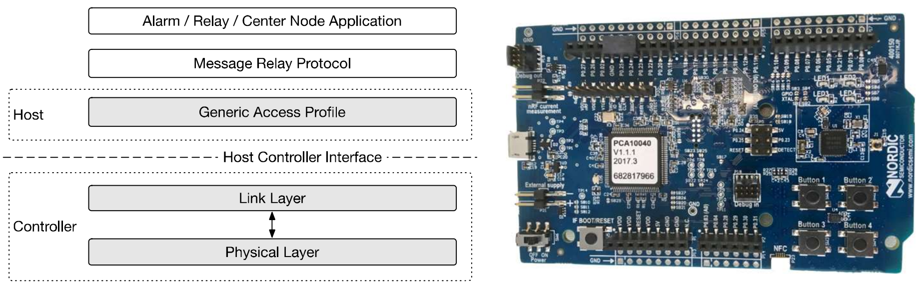
The distributing network nodes installed in the target environment form a mesh-network that scans any alarm signal regularly. If there is a fall accident, the network nodes that are close to the fall victim would get a high Received Signal Strength Indicator (RSSI) value. With the help of the physical network nodes' topology, the position of the fall victim can be located inside the building or area within the network coverage.

The fall detection network consists of three types of network devices, namely alarm node, relay node, and center node. Alarm node is the device with the following abilities: fall detection, radio transmission, and radio reception. The alarm nodes are worn by the elderly which can move around inside the coverage area. Relay node is the device which can perform radio transmission and radio reception. The relay nodes are installed in the building or area at fixed positions to perform a mesh-network infrastructure for detecting alarm nodes. The center node has all functionalities of the relay node and is connected to the Internet. There is only one center node in a building which works as the hub and gateway for the whole network. To form a network, the relay nodes must be installed in such way that they can cover the overall area or building while maintaining at least one relay node in the transmission range of the center node.

When an alarm node detects a fall accident, it will send out fall alarm signals. One or more relay nodes might receive the signal, they will record RSSI value and the alarm node's device number. They will then send a message towards the center node. If the center node is not in direct transmission range, the message will be relayed through another relay node(s) until it arrives at the center node. The center node displays the alarm messages on the console and additionally sends a notification to the devices that are registered to the alarm node via Internet, i.e., iMessage.

3.1. Network Software Architecture

The network software architecture is structured in layers as shown in Figure 1a. The message relay protocol is used as underlying communication scheme for the whole network. The lowest layer is implemented on Bluetooth low energy (LE) due to two reasons. First, Bluetooth LE suits for low energy operation. The drawback of low power consumption is the small data throughput, however, in this application the amount of data need to be sent across the network is small. Second, Bluetooth LE is being implemented in more and more embedded devices, especially in smartphones and notebooks. By taking advantage of Bluetooth technology, the network can easily interact with other devices, which brings more possibilities in the future to integrate the system in a larger network.



(**a**) (**b**)

Figure 1. (**a**) Architecture of the fall detection network software. (**b**) nRF52 Development Kit.

3.2. Alarm Node

The alarm node detects the fall accident using the algorithm introduced by Bourke et al. [13]. This algorithm showed the best performance with 83% sensitivity and 97% specificity in comparison with other 13 fall detection algorithms applied on real life falls data [15]. The algorithm uses a 3-axis accelerometer to monitor the *vertical velocity* at sampling rate 50 Hz, *impact* at sampling rate 200 Hz, and *posture* of the wearer. The algorithm uses the following physical phenomenon occur on a fall accident:

- Before the body reaches the ground, the body usually goes down quickly, which means the vertical velocity is high.
- When the body reaches the ground, the body's velocity will change to zero dramatically, which means the acceleration is high.
- After the body reached the ground, the fall victim usually lies on the ground, which means the gravity vector changed in the accelerometer's coordinate system.

The algorithm has three thresholds: threshold one for the vertical velocity is fixed at −0.7 m/s, threshold two for the acceleration is set at 2.8 g (g = −9.81 m/s), and threshold three for the angular change of the gravity vector is at 60°. When any of the first two thresholds is reached, the algorithm will start detecting the posture by recording the time t. If the change of the gravity vector's angle exceeds the threshold 3 and this condition occurs for more than 1.75 s, e.g., from $t + 1$ s to $t + 3$ s, then a lying posture is detected. A fall accident is triggered if and only if all three thresholds are exceeded and the lying posture is detected.

3.3. Relay Node

The relay node has three main functions for transporting the messages, namely initialization, message creation, and message relay. Initialization is used to form the hierarchical structure among all relay nodes and the center node. This function enables all relay nodes to advertise a package in which their level can be updated. The function itself can only be triggered by receiving an *Initialization command* which is sent by the center node.

Message creation is the function that produces a new message to be sent out to the neighbouring nodes. The messages are differentiated into two categories: self-state report and alarm report. The self-state report message will be sent periodically as alive signal of the node. This information is crucial for the whole system to guarantee the integrity of the network. The alarm report will only be sent if the relay node receives an alarm signal from an alarm node.

