iFall - Case Studies in Unexpected Falls

Ralf Salomon
University of Rostock
Faculty of Computer Science
and Electrical Engineering,
18051 Rostock, Germany
Email: ralf.salomon@uni-rostock.de

Marian Lüder
University of Rostock
Faculty of Computer Science
and Electrical Engineering,
18051 Rostock, Germany
Email: marian.lueder@uni-rostock.de

Gerald Bieber
Fraunhofer-Institute
for Computer Graphics Rostock
Joachim-Jungius-Strasse 11
18059 Rostock
Email: gerald.bieber@igd-r.fraunhofer.de

***Abstract*—Previous research has developed a new embedded system, called iFall, for the detection of unexpected falls for elderly people. This paper reports a larger set of fall experiments that have been done in laboratory setups, similar to typical real-world experiments. These experiments indicate that with monitoring its own rotation along any axis, iFall is able to detect a fall in its very beginning. iFall is thus able to protect its user from severe injuries and its consequences, by initiating some emergency actions, such as inflating a tiny airbag.**

I. Introduction

For elderly people, unexpected falls can be a major problem, since they often go along with severe injuries, such as femoral neck fractures [1], or might even cause the person's death. In addition to the direct monetary costs, such unexpected falls also cause significant problems to a person's social environment.

Unexpected falls of elderly people are not rare events but a major global problem: Currently, 60% of all elderly people of 65 years in age or older are falling at least once a year in their home environments. Moreover, in nursing homes, the rate is with 2.4 falls per year per person even higher [1].

Due to the *global* significance of this problem, previous research has proposed several systems for the dection and/or avoidance of unexpected falls and their consequences. For example, some systems try to detect a fall by camera systems [2], by activity monitoring, e.g., the IST Vivago system [3], and portable measurement devices [4]. Other systems, such as FADE [5], incorporate the sound of the falling (and crashing) body in order to increase the system's reliability. Previous research has also proposed to include barometric information, in order to detect a fall.

Even though the existing approaches do provide significant steps towards the assistance of elderly people, they suffer from one or more of the following problems: (1) they issue false alarms, (2) they depend on the spatial orientation of the fall detector, and (3) most severely, they detect a fall only *after* it has happend. Because of these deficiencies, existing systems might issue an alarm, if a person takes a nap, or is not able to prevent the user from severe injuries.

Recent research [6] has proposed a simple embedded system, called iFall, for the investigation of unexpected falls. iFall consists of a small processor, and some acceleration and air pressure sensors. This system is described in more detail in Section II, and provides enough resources for the detection and analysis of unexpected falls. The iFall system also incorporates a new algorithmic approach for the detection of a fall. In contrast to the measurement of pure acceleration values, the new algorithm monitors the angle between consecutive readings of an arbitrarily oriented, three-dimensional acceleration sensor. The description of this algorithmic approach is the subject of Section III.

The utility of the iFall system has been tested in a series of indoor experiments. These experiments are reported in Section IV. The results indicate that iFall is able to detect a fall in its very beginning. This early-stage detection allows future system releases to issue appropriate emergency actions, such the inflation of an airbag. These options are briefly discussed in Section V.

II. iFall

iFall is an embedded system with both its hardware and software tailored to the detection of unexpected falls. This section describes the hardware architecture in some detail, whereas the description of the software is deferred to Section III.

A. iFall's Hardware Architecture

iFall is based on its predecessor, known as the StairMaster [7] (Fig. 1). Its hardware architecture is fairly standard and sketched in Fig. 2. In its core, it consists of an 8-bit Atmega644

Fig. 1. StairMaster

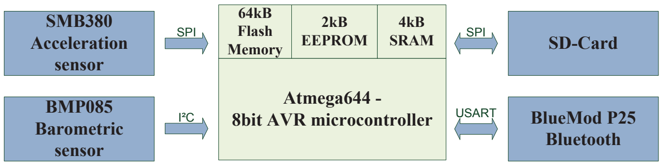

Fig. 2. Schematic of the inner communication structure

micro controller [8] with 64 kB internal Flash, 4 kB internal SRAM, and 2 kB of internal EEPROM. In addition, iFall employs a 2GB secure digital (SD) memory card to backup all sensory data and all the computational results.

