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Wireless Sensor Network for Fall Prevention on Geriatric Wards: A Report

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Abstract

With regard to the growing number of older adults, it needs smart solutions for fall prevention. Especially at geriatric institutions, the risk of falling is very high and frequently leads to injuries, resulting in serious consequences. We present the Inexpensive Node for Bed Exit Detection (INBED), a comprehensive signaling system for fall prevention. The INBED system is based on a wireless sensor network infrastructure via IEEE802.15.4 and highly-specialized open hardware in-house developed wearable. The device, which will be attached to the patients, can detect several types of movement. Occurring events are forwarded to the nursing staff immediately by using the self-organizing and scalable network including wide area network integration. The system can help to relieve the staff while the personal freedom of movement and privacy of patients is increased. With this development, the energy-efficient, simple and intuitive mechanisms of proximity communication can be combined with broadband benefits.

Keywords:

Accidental falls, Accident prevention, Geriatrics.

Introduction

As a result of demographic change, the number of people to be cared for, and thus also the challenges and demands on health care, are increasing. Falls in older adults are frequent and fatal events with mostly serious consequences for the individual as well as considerable financial expenditures for the society.

For geriatric wards the average fall ratio per 1000 bed days is more than twice as high as on other clinical wards, which has been validated by the German quality report benchmark in geriatric health care from 2007 [1]. This can be significantly higher if you look on specialized clinical departments such as gerontopsychology wards. A large part of the falls occurs as a result of getting up in the immediate vicinity of the bed [2]. Usually high fall risk patients are encouraged to call the nurses for help if they wish to get up, this directive is not always followed (e.g. due to cognitive impairments). The situation in outpatient areas are similar and again most of the falls occur during rising events for transitions.

The increased falling risk of older adults is mainly caused by chronic diseases and predisposing factors like gait and balance disorders [3]. Furthermore, dementia and motor deficits patients fall twice as often as patients with normal cognitive abilities [4]. One of the most common consequences for elderly fallers is the femoral neck fracture [5]. The incidence among the over-65s in Germany for such an injury is 600 to 900 fractures per 100,000 people per year [6]. Beside the mental and physical strains, fall events are associated with immense consequential costs. The estimated overall annual costs of treatment of fall-related hip fractures in German hospitals and rehabilitation centers are up to 2.77 billion Euro [7; 8].

We designed in several iterations a highly specialized Wireless Sensor Network (WSN) system in different architectures to recognize an attempt to leave the bed for fall prevention. On the one hand, the system should not restrict the patient's movement. On the other hand, it has to recognize potential fall risks in a timely manner, so that an active intervention by nursing staff is possible to maintain the patient's care and safety. Furthermore, the diversity of clinical structures is quite challenging. Other more practical issues are the availability and amount of power sockets, the type of communication infrastructure (Wi-Fi, Ethernet, etc.) and individual restrictions of the specific country (e.g. hygiene requirements, care regulations or patient protection laws, limitations of the use of protocols e.g. Bluetooth or Zigbee). Hence, the following objectives for the development of the INBED fall prevention systems are:

- Development of a reliable and cost-effective solution for a sensor-based bed-exit/rising detection system (primary function) based on initial research results with different sensor prototypes.
- Recognition of restlessness conditions of patients prior to a rising attempt (optional primary function), so that the nursing staff can intervene immediately.
- Detection of falls (secondary function) and provision of virtual risk areas, such as stairs (secondary function).
- State-of-the-art technological concept, focusing on a minimal price for the end customer without reducing the quality of the overall system or individual functional areas.
- Creating an adaptive, scalable and modular communication infrastructure to include the wearables at a ward.