Message relay forwards any received message to the upper level according to the hierarchical structure of the network. Its main function is to remove any duplicate packet from being propagated to the upper level for reducing the bandwidth usage.

3.4. Center Node

The center node initializes the network at the beginning of the program by inclusion of all relay nodes in the environment. It scans regularly for any alarm report and registers the reception notification to the advertising list by the node ID and RSSI information. This report will then be forwarded to the fall accident monitor for further actions. The alarm report contains the information where the fall victim locates by referring the physical topology of the relay nodes and the RSSI value. The higher the RSSI value, the closer the distance between the fall victim and the corresponding relay node. The alarm node's device number indicates the location of the fall victim.

Fall accident monitor is an application that has a graphical user interface showing any alarm signal occurred within the network. Based on the ID of the alarm node, the alarm information will be forwarded to the corresponding devices via Internet, i.e., iMessage notification or E-mail. The center node monitors the live signal of all relay nodes within the network and notifies the operator in case of any network interruption.

4. Implementation

The proposed fall detection system is designed to work on a Nordic nRF52832 System-on-Chip (SoC) microcontroller. The nRF52832 is an ARM Cortex M4F CPU that is equipped with radio transceiver, 512kB flash, 64kB RAM memory, and other peripherals; most importantly, it supports Bluetooth LE. The prototype is implemented on the Nordic nRF52 development board, as shown in Figure 1b, which additionally is equipped with a built-in antenna, four LEDs, and four buttons. A 3-axis accelerometer, MPU9250, is used on the alarm node to detect a fall incident. It is connected through the serial peripheral interface (SPI) to the nRF52 development board.

The fall detection system runs on Bluetooth LE profile specification that is designed by the Bluetooth Special Interest Group (SIG). The two top layers are created specifically for the fall detection system and the rest are implemented by Nordic as part of its SDK.

5. Experiments and Results

In the experiments, all functionalities from the fall detection system were evaluated, starting from the network initialization to receiving alarm message via iMessage notification. During the development process, each functionality was tested independently 10 times. Once all functionalities have passed the tests another 10 integration tests were conducted. Thereafter various different scenarios were evaluated five times each. The results from the initialization process showed that relay nodes were automatically sorted hierarchically and were able to transmit messages from the alarm node to the center node.

In one experiments, the alarm node was placed in such a way that two different relay nodes could listen to it. The center node received both messages via two different network paths and was able to determine the position of the alarm node by analysing the RSSI of the signal, in which the higher signal was representing the closer node.

An additional experiment that emulated a network interruption was performed by powering down one relay node. As a result, after a timeout period of 30 s, a warning message was displayed on the center node application with the information which node was not reporting.

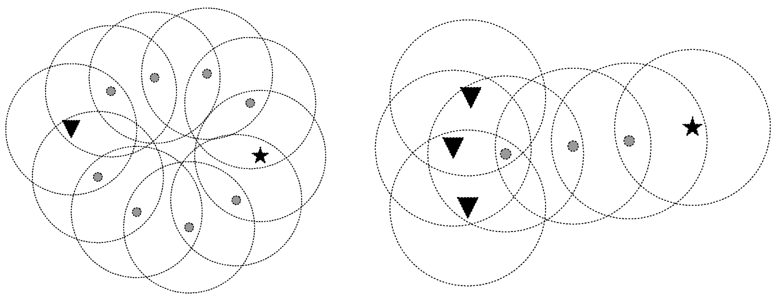
From the test results, the fall detection network can be used to estimate the location of the fall victims. It's scalable, more relay nodes can be employed to expand the monitored area. However, there are also shortcomings about the fall detection network, namely power consumption, message duplication, and latency.

The power consumption of each node was measured during radio transmission and idle state. The system was tested under two configurations of radio transmission, continuous mode with scanning interval of 1000 ms and periodic mode using scanning interval of 30 ms. Both modes use the same scan window of 30 ms. The results are shown in Table 1; continuous mode consumed more energy (12.29 mA) in comparison with periodic mode (0.371 mA). Depending on the battery capacity, the operation duration in single charge will vary from hours to days. When the advertising list is not empty, continuous mode will be used instead of the periodic one.

Table 1. Operation time comparison between continuous mode versus periodic mode on a relay node operated with two different battery capacities.

Battery Capacity	Continuous Mode	Periodic Mode
330 mAh	26 h	888 h/37 days
1000 mAh	81 h	2692 h/112 days

Message duplication occurs when more than one path from the alarm node to the center node exists. One example of this issue is shown in Figure 2a, where two different paths from alarm to center nodes are available. This problem can be solved by using a simple filter avoiding multiple messages. Latency happens whenever more than one alarm node that is connected to the same relay node is sending an alarm at the same time. Each alarm will be send one after another sequentially to the center node resulting in a small delay. Each additional node contributes approximately 4 s delay in addition to the 4 s delay of the direct transmission. A possible solution is to implement a dynamic message that combines all alarm messages which occur on the same periodic time into a single alarm message.