In addition to the standard communication interfaces, iFall is also equipped with a class-2 Bluetooth module BlueMod P25 [9], which allows for a communication range of up to 25 meters. This module constitutes iFall's interface to the outside world, e.g., cellular phones, laptops, or any other Bluetoth-capable device. This Bluetooth module is connected to the micro controller via the USART interface, which operates at 9600 Baud, and utilizes the Serial Port Profile to emulate a serial interface to other Bluetooth clients. In this configuration, all data that are sent by the micro controller are directly forwarded to the connected Bluetooth client, which can be a cellular phone, for instance. The purpose of the connected Bluetooth client is to perform further user-specific data processing and/or to issue an emergency action, such as inflating an airbag or performing an emergency call. The chosen communication approach has the following three advantages: (1) it increases the overall system flexibility, (2) it allows for the utilization of further, more powerful processing devices, and (3) it allows for the integration of further modalities, such as GPS position data, which might be helpful in finding helpless persons.

B. iFall's Sensory System

iFall is equipped with a three-dimensional acceleration sensor SMB380 [10], which can be operated in a 2 g, 4 g, and 8 g mode. This sensor is connected to the processor by the SPI interface, which utilizes a 10-bit wide data bus and can operate with a maximum data rate of 10 Mbits/s.

In order to increase iFall's reliability, it also employs an additional state-of-the-art air pressure sensor BMP085 [11]. This sensor is connected to the processor via the built-in I^2C interface, which operates at about 800 kbits/s. This sensor yields a resolution of about 0.03 hPa, which corresponds to a change of about 25 cm in altitude, at an effective range of 300 hPa to 1100 hPa. This sensor provides 133 measurements per second. Because of its fabrication, i.e., utilizing the piezoresistive effect and employing the advanced-porous-silican-membrane technology, the sensor consumes about 3 μA and is as small as 5 mm×5 mm×1.2 mm in size, which might be very interesting for mobile embedded systems.

C. iFall's Hardware Properties

iFall's hardware platform is particularly tailored to the usage as an embedded system. Thus, all components are low-power devices, with a required voltage of 3.6 V at a total current of about 45 mA. For these power requirements, a simple lithium polymere battery with 3.6 V and a capacity of 1200 mAh is sufficient to operate iFall for more than 24 hours with Bluetooth activated all the time; with Bluetooth shut off, the battery allows for an operation of about seven days in a row. Overall, iFall's dimensions are as small as 70 mm×26 mm×49 mm at a total weight of 78 gramms. With these physical properties, iFall can be easily used as a mobile embedded system for everyday use. With its plastic case, iFall is very robust and can thus also be used in rough terrains, such as on ski slopes and mountaineering. A further application area are roofers, for whom iFall might be used as a full protection guard.

III. The Fall-Detection Software

Most existing systems, for example the fall detector FD-100 [12], the Piper Falldetector [13], and the Vivago Sicherheitsarmband [3], as well as current research [14], [15] monitor the acceleration along the sensor's three principle axes. In case, the acceleration value along a specific axis exceeds a prespecified value, the system would assume that the subject, i.e., the person who wears the device, has crashed onto the floor, which would mark the end of an unexpected fall, or the device would assume the actual falling, i.e., a free fall, if the acceleration falls below another certain threshold. These approaches work to some extend, but have to cope with one or more of the following difficulties:

