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Framework for Preventing Falls in Acute Hospitals using Passive Sensor Enabled Radio Frequency Identification Technology

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Abstract— **We describe a distributed architecture for a real-time falls prevention framework capable of providing a technological intervention to mitigate the risk of falls in acute hospitals through the development of an AmbIGeM (Ambient Intelligence Geritatric Management system). Our approach is based on using a battery free, wearable sensor enabled Radio Frequency Identification device. Unsupervised classification of high risk falls activities are used to facilitate an immediate response from caregivers by alerting them of the high risk activity, the particular patient, and their location. Early identification of high risk falls activities through a longitudinal and unsupervised setting in real-time allows the preventative intervention to be administered in a timely manner. Furthermore, real-time detection allows emergency protocols to be deployed immediately in the event of a fall. Finally, incidents of high risk activities are automatically documented to allow clinicians to customize and optimize the delivery of care to suit the needs of patients identified as being at most risk.**

I. Introduction

Falls in hospitals is estimated to increase hospital bed days by 886,000 per year and cost AU$1375 annually [1]. This is only set to increase given population ageing. As a result of a fall, there can be a loss of independence, a decline in health status and the development of psychological consequences such as anxiety, depression and loss of confidence [2, 3]. Falls impact on others such as staff and family resulting in feelings of fear, guilt, anxiety, defensive actions and at times these can contribute to conflict and result in complaints, coroner's inquests and litigation [2, 3]. Consistent with what is reported in the literature, a recent audit (unpublished data) of in hospital falls within the medical division of the Queen Elizabeth Hospital (TQEH), Central Adelaide Local Health Network (CALHN) in South Australia (SA) revealed that falls occurred commonly in older people and those with conditions such as delirium or dementia [4].

In the TQEH, in hospital falls were common in patients admitted to the general medicine and geriatrics unit. The current target setting for our research is inpatient units that focus on the specialized geriatrics care of older people such as Geriatric Evaluation and Management (GEM) Units. Patients in acute hospital based GEM Units are managed by geriatricians and a multi-disciplinary team of nursing, allied health and clinical pharmacy staff with gerontology skills. These units manage frail older patients who following a short acute hospital stay (mean < 5 days) have evidence of decline in function (physical and cognition) and geriatric syndromes such as dementia and delirium. These patients have also been identified as likely to improve through the inpatient GEM model of care. GEM units provide for holistic assessment of patient's care needs and these include medical, psychological, cognitive and functional needs. A management plan is developed to address these care needs and multi-disciplinary interventions including acute disease management, chronic disease optimization, rehabilitation and/or palliative care management amongst others are implemented [1].

Current best practice strategies for falls prevention in hospitals are based on the findings of older studies involving older patients with length of hospital stays of 7 days or more and the interventions consist of risk identification followed by implementation of multi-dimensional falls risk minimization strategies (e.g. exercise, reducing risk medications etc.) [5-8]. It is acknowledged that these can be difficult to implement within busy ward environments especially with limited existing staffing resources [9]. Applying these principles, South Australian GEM units, through their service design, and because of their patient groups, implement best practice falls prevention strategies within their existing resources. However, falls rate remain high (9.93 per 1000 bed days at 2 SA units in 2010) because of the concentration of a high-risk patients, many with cognitive impairment, within these inpatient units [10]. Consistent with literature reports, the hospital audit (unpublished data) revealed that in hospital falls were frequently not witnessed, commonly occurred in the evening or night, involved patients with delirium or dementia, were related to patient transfers or ambulation and occurred in the patient room or bathroom [11].

To date there have been very few falls prevention studies involving technological solutions. In fact, there has been only one large cluster randomized study (10,264 patients) where clinical staff completed a falls risk assessment scale and the computer system then generated a care plan, bedside poster and patient education material. In this study, the falls rate in the intervention arm was lower compared to usual care [12].