Related Work

In the last years, several studies showed a positive impact of bed exit systems on the fall rate of older adults [4; 9]. Currently, there are two main types of systems available. Distinguished in body worn and ambient variants, they can occur in different forms, e.g. mattress pad systems, ground pressure mats, infrared systems or garment clipping sensor systems [10]. Those systems have advantages and disadvantages depending on the symptoms of the patient and the surrounding. Hygiene requirements that demand special cleaning can exclude the use of system components if they cannot be cleaned to rule. The false positive alarm caused by objects like mobile dining tables, suit cases or by the patient's restlessness leads to dissatisfaction of the nursing staff. Furthermore, one of the main reasons for an increased risk of falling is dementia [4] which often involves underweight and restlessness [11] whereby the reliable functionality of the system can be affected as well.

For example if a patient weighs under 50 kg, proper function of pressure sensors is not guaranteed so that mattresses or ground pressure mats (cf. [12]) are useless. In addition, mobile dining tables or suitcases can lead to false positive alarms by standing on such floor sensors, which can affect a discontent of the nursing staff. Moreover, special cleaning procedures of nursing and/or clinical facilities can lead to the exclusion of such system components. Having this in mind, the implementation of a proper fall prevention system should be suitable to diagnoses and symptoms of the particular patient condition. This is also in line with the National Institute for Clinical Excellence findings; *"To be effective, they [Bed-Exit Alarms] need to be implemented with care and with a clear understanding of their limitations"* [10].

In general, video monitoring would be a proper solution but besides legal restriction relating to the usage of camera recordings in public, the basic acceptance is an important field. The acceptance of cameras surveillance impartial is quite low in a major group (in general under 50 percent) (see [13; 14]).

In recent years the Peter L. Reichertz Institute for Medical Informatics have worked on the field of fall prevention by developing several prototype systems. This led to first clinical study with the aim of measurement of the reduction falls on a geriatric ward, by close monitoring with a portable proprietary sensor system (www.shimmersensing.com). For this purpose, a bed exit alarm with this wearable was developed as a core component, which reliably detects rising attempts [9].

With the results and experience of this first clinical trial and close collaboration of various clinicians and nursing staff, we were able to further improve the system and adapt it to the conditions of clinical use. Last but not least, this includes the development of various hardware-software-components for the implementation of an adaptive, scalable and modular overall system for fall prevention, which will be presented in this paper. In addition, compared to existing solutions the INBED system is highly cost efficient and comprises the specific requirements of clinical use cases.

INBED system

The first version was tested within a larger 15-month study. For this iteration of the system, we designed the base station using an Arduino with an Atmel ATmega168 micro controller unit (MCU) and a Bluegiga WT11 Bluetooth module. If regular messages from the sensor are missing or the sensor detects a rising attempt, it triggers an alarm and the base station activates the nurse call. For each patient, one pair, that can easily be connected to the nurse call system at bedside, is needed [9].

The wearable part on the fall prevention system was the Shimmer sensor system. Via Bluetooth connection, a variety of receivers can be used to integrate the new modality into the clinic's system. Porting the algorithms to the hardware was straightforward. The Shimmer device provides enough resources, making it possible to detect additional states of the patient [15].

With the gathered information and data from the 2012 study, we could determine new challenges of the clinical everyday life and master them through further development of the system.

In order to cover all requirements, we decided to develop our own scalable system with a wearable core component, the INBED, in close cooperation with the clinical partners. The wearable itself is a small, affordable wireless sensor board based on an ATmega2564rfr2 System on Chip where the MCU as well as the transceiver unit are fully integrated on a single chip combined with a Bosch BMX055 Microelectromechanical systems. In Figure 1 the board can be seen, including an image of a coin scale and in comparison, with the relay node.