1) The acceleration sensor, and thus the fall detection device, has to know its orientation relative to the subject in order to derive a movement towards the ground.
2) The fall detection device has to define a certain threshold, which might also be exceeded by regular activities, such as fast walking, hopping, using an elevator, or driving a car on a rough road, which all might be the source of false alarms.
3) The total length of the three-dimensional acceleration sensor provides conclusive information only at the end of a fall, since a crash onto the floor leads to significantly pronounced acceleration values; at the beginning of a fall, the device's acceleration changes only very marginal and slowly (see, also Section IV). Therefore, all existing devices more or less detect a fall too late, but can nevertheless automatically issue an emergency (phone) call after the fall has occurred.

iFall employs two different sensor modalities, i.e., a three-dimensional acceleration sensor as well as an air pressure sensor. In order to approach the difficulties discussed above, it monitors the change in orientation of its acceleration vector, as is explained in the remainder of this section.

iFall monitors the three acceleration values a_x, a_y, and a_z along the sensor's three axes individually. It then constantly calculates the angle

$$\cos\varphi = \frac{\vec{A}_t \cdot \vec{A}_{t+1}}{\|\vec{A}_t\|\|\vec{A}_{t+1}\|} \quad (1)$$

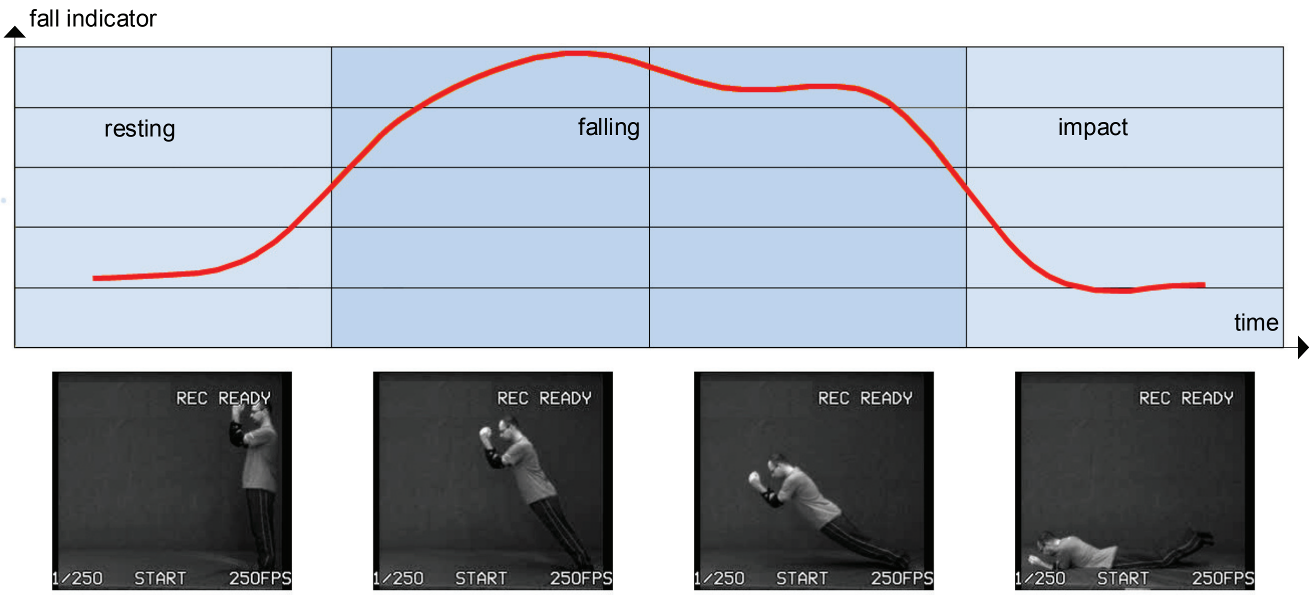

Fig. 3. The fall indicator signals the fall, even at the beginning of the fall (second part of the picture). The time between the subframes two and four is sufficient to initiate some emergency actions.

between two consecutive time steps t and $t+1$ of the acceleration vector $\vec{A} = (a_x, a_y, a_z)^T$, with "·" denoting the inner or scalar product of the two vectors.