In this paper, the researchers describe a falls management framework based on a novel movement sensor–alarm intervention as a strategy to reduce falls risk in acute care, especially in clinical settings where patients may have cognitive impairment. The same intervention may also be beneficial in residential care settings for the same reason. The authors hypothesize that this intervention is effective because: i) the one intervention monitors multiple risk

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activities such as entering and leaving the bathroom/shower and getting up from the bed or chair; ii) it incorporates staff's assessment of patient risk and is adjusted as per risk level to alert only in areas/situations where patients require supervision; iii) the intervention provides an alert to staff when patients exhibit significant signs of restlessness indicating that they have a care need that may need to be met (e.g. wanting water or in pain) allowing for prevention in contrast to falls detection [13-15]; iv) the intervention will detect when staff are present indicating supervision or care giving, reducing false positives; v) the patient wears a device allowing for patient monitoring and consequently enabling complementary applications such as wandering alarms; vi) despite monitoring patient movement, privacy is maintained, in contrast to other systems such as video-monitoring, where patients/clients have reported privacy violations [16, 17]; and vii) the intervention has the potential for wider application and therefore cheaper in the longer term (e.g. the system can be used in the ward area to track equipment, e.g. IV-pumps and guide restocking).

II. High Risk Activities

In hospitals, falls commonly occur around patient beds, in the corridors, around bathrooms and/or the toilets [18]. The majority of falls are not witnessed with patients not seeking assistance when transferring or toileting even when they are carefully instructed [12]. A study of an older persons unit revealed that 65.9% of falls occurred in the bedroom with 80.1% of these falls occurring around the bed [9]. Many falls occur at night when nurse staffing levels are lowest and confusion or nocturia occur [19]. In one UK report, only 5% of reported falls incidents were witnessed [3]. Similarly, over 54% of the bedroom falls in an older person's assessment, treatment and rehabilitation unit were un-witnessed [20]. The researchers have confirmed these findings through a recent audit of in hospital fallers in TQEH.

Clearly, for a large number of falls, staff members are not alerted to the fact that patients are undertaking risky movement activities and therefore have no opportunity to intervene in a timely manner. Consequently, the researchers have identified the following high risk activities: i) entering into a toilet or a bathroom facility without the aid of caregiver or leaving a patient's room without the aid of a caregiver; ii) getting up from a chair without the aid of a caregiver; iii) activity involving getting off a bed; and iv) mobilizing without a walking aid. Our falls management framework will automatically identify patient activities falling into the high risk activity set and seek the intervention of a caregiver.

III. Fall Management Framework

Low cost and privacy preserving sensor enabled RFID technology will be used to monitor activities recognized as leading to situations of increased falls risk (e.g. attempting to get out of bed or stand from a chair unsupervised and leaving a room unsupervised). The fully automatic detection of such high risk activities by patients will result in the patient monitoring software generating an automated alert via a paging system to seek attention from staff to mitigate the risk. There are three key elements to this intervention based on the AMBIGeM: i) Real-time monitoring environment; ii) Patient Monitoring Software; and iii) Response.

This intervention builds on other related technologies such as Wireless Sensor Networks (WSN) which have been used to monitor activities [13-15, 21, 22]. These technologies are relatively large, expensive and required battery replacement. The recent development of low cost, battery-free and therefore smaller wireless sensing technologies based on passive Radio Frequency Identification (RFID) technology have allowed for this novel intervention.

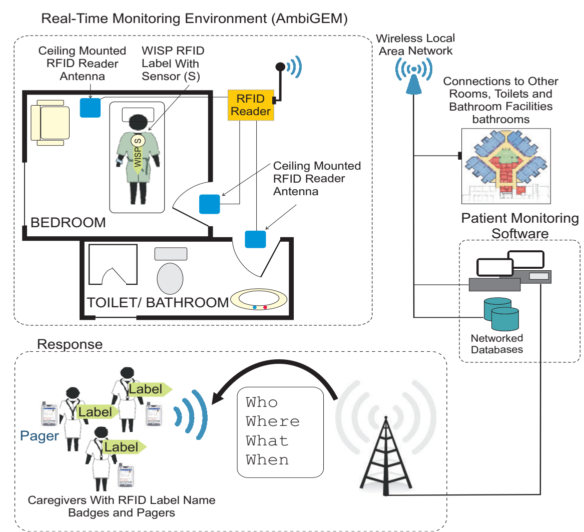

Figure 1. An overview of the the AMBIGeM falls prevention framework and the propsed deployment of the intervention.