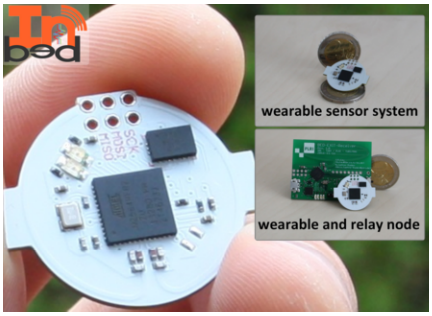

Figure 1– Current INBED wearable board with relay

The ATmega2564rfr2 includes both a low-power 8-bit MCU based on the AVR enhanced RISC architecture as well as a fully IEEE 802.15.4 compliant radio transceiver for the 2.4 GHz ISM band. To reduce the costs, a simple PCB dipole antenna is used. For the sensing part we used a small footprint Bosch BMX055 9-axis sensor module (3-axis accelerometer, 3-axis gyroscope, 3-axis magnetometer). The BMX055 is connected to the ATmega2564rfr2 via Inter-Integrated Circuit (I2C)-bus. By using the accelerometer, the BMX055 implements the option of a free fall detection which can trigger an interrupt. However, many other interrupts can be configured to trigger on several events, e.g. thresholds. Hence, by extensively using the pre-configurable interrupts, the energy efficiency of the entire wearable can be increased as reactive programming models can be applied.

The wearable is powered by a standard CR2032 battery. Thus, the cost overhead and efficiency limitations when using voltage regulators is excluded. To guarantee that the voltage level never undershoots the required level for reliable operation, the ATmega2564rfr2 integrates mechanisms like brown-out detection and a battery monitor. The voltage can be sensed continuously to allow an early notification when a battery runs out of energy.

All components are mounted on a 2-layer PCB with the dimension of 20mm diameter plus two 1mm wings and 6mm in height. The wearable detects several patient related movement events, like rising attempts, and sends a signal to the nursing staff immediately, using a relay node based on IEEE802.15.4. Finally, a signal processing base station (Raspberry Pi 3) to create a modular communication network. The base station provides an alarm which is displayed (optical, acoustical or haptic) on the user interfaces (hardware-enhanced mobile phone) and the staff terminals [15].

Overview and Scenario

The main goal of the INBED system is to inform the nursing staff about pre-fall patient movement events in appropriate time, that they can help the patient to get up and assist the walk (e.g. for the toilet) and prevent falls.

For the application of the system the INBED wearable will be attached to the patient's upper leg on the upper half of the thigh. This position is optimal to detect rising event by angle changes of the legs without affecting patient's comfort to much. Furthermore for a functional system, relay nodes have to be positioned on the ward at strategic points, like patient rooms, at a maximum distance of 20m from one another to form a suitable network for data transmission and node locating. Finally, the base station has to be set up. It should be equipped with some patient information and at least with system information, which relay nodes is where at the ward and which wearable node is in circulation.

For a better description of the system and its functions, we will use a fictional but typical clinical scenario described in Figure 2.

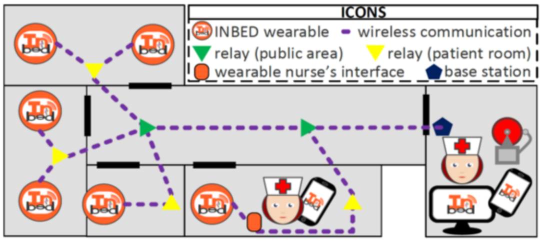

Figure 2– Floor plan of an exemplary ward with installed INBED system

The setting: The initial situation is to serve a regular geriatric ward. Here, the focus should be on patients with the following characteristics: high fall risk, motor functional deficits, sensory restricted, basically self-sufficient. In case of problems (pain, urgency) these patients are advised to contact the nursing staff to reduce the risk of falls. But in the majority of cases this instruction is ignored. Hence, in this scenario the patients are equipped with INBED wearables, which has been attached to the thigh by means of a regular band aid, at admission on the ward. A relay node has been installed in the rooms where the patients are located, as well as at certain distance on the ward floor, and at strategic points in the ward, like exits, elevators or public common area and the drug delivery. The base station is located in the nursing room and connected to the ward Wi-Fi. Ward internal mobile devices are available as an interface for the nursing staff. The model from Figure 2 can be assumed as a regular station. The overall system deploys an IEEE802.15.4 communication network and is therefore not dependent on external infrastructure. The network is structured as a tree with the base station as root node, relay nodes as intermediate nodes and the INBED wearables as leaf nodes while the wearables for the nursing staff can join the tree at any point. In every patient's room lays at least one patient, wearing an INBED device. The nurse's room is equipped with alarm interface devices, like a ward computer and the internal ward patient alarm system. Moreover, the simplified communication paths of the system can be seen, including broadcast communication of the wearables to fix patients room relay nodes as well as the unicast communication between the relay nodes and the base station. As can be seen one nurse is close to a patient, equipped with a smart phone including a system interface, which is utilized as a mobile relay node.