This option is motivated by the observation that a fall is not just "jumping" up or down, but that it is inevitably linked to a rotation of the entire body. Then, iFall assumes a fall, if this angle $\varphi > \theta$ exceeds a prespecified threshold θ, which depends on various factors, such as the sampling rate of the sensor as well as the regular activities of the subject. The threshold θ should thus be calibrated in cooperation with a doctor, a physiotherapist, or the like.

By monitoring the angle φ, the fall detection is independent of the actual orientation of the system with respect to the subject's body.

A further remark should be made on the usage of an air pressure sensor: this sensor might lead to a more robust behavior of the entire system, since a change in altitude might verify or invalidate other sensory data. However, it frequently happens that the air pressure is suddenly rising or falling. Reasons might be a wind gust, opening or closing a door, walking up or down one floor, or even changing weather conditions. Thus, such a fall detection device would benefit from a reference system that is placed, for example, on the table within the same room. Unfortunately, the utility of this approach is limited due to practical considerations. But nevertheless, the air preasure sensor is worth it to be considered, which will be done in future research.

IV. Results

The iFall system was tested in a series of indoor experiments of different types. In all these experiments, iFall was mounted at the hip of a subject. The subject did a series of falls and always "landed" on a soft mat. The results are summarized in Figs. 4-11. Every performance figure shows both the angle φ and the normalized length of the acceleration vector $|\vec{A}|$ over some selected time steps.

Figure 3 shows how the angular velocity $\omega = \varphi_t - \varphi_{t-1}$ changes during the course of a fall. As can be seen, the angular velocity quickly indicates the fall quite early. It can also be seen that the angular velocity increases during the fall and vanishes at its end.

In the first experiment (Fig. 4), the person was standing in front of the mat and was then falling forward. It can be seen that at time step 21, the angle φ shows a significant change, which indicates the beginning of a forward rotation, and thus, the beginning of a fall. At that time, the total length

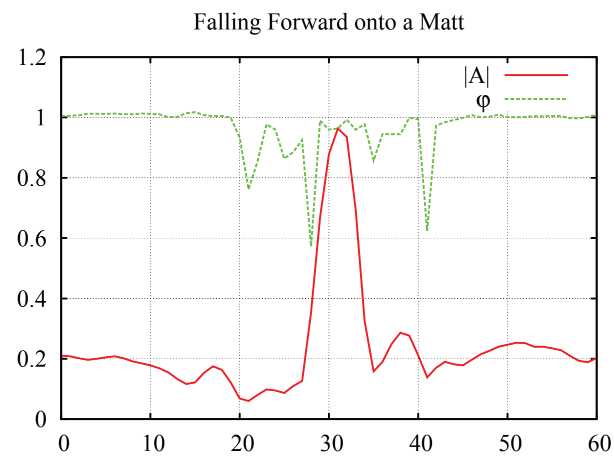

Fig. 4. Falling forward onto a mat: the fall began at time step 21 and first contact with the mat happend at time step 28.

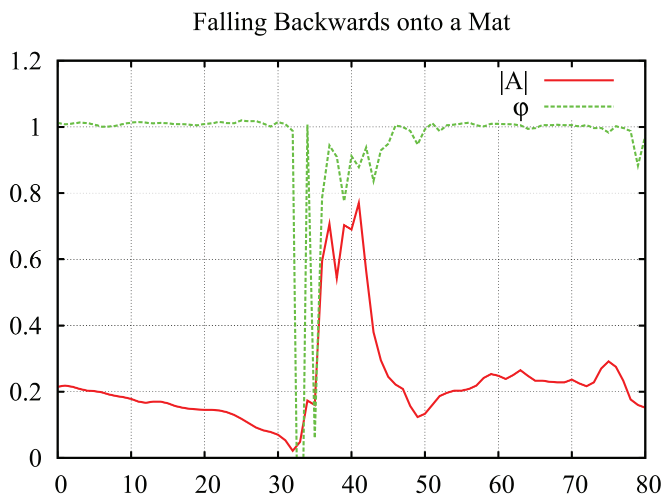

Fig. 5. Falling backwards onto a mat: the fall began at time step 32 and first contact with the mat happend at time step 36.