A. *Real time monitoring environment*

The environment consists of fixed infrastructure such as the RFID Readers and Antennas. The RFID readers communicate with the Monitoring Software using existing wireless local area (WLAN) infrastructure. The patients are attached with wearable Wireless Sensing and Identification (WISP) device with an onboard tri-axial accelerometer.

Real-Time Monitoring Device, WISP: The *Wireless Identification and Sensing Platform* [23] combines passive (operates without batteries) Radio Frequency Identification (RFID) technology with traditional sensors. The device is 20 mm × 20 mm and 2 mm thick with an antenna for transmitting and receiving signals. The WISP devices weigh approximately 2 g. WISPs are a low cost, novel, battery free, sensing technology.

Similar to other passive RFID tags, WISPs are powered by harvested energy from radio waves transmitted from RFID readers. The harvested energy operates a 16-bit microcontroller (MSP430F2132) and a tri-axial a accelerometer (ADXL330). The microcontroller can perform a variety of computing tasks, including sampling sensors, and reporting that sensor data back to the RFID reader. The WISPs can be read at moderate range (about 3 meters) and are estimated to cost around $1 when mass manufactured [24].

RFID Readers and antennas: Also called interrogators, are responsible for powering and communicating with WISP tags. There are two different approaches for transferring power from the reader to the tag: magnetic induction and coupling to the electromagnetic (EM) waves transmitted by an RFID reader. The powering method depends on the distance of the tag to the RFID reader antennas where a distinction is made between a near field (energy storage fields) and a far field (where electromagnetic wave propagation is dominant). Through various modulation techniques, data is also encoded onto the same transmitted signal from the reader to the tag and the received signal from the tag to the reader. Interested readers are referred to [25].

RFID readers are generally placed at fixed locations with their antennas strategically placed to detect tagged objects passing through their EM field. RFID readers can read multiple co-located tags simultaneously (e.g., up to several hundred tags per seconds can be read by a modern RFID system). The reading distance ranges from a few centimetres to more than 10 meters, depending on the types of tags, the transmitted power of readers, antenna gain, interference from other RF devices and so on [25].

RFID readers are generally capable of multiplexing between multiple antennas (usually 4) which are used for transmitting RF (radio frequency) signals and receiving RF signals from tags that contain various information, particularly a globally unique identification number and other data such as acceleration readings of the 3-D accelerometer. Readers interface with local area networks, similar to the way laptops connect to wireless local area networks.

Ultra High Frequency (UHF) RFID readers operates between 920 MHz and 926 MHz in Australia. Currently, based on present studies, there are no known adverse effects from RFID readers operating in the UHF region on pace makers or implantable cardioverter-defibrillators. Furthermore, there is no known evidence that RFID systems operating in the far field (as proposed in the clinical study) using the UHF spectrum influences the performance of commonly used medical devices such as physiological monitors (such as electrocardiogram monitors) and intravenous pumps.

The proposed deployment of the falls management framework is illustrated in Fig. 1(the exact number of antennas is dependent on the dimensions of the patient's room and identifying the direction of patient movement requires that two antennas be deployed at a threshold). The reader antenna configuration used is capable of communicating with RFID tags (up to 10 m away) and WISPs (up to 3 m away).

B. *Patient Monitoring Software*

Overall architecture of the software is based on an *event-driven paradigm*, where data received from the underlying passive sensors are classified into high risk events and non high risk events. The high risk events are then analyzed by an expert system based on rules to make a decision regarding the final response.

The inference engine interacts with RFID readers using wireless local area networks within the ward areas to gather and to process data received and collected by RFID readers to identify patient activities in real-time (Fig. 2). The interface between the Inference Engine and the RFID readers is the Low-Level Reader Protocol (LLRP) [26]. Sensor data is gathered from the distributed network of RFID readers using the LLRP interface.