The procedure: A typical scenario might be, that a patient will wake up in the night e.g. due to a strong urinary urge. The patient begins to move in bed, due to a certain degree of physical restlessness is associated with the urge to urinate. This unusual high variance of the movement of the patient triggers a restlessness event. The event message is sent via a broadcast and received by the patient room relay node (nearest node). For each generated event alarm by the wearable will send various encrypted and pseudonymized information. These are information about the origin (ID of the sender), the nature of the incident (code of the event) and logistic data for the processing or function provision (battery voltage, etc.). While the INBED wearables send their messages via omnidirectional broadcast, the relay nodes forward their messages via directed unicast towards the base station.

A message contains message prefix, which shows the state of the current message within the system structure (new or already known), event identifier, device ID (wearable device), battery voltage (wearable devices), first relay node that received the massage (ID) and received signal strength indicator (RSSI) of the first receive. If the message is received by the base station, the contained data will be stored in a database which provides the information on several nursing staff devices (e.g. smart phones).

This alarm is displayed prioritized with the database's join information, affected patient, room, event type. The event is displayed via the ward computer as well as on the mobile devices of the nursing staff. Moreover, both acoustic or haptic alarm were optionally used. While the nursing staff is often quite busy and ignore restlessness warning and decides to continue with the current work, the restlessness warning can be deactivated via all interfaces. Further restless warning will be triggered by the system and notified by the staff, if the urge to urinate persists. In doing so, the nursing staff obtains knowledge about the urgency of an intervention on the patient.

With increasing urgency, the patient decides to go to the toilet without contacting the nurses. This triggers a rising-up-event which is distributed according to the restlessness event. At the base station, the rising-up alarm will be triggered with a higher priority compared to the restlessness alarm. Due to multi-morbid and motor-functionally restrictions of geriatric patients, the rising from reclined position will usually take some time (cf. [12; 14]). With the information about the patient's attempt to get up, the nursing staff is called to go to the patient as soon as possible. The alarm cannot be cancelled via application buttons.

When the nursing staff arrives at the patient, they can take care of his/her needs. By measuring the signal strength of the wearable's signal, the proximity to the nursing staff, can be estimated. Then an existing alarm will be switched off when staff is near an alarming device. Figure 3 shows the overall functions of the whole INBED system.