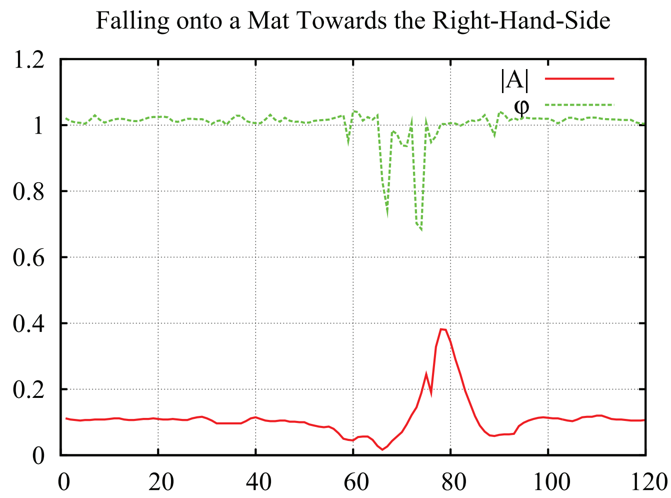

Fig. 7. Falling sidewise onto a mat: the fall began at time step 66 and first contact with the mat happend at time step 78.

of the acceleration vector $|\vec{A}_t|$ shows only a very slight change, which is as small as the present noise, since the falling has just begun. The length of the acceleration vector $|\vec{A}_t|$ changes as late as time step 28 at which the person made his/her first contact with the mat. This example clearly shows that the angle φ indicates the fall very early in time, which would provide enough time to issue some emergency actions.

The second experiment (Fig. 5) used the same setup as the first one, except that the person was falling backwards. Conceptually, the data is very similar, except that the rotation is much stronger. This might be due to the fact that when falling backwards, a subject has less control, which is much more uncomfortable.

In the third experiment (Fig. 6), the person was walking straight ahead and then stumbling at the mat causing a forward fall. The walking behavior is indicated by the periodic changes of the length of the acceleration vector $|\vec{A}_t|$.

At time step 90, the graph indicates a very slow decreasing trend, which however is impossible to be timely detected by a fall detection device, since the changes are way below the periodic changes of the regular walking behavior. However, the change of the angle φ clearly signals the beginning of a fall at time step 97; the length of the acceleration vector signaled this fall as late as time step 112 when the person made contact with the mat, which would be way too late for any protection actions.

In the fourth experiment (Fig. 7), the subject fell onto a mat, which was located at the right-hand-side of his body. It can be clearly seen that as compared to the acceleration vector $|\vec{A}_t|$, the angular change φ signals the beginning of the fall already 9 time steps earlier, which corresponds to 281 ms.

The fifth experiment (Fig. 8) shows an extraordinary fall: a

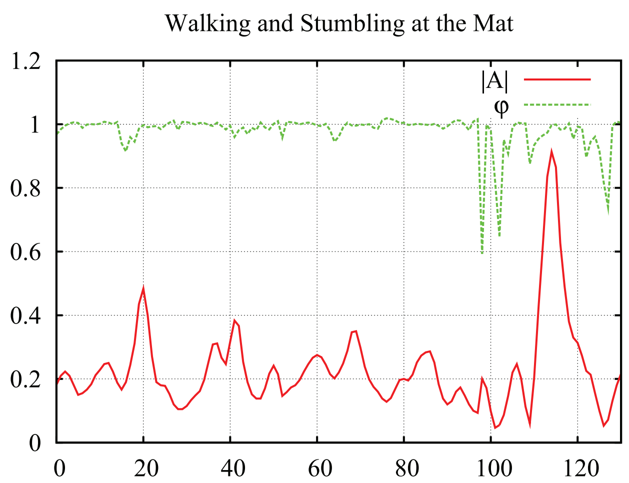

Fig. 6. Walking and stumbling at the mat: The walk lasted for about the first 100 time steps. The fall began at time step 97 and first contact with the mat happend at time step 112.