Multiple data streams (accelerometer readings, location information, direction of motion or velocity, strength of the received signal from the tags, time of event) are analyzed and used to detect the high risk activity by the inference engine (see Fig. 2). Then the monitoring application uses *Event-Condition-Action* (ECA) type rules to determine the course of action to take given high risk activity events reported by the inference engine. ECA rules are a popular paradigm for specifying behavior, for example:

Rule 1: `ON patient leaving room IF` (*`no walking aid AND unsupervised)`* `DO` *`send alarm`*.

Furthermore, ECA rules have clear declarative semantics and allow an instant operational realization.

C. *Response*

A rule based, multi-level response system is employed in the falls management system as illustrated in Fig. 2. The monitoring application is responsible for making a decision to send an alert to care givers based on assessing the particular high risk activity of the patient as well as their individual assessment of falls risk recorded at the time of admittance to the hospital.

Caregiver carry pagers (in order to receive timely alerts) and wear RFID name badges to facilitate the automatic identification and localization of caregivers to eliminate falls alters as well as monitor that an intervention is being administered.

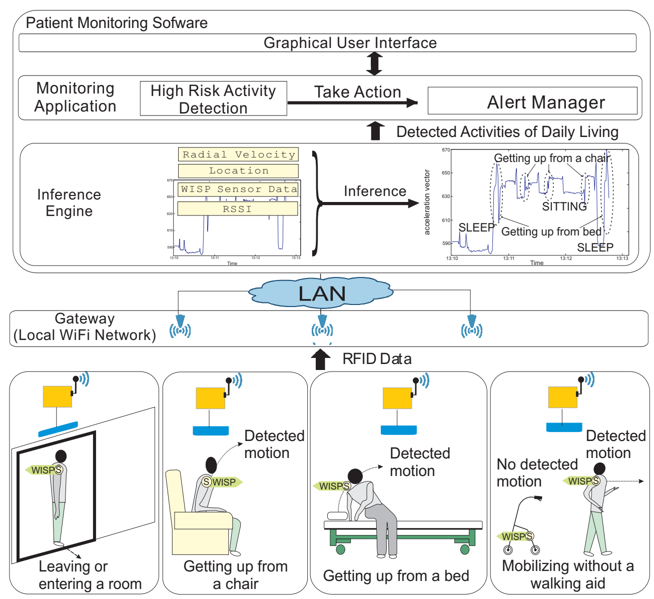

Figure 2. Systems architecture

IV. Systems Operation

Each patient is automatically and uniquely identified by the RFID tags. This identity acts like a license plate for accessing information regarding the falls assessment of that patient as well as set of activities the patient is not permitted to perform stored in backend databases. This information is expected to be collected when the patient is admitted to the hospital and stored securely in the networked databases.

Hidden from the view of the user, the fixed RFID infrastructure will collect sequences of accelerometer readings, patient identity, direction of travel of a patient and spatial location. RFID readers are capable of determining the location of patients (wearing WISP tags) and caregivers (wearing name badges with RFID tags) relative to the fixed antenna infrastructure based on measurement of change in phase and signal strength of the received signal from WISP as well as RFID tags [27]. Furthermore, carefully configured RFID reader antenna orientations provide the direction of travel past an RFID reader (such as a patient leaving a room without the supervision of a carer). The data collected by the RFID infrastructure is forwarded to the Patient Monitoring Application.

The data forwarded from the RFID reader layer is used by the inference engine to identify activities being performed by patients in real-time. The high risk activities outlined in Section II are detected by the Inference Engine (see Fig. 2). The corresponding activity identified by the inference engine is then forwarded to the monitoring application.

A. Ambulatory monitoring

In our pilot study to evaluate the falls management framework components, healthy adult volunteers wore a light Wireless Identification and Sensing Platform (WISP) tag attached to a Styrofoam over their garment situated over the sternum. As the device was light and small, it did not cause distress or harm to the subjects. Radiofrequency Identification Readers and antennas were strategically placed within the room to collect data from the WISPs. These devices were small and posed no risk to subjects.