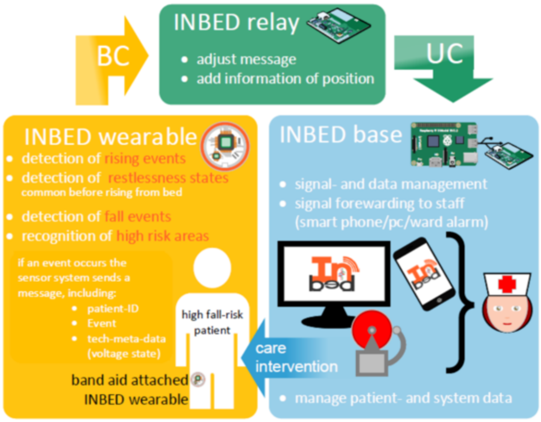

Figure 3– INBED system functionality diagram

Communication and Energy Efficiency: The past ten years research show a widespread of IEEE 802.15.4-based communication in small range Personal Area Network and for sensor communication [16; 17]. However, during the first bed-exit study an intuitive shortrange one-on-one Bluetooth communication of the wearable part to the base station, that triggers an alarm via nurse call were used. The unidirectional communication via the already installed, analogue and functional nurse call system allows only alarm triggering and not the raw data transmission. The follow-up system consists of commercial-of-the-shelf components on an open hardware-design. This enables short-range communication via its own modular, intuitive and highly energy-efficient IEEE802.15.4-network and is therefore largely. Its own network provides additional side-effects, such as indoor tracking or risk area detection. Due to the bidirectional connection, an adjustment of thresholds while operation is possible [15].

Testing: The functionality test of the entire system was performed under real conditions, with all components. Three test subjects (m=1, w=2, age=28±3), for three trials per subject and event were equipped with an INBED wearable before different scenarios have been investigated. The test cases include both, intended triggering of events (e.g. by standing up, falling, restlessness, error triggering) and testing of the normal case without explicit supervision. For the tests the wearable was attached to the upper front of the thigh as described before.

To underline the suitability for daily use the test series were performed in a clinical environment. For the validation of rising detection, the test subjects started from a lying position and slowly began to rise. Finally, they stood up and get out of the clinical bed, as can be seen in Figure 4. The first three phase images show the approach to the edge of the bed and the beginning of the uplift of the upper body. The phase images four to six show the overcoming of the bed edge with the body and the final raising to the standing position (#7).

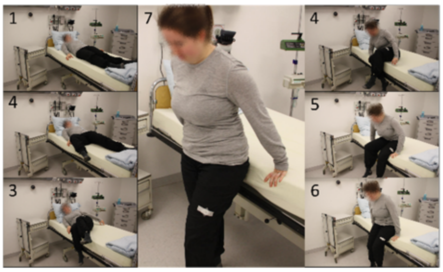

Figure 4: Procedure of a general rising out of bed, represented by seven phases.

We also validated the detection of fall events with six subjects (m=2, w=4, age=28±3), for five trials per subject, as well as restlessness events with two subjects (m=1, w=1, age=26±1), two nights with four wearables per subject, and the corresponding alarms. It should be mentioned, that these sequences of falls were exemplary but representative fall event in clinical environments like the rising before. Within the Figure 5 the raw acceleration data of the three axes are shown, as well as the restlessness counts at the bottom of the diagram and at the point when the interrupt occurred a dotted line can be seen. The counts of the diagram are weighted by the kind of the movement related to the intensity of the motion itself (calm motion = 1, stronger/quicker motion = 2).

The rise up is complete with the final standing of the subject. Thus, a measurement of a fixed period of time is not practical. In the shown case, the recording is about ten seconds long. The restlessness is transmitted after about one second and after about three seconds the rising was transmitted as an alarm.

For the fall test it can be said that the procedure is more or less the same as can be seen at rising with the slight difference that the trial isn't ending by standing but by a subject fall. While a fall the slight decreasing acceleration (near 0.4g) can be followed by high g peak by subject impact.

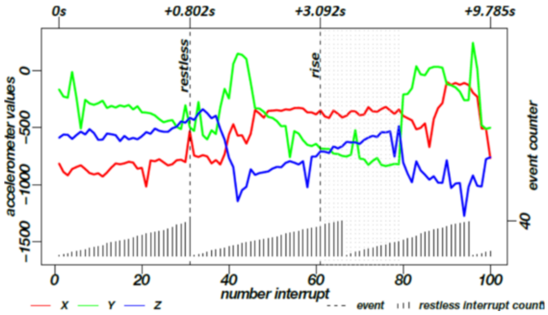

Figure 5– Diagram of the recorded INBED data during rising (raw triaxial acceleration data lines) – in lower area the restlessness counter lines - dashed line show the triggering of the alarms (restlessness and uprising) - grey dotted lines represent standing

For the test of restlessness events, the subjects went to a lying position and then turn from side to side. The recording of the uprising or falling test process differs from the restlessness in terms of duration, this is due to the functional determinism of rising. The recordings of the restlessness measurement are about 35 seconds long for the test trials. The triggering of the corresponding event is expected during the repeated rotation process. Within the tests the actual alarm triggered after about 20s under described circumstances. But it has to be mentioned that the trials aren't representative for every "real" geriatric patient hurry.