Fig. 8. Martial Arts throw (Morote-Seoi-Nage): The throw began at time step 95 and ended with a roll of the subject at time step 130.

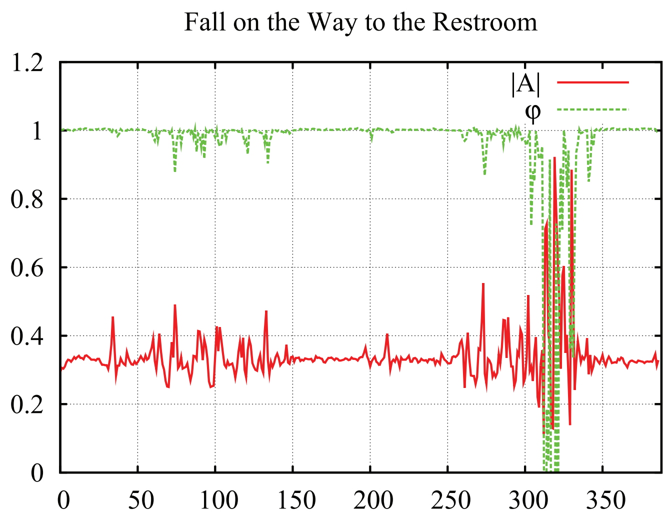

Fig. 9. The first 150 steps indicate the person's walk to the restroom during which the angular velocity is rather small. At time step 305 the person falls, as is clearly indicated.

Fig. 11. This figure clearly indicates that the monitoring of the angle between two acceleration vectors is also suitable to detect a person getting unconscious.

martial arts was throwing (Morote Seoinage) the subject over his shoulder. The resulting extreme rotation φ can be identified at time step 100. The subject's landing on the mat was at time step 120, as can be seen from the acceleration vector $|\vec{A}_t|$. After the strong impact, the subject was rolling on the mat, which explains the second change of the angle φ around time step 130.

Fig. 9 shows the acceleration vector $|\vec{A}_t|$ and the angle φ during a walk to the restroom. At the beginning of this figure, the person walked normaly, so that the change of the angular velocity is small. Between time step 150 and 250, the person stopped. After time step 250 the person hits a door frame, so that the acceleration vector changes stronger. At the end (time step 305), the extreme rotation of the angel φ signals that the person begins to fall.

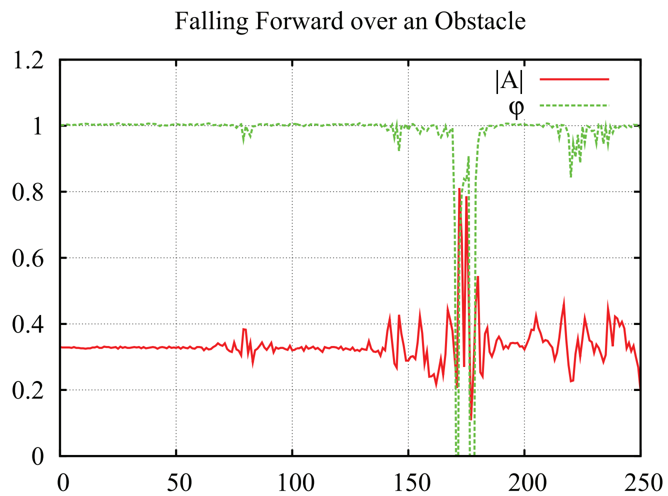

Fig. 10. A fall over an obstacle is similar to the falls described above: the angular velocity is a clear indication of a fall, which beginns to happen at time step 269 and ends at time step 278.