Fig. 3 shows a representative, contiguous sample of ambulatory data processed from a volunteer during the evaluation of the falls management framework. It should be noted that the recordings for the samples in Fig. 3(a) and (c) have been filtered to isolate the information signals obtained from the raw accelerometer readings using a direct-form II second-order Butterworth low pass filter, with a cut-off frequency of 6.5Hz, and Fig. 3(b) was filtered through a band pass filter with cut off frequencies at 0.04 and 0.7 Hz.

Najafi et. al. in [21] has shown that in both standing-to-sitting and sitting-to-standing transitions associated with getting up from a bed and chair or sitting down on a chair or a bed, there are two phases: an initial leaning forwards followed by a leaning backwards. This postural transition results in the displacement of inclination angle between trunk and vertical axis of the body. The inclination angle can be estimated using the tri-axial accelerometer readings to identify activities involved in getting up from a bed or a chair without the help of a care giver. In particular the transition from lying in bed to sitting can be identified prior to sitting to standing (see Fig. 3(c)) from a bed based on the change in orientation of the anteroposterior and dorsoventral axis acceleration signals as shown in Figure 3(c).

In order to discriminate between sit-to-stand and stand-to-sit transitions involved in getting out of a chair we have used the Received Signal Strength Indicator (RSSI). The RSSI is correlated with the distance of the patient to the antenna receiving the data from the WISP tag. As we have shown in Fig. 3(b) this RSSI indicator is adequate, fast and sufficiently reliable.

It is demonstrated in [27] that the projection of the tag velocity vector on to the line of sight between the tag and the reader can be estimated by Time Domain Phase Difference of Arrival (TD-PDOA) measuring the phase of the tag at different times at the same interrogation frequency. In this approach the radial velocity component of the WISP tag changes from positive to negative or negative to positive depending on the direction of travel as the patient with the WISP walks past an RFID antenna. Then it is possible to detect the direction of travel by monitoring the times at which a patient passes across two antennas as shown in Fig. 3(d).

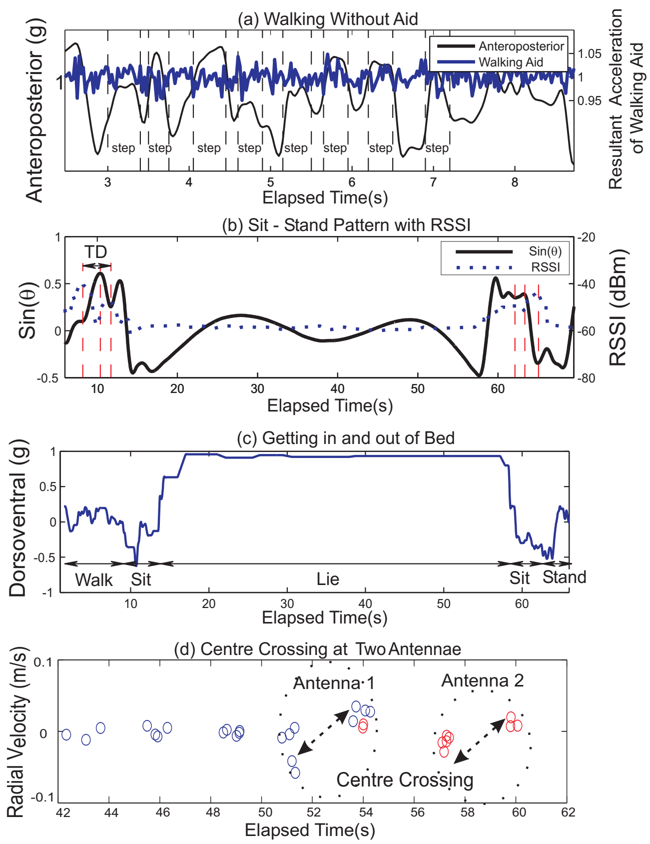

Figure 3. Representative data showing the classification of various high risk events based on the real-time monitoring environment: (a) walking pattern of a person and the resultant acceleration of the walking aid when not used; (b) sitting down and standing up with respective RSSI information, (c) walking, getting into bed, lying, and getting out of bed; (d) centre-crossing at two antennas showing the walking direction of the sensor bearer out of a room (going past antenna1 first then antenna 2).