(**a**) (**b**)

Figure 2. Two scenarios on message duplication and latency; triangles represent the alarm nodes, dots represent the relay nodes, and stars represents the center node; (**a**) Message duplication with two propagation paths; (**b**) Latency occurring when multiple relay nodes exist.

6. Conclusions

The fall detection system using Bluetooth low energy could help detecting and locating fall incidents within a specified area or building where the mesh local area network is installed. The system requires the persons to wear an alarm device as well as the installation of relay nodes covering the area or building. This system has the advantage over context-aware systems where the detection area is not limited by the sensor's measuring range, i.e., view angle of a camera system. Additionally, in places where cameras cannot be installed, a fall detection would be still possible. The wearable device uses small amounts of energy which allows the user to use the device for months before changing the battery. The relay node can be powered either by battery or power outlet to allow a maintenance free installation.

The fall detection system can still be improved in various ways as future works. First, increasing the security as the current implementation does not use any security, however, this might increase the power consumption. Second, adding an emergency button on the alarm node which will allow the person with the wearable device to trigger an alarm to get help. For this purpose, a new message signature shall be used to inform the helper about the type of alarm. Third, integrating a smartphone as a secondary center node which can be carried by the elderly while roaming out of the fall detection network. The smartphone will then send the alarm signal using the mobile phone network and sending the GPS location of the victim as location information. Fourth, implementing another messaging system in addition to iMessage, i.e., SMS, push notification, WhatsApps, etc.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Maarsingh; O.R.; Dros, J.; Schellevis, F.G.; van Weert, H.C.; van der Windt, D.A.; ter Riet, G.; van der Horst, H.E. Causes of Persistent Dizziness in Elderly Patients in Primary Care. *Ann. Fam. Med.* **2010**, *8*, 196–205.
2. Baker, S.P.; Harvey, A.H. Fall injuries in the elderly. *Clin. Geriatr. Med.* **1985**, *1*, 501–512.
3. Stevens, J.A. Falls among older adults—Risk factors and prevention strategies. *J. Saf. Res.* **2005**, *36*, 409–411.
4. Scuffham, P.; Chaplin, S.; Legood, R. Incidence and costs of unintentional falls in older people in the United Kingdom. *J. Epidemiol. Community Health* **2003**, *57*, 740–744.
5. Vellas, B.; Cayla, F.; Bocquet, H.; de Pemille, F.; Albarede, J.L. Prospective-Study of Restriction of Activity in Old-People After Falls. *Age Ageing* **1987**, *16*, 189–193.
6. Drennan, V.; Goodman, C. *Oxford Handbook of Primary Care and Community Nursin*g; Oxford University Press: Oxford, UK, 2014.
7. Tinetti, M.E.; Liu, W.L.; Claus, E.B. Predictors And Prognosis of Inability to Get up After Falls Among Elderly Persons. *JAMA J. Am. Med. Assoc.* **1993**, *269*, 65–70.
8. Wild, D.; Nayak, U.S.L.; Isaacs, B. How Dangerous are Falls in Old-People At Home. *Br. Med. J.* **1981**, *282*, 266–268.
9. Noury, N.; Fleury, A.; Rumeau, P.; Bourke, A.K.; Laighin, G.O.; Rialle, V.; Lundy, J.E. Fall detection—Principles and Methods. In Proceedings of the 2007 29th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, Lyon, France, 22–26 August 2007.
10. Igual, R.; Medrano, C.; Plaza, I. Challenges, issues and trends in fall detection systems. *BioMed. Eng. OnLine* **2013**, *12*, 66.
11. Sixsmith, A.; Johnson, N. A smart sensor to detect the falls of the elderly. *IEEE Pervasive Comput*. **2004**, *3*, 42–47.
12. Rougier, C.; Meunier, J.; St-Arnaud, A.; Rousseau, J. Monocular 3D Head Tracking to Detect Falls of Elderly People. In Proceedings of the 2006 International Conference of the IEEE Engineering in Medicine and Biology Society, New York, NY, USA, 30 August–3 September 2006.
13. Bourke, A.K.; van de Ven, P.; Gamble, M.; O'Connor, R.; Murphy, K.; Bogan, E.; McQuade, E.; Finucane, P.; ÓLaighin, G.; Nelson, J.; et al. Assessment of waist-worn tri-axial accelerometer based fall-detection algorithms using continuous unsupervised activities. In Proceedings of the 2010 Annual International Conference of the IEEE Engineering in Medicine and Biology, Buenos Aires, Argentina, 31 August–4 September 2010.

14. Kepski, M.; Kwolek, B. Detecting human falls with 3-axis accelerometer and depth sensor, in Engineering in Medicine and Biology Society (EMBC). In Proceedings of 2014 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, Chicago, IL, USA, 26–30 August 2014.
15. Bagalà, F.; Becker, C.; Cappello, A.; Chiari, L.; Aminian, K.; Hausdorff, J.M.; Zijlstra, W.; Klenk, J. Evaluation of accelerometer-based fall detection algorithms on real-world falls. *PLoS ONE* **2012**, doi:10.1371/journal.pone.0037062.