Prior to the test runs, we performed a learning phase based on collected data of rising events from different subjects within a cross-validation. According to the person's movement, interrupts are trigger the wearable to wakes up. Subsequently it reads out information about the three axes and the type of interrupts, e.g. if restlessness occurred. Due to the constant restlessness caused by the subject's movements, the INBED node does not have the opportunity to let the restlessness count decay again, by fading. Thus, the count is reset only after reaching the restless threshold. Besides the more detailed described tests above, further trials have been performed.

The testing of the main feature, the rise detection, was evaluated by a comprehensive assessment with 224 different subjects (mostly young students with knowledge of the functionality). The measurement was totally anonymous by means no subject meta data was stored. All subjects were placed in a laying position on a regular hospital bed like height cot.

Parallel to the described testing, several overall system interviews and demonstrations, for health care professionals and clinical IT experts, were done to improve the system and the system settings.

To test the communication features, as well as the energy-efficiency we investigated the communication range of the wearables. Therefore, INBED wearables were equipped with batteries and iteratively moved remoter away from a relay node. On average a communication range of 25m is reached for line of sight while about 15m-25m are usual in a common building structure. The different results are related to the specific structure of the sending path's obstacles, like walls, water pipes or power lines.

Results

For the main functionality the rising detection a sensitivity of 100% in total only slight differences in detection speed were mentioned (few seconds) could be achieved. Within the learning process we identified an angle threshold of 63−117° in sagittal axis.

For the fall events, an optimum value for the free fall phase is ≤ 0.4g and for the impact variance of ≥ 1.3g. However, problems were encountered, while heavy stomping gait pattern and individual steps can also be detected as a false-positive fall.

Within the restlessness detection tests no false-positive events were recorded. Any larger movement (e.g., rotation) seen in the reference camera footage has also been recognized by the INBED system as restlessness event and any documented false-positive rising was be detected by the system, as well.

To evaluate the energy efficiency of the nodes, we assume a battery power of 230mAh, a clock frequency of 8MHz of the MCU and a standard room temperature of less than 20°C. In "worst-case", which means a continuous transmission of a fixed message every 0.9s, the INBED wearable lasts about 52 hours (approx. 200,000 transmissions). The "best-case", where only life-sign messages occur, results in more than 19 days lifetime for the wearable.

Conclusion

The main functionality, the rising detection showed a high sensitivity (100%) for the tests. The specificity, under controlled circumstances, is also high (no false-positive while tests), but real clinical conditions will show reliable results. Former study results are promising (see [9]).

For the restlessness test a high specificity could be measured as well, but the arranged tests are maybe not that expressive, cause no older adult subjects were included for now, which may lead to inaccurate movements. Within a future study we will assess the specificity under real conditions.

The fall test results show quite good sensitivity in heavy falls, but the final sensor system setting can lead to false-positives while heavy gait or subject bumps. A strong bump of a patient, e.g. at a table, is interpreted with high probability also as a fall. However, this can be clarified by the staff by asking. In addition, such a strong impact can also lead to injury, hematomas, which may need treatment. The sensitivity is limited for short height falls, e.g. out of low-floor bed.

By a hybrid approach, both the advantages of short-range, e.g. energy efficiency, as well as the benefits of larger bandwidth of Wi-Fi from the base station can be used [15].

The further integration of other sensors, e.g. gyroscope is planned. Another goal is to further optimize internal processes by adding the possibility to adapt individual configuration values remotely. As the INBED system is operational in our second clinical long-term study, this time as a multi-centric and randomized study within two geriatric wards, starting soon.

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