B. Intervention

The monitoring application uses a rule engine to evaluate the events being received and uses the rules to decide on a course of action. The rules are designed to incorporate the high risk activities of individual patients, the time of day, the location of care givers with respect to the spatial location of patients, previously known locations of patients as well as the last time at which an alert was sent to decide if a paging message is to be sent to a care giver.

Then the alert manager executes various integrated actions, such as recording the incidence on file, sending an automated alert via a paging system to pagers carried by staff to seek attention from a caregiver to mitigate the risk, and displaying an alert on screen at the nurses' station. The alerting message transmitted includes: i) the identity of the patient (*who – provided by the RFID tags automatically*), ii) the physical location of the patient (*where – provided by the localization performed by the RFID readers and tags*), iii) the type of high risk activity (*what*), and iv) a timestamp of when the high risk activity was detected (*when*).

The alarm will not be activated or will be turned off when staff members are detected within a designated range of a patient at risk as this will be inferred as an intervention or a patient that is already supervised. The alarm can also be turned off at the nurses' station. If intervention by staff is not detected within a short preset time, the alarm will be triggered again. The threshold for alarms can be set by senior clinical or research staff following admission and falls risk assessment, and adjusted for variation to risk during the patient stay.

V. Conclusion

Our approach is not to detect falls in living or hospital environments but to address a need for preventing falls in acute hospitals and possibly residential care facilities using a technology based intervention. This paper described a proposed falls management framework developed for acute hospitals in terms of falls prevention using an AmbIGeM environment. The real-time monitoring device is low cost, battery free and wearable continuously without any maintenance. The system is customizable to individual patients and automatically determines the level of monitoring and care required for each patient based on the expert knowledge of physicians and clinicians.

In the future, we will work towards packaging the WISP sensor to allow reuse and insertion into a pouch with a Velcro fastener placed on the sternum of garments to enable the detection and inference of movements. This will also facilitate the wearing of the WISP 24 hours.

The described architecture forms part of an ongoing ageing and technology research project at the Basil Hetzel Institute and the Queen Elizabeth Hospital, Adelaide, Australia. The next stage of the project is a pilot clinical trial at the Queen Elizabeth Hospital.

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References

[1] Australian Comission on Safery and Quality in Health Care. Preventing falls and harm from falls in older people: best practice guidelines for Australian Hospitals, 2009.

[2] D. Oliver, "Prevention of falls in hospital inpatients: agendas for research and practice," *Age Ageing*, vol. 33, pp. 328-330, 2003.

[3] D. Oliver, F. Healey, T. P. Haines, "Preventing falls and fall-related injuries in hospitals," *Clin. Geriatr. Med.*, vol. 26, pp. 645-692, 2010.

[4] K. D. Hill, M. Vu, W. Walsh, "Falls in the acute hospital setting-impact on resource utilization," *Aust Health Rev.* vol. 31, pp. 471-477, 2007.

[5] F. Healey, A. Monro, A. Cockram, V. Adams, D. Heseltine, "Using targeted risk factor reduction to prevent falls in older in-patients: a randomised controlled trial," *Age Ageing*, vol. 33, pp. 390-395, 2004.

[6] M. Vassallo et. al., "The effect of changing practice on fall prevention in a rehabilitative hospital: The hospital injury prevention study," *J Am Geriatr Soc.*, vol. 52, pp. 335-339, 2007.

[7] T. P. Haines, K. L. Bennell, R. H. Osborne, K. D. Hill, "Effectiveness of targeted falls prevention programme in subacute hospital setting: randomised controlled trial," *BMJ*, vol. 328, pp. 676, 2007.

[8] R. Schwendimann, K. Milisen, H. Buhler, S. De Geest, "Fall prevention in a Swiss acute care hospital setting reducing multiple falls," *J. Gerontol. Nurs.*, vol. 32, pp. 13-22, 2006.

[9] R. G. Cumming et. al. "Cluster randomised trial of a targeted multifactorial intervention to prevent falls among older people in hospital," *BMJ.*, vol. 336, pp. 758-760, 2006.

[10] M. Stenvall et. al., "A multidisciplinary, multifactorial intervention program reduces postoperative falls and injuries after femoral neck fracture," *Osteoporos. Int.*, vol. 18, pp.167-175,m 2007.

[11] M. Hitcho et.al., "Characteristics and circumstances of falls in a hospital setting: A prospective analysis," *J. of Gen. Int. Med.*, vol. 19(7), pp. 732-739, 2009.

[12] P. C. Dykes et. al., "Fall prevention in acute care hospitals: a randomized trial," *JAMA*, vol. 304(17), pp. 1912-1918, 2010.

[13] M. R. Narayanan, M. E. Scalzi, S. J. Redmond, S. R. Lord, B. G. Celler, N. H. Lovell, "A Wearable Triaxial Accelerometry System for Longitudinal Assessment of Falls Risk," *The 30th Annual International IEEE EMBS Conference*, Vancouver, British Columbia, Canada, August 20-24, 2008.

[14] A. K. Bourke, K. M. Culhane, J. V. O'Brien and G. M. Lyons, "The development of an accelerometer and gyroscope based sensor to distinguish between activities of daily living and fall-events," *Proceedings of the European Medicine, Biology and Engineering Conference (EMBEC)*, Prague, Czech Republic, November 20-25, 2005.

[15] M. R. Narayanan, S. R. Lord, M. M. Budge, B. G. Celler, N. H. Lovell, "Falls Management: Detection and Prevention, using a Waist-mounted Triaxial Accelerometer," *29th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, 22-26 Aug. 2007.

[16] S. T. Londei et. al. "An intelligent video monitoring system for fall detection at home: perceptions of elderly people," *J Telemed Telecare.*, vol. 15, pp. 383-390, 2009.

[17] C.J. Lord, D. P. Colvin, "Falls in the elderly: Detection and assessment," *Technology for the Aging*, vol. 35, pp.1-4, 1991.

[18] Nursing. JBIfEC: Falls in hospitals: fact sheet, Adelaide, 2007.

[19] G. R. Murray, I. D. Cameron, R. G. Cumming, "The consequences of falls in acute and subacute hospitals in Australia that cause proximal femoral fractures." *J. Am. Geriatr. Soc.*, vol. 55, pp. 577, 2007.

[20] H. C. Hanger, M. C. Ball, L. A. Wood, "An analysis of falls in the hospital: can we do without bedrails?" *J. Am. Geriatr. Soc.*, vol.47, pp. 529-531, 1999.

[21] B. Najafi, K. Aminian, A. Paraschiv-Ionescu, F. Loew, C.J. Bula, and P. Robert, "Ambulatory system for human motion analysis using a kinematic sensor: monitoring of daily physical activity in the elderly," *IEEE Trans Biomed Eng*, vol. 50(6), pp. 711-23, 2003.

[22] M. Philipose et. al., "Inferring activities from interactions with objects," *IEEE Pervasive Computing*, vol. 3(4):50-57. October-December 2004.

[23] A.P. Sample, D.J. Yeager, P.S. Powldge, J.R. Smith, "Design of an RFID-based Battery-free Programmable Sensing Platform," *IEEE Transactions on Instrumentation and Measurement*, vol. 57(11), pp. 2608-2615, 2008.

[24] M. Buettner, B. Greenstein, A. Sample, J.R. Smith, D. Wetherall, "Revisiting Smart Dust with RFID sensor networks," *Proc. of the 7th ACM Workshop on Hot Topics in Computer Networks*, Calgary, Alberta, Canada. 6-7 October, 2008.

[25] K. Finkenzeller, *RFID Handbook: Fundamentals and Applications in Contactless Smart Cards and Identification*, John Wiley & Sons, Inc, 2003.

[26] EPCGlobal. Low level reader protocol (llrp), version 1.0.1. Available from: http://www.gs1.org/gsmp/kc/epcglobal/llrp, accessed 27/03/2012.

[27] P. V. Nikitin et al., "Phase Based Spatial Identification of UHF RFID Tags", IEEE RFID, Orlando, Florida, USA, 15-20 April, 2010.