In the seventh experiment (Fig. 10), the person fell over an obstacle. In the first 250 time steps, the person did nearly nothing. At time step 175 the very slight change of the angle φ and the small peak of the acceleration vector $|\vec{A}_t|$ signals a jump of the person. Furthermore, this figure shows that a fall over an obstacle is similar to the falls described above. The change of the angle φ clearly indicates the fall, which started at time step 269 and ends at time step 278.

A frequently discussed problem is a situation in which a person gets unconscious, since the acceleration values change quite late; in the beginning, the changes are rather small and increase only towards the end of the fall, which happens around time step 88 in Fig. 11. However, as was already seen in all the experiments discussed above, the angle φ between two consecutive measurements significantly increases already in the beginning of this process, as can be seen around time step 78 in Fig. 11.

In summary, all experiments have shown that the monitoring of the orientation of the acceleration vector $|\vec{A}_t|$ over time is a reliable indicator for the beginning of an unexpected fall.

V. Discussion

This paper has presented a new embedded system, called iFall. It has been shown that a rather standard embedded system hardware in combination with a new algorithm is able to detect an unexpected fall both timely and reliably. If assuming a free fall without any action of the subject, the time between the signal and the end of a fall is roughly 400 ms. Since this time span is roughly ten times longer than a car airbag has, it is more than sufficient to inflate some body protectors with low impact.

The proposed fall detection device has been developed as an embedded system with low energy demands, as light as possible, and with very small dimensions, such that it can be worn unintrusively by almost anyone. Because of the very low

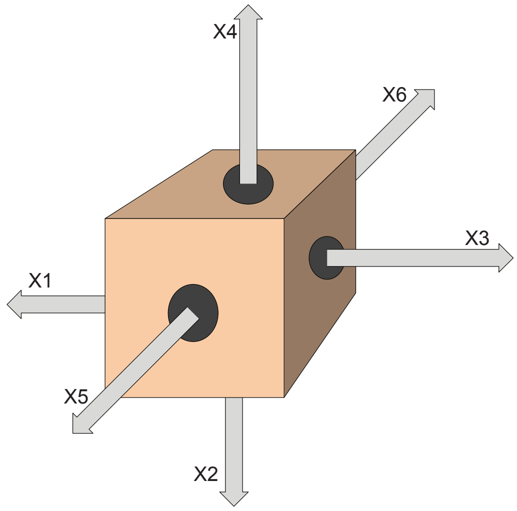

Fig. 12. The composed air pressure sensor consists of six elementary sensors, which are mounted perpendicular to each other.

resource demands, future iFall releases might be integrated into, for example, high-performance cellular phones.

In all experiments so far, the rotation of the subject was sufficient to detect an unexpected fall; the air pressure sensor has just supported this indication a posteriori by signaling a significant change in altitude. Future research will be dedicated to a better integration of the air pressure sensors. The goal will be to upgrade these sensors from a secondary information source to a primary one. One option towards this goal is the realization of a complex air pressure sensor as shown in Fig. 12.

It consists of six (at least four) air pressure sensors that point towards the three principal axes x, $-x$, y, $-y$, z, and $-z$. Such a sensor has the following properties: any change of the current air pressure would apply to all sensors simultaneously. Since all sensor readings would change in synchrony, iFall could derive that no movement has occurred. In case of a movement, however, the sensor readings change differently. Lets assume a movement in the x-direction. Then this sensor would read a higher pressure than the sensor in the reverse direction. Also, the other sensors would provide slightly decreased readings, since the air is flowing along the sensors, which reduces their pressure readings. The validation of this concept, however, is subject of future research.

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References

[1] G. W. Brag, “Falls Risk Factors for Persons Aged 65 Years and Over - New South Wales,” Australian Beuro of Statistics, Tech. Rep., Oct. 1995.

[2] C. Rougier, J. Meunier, A. St-Arnaud, and J. Rousseau, “Fall Detection from Human Shape and Motion History using Video Surveillance,” in *21st International Conference on Advanced Information Networking and Applications Workshops (AINA 2007)*, 2007.

[3] IST International Security Technology Oy. [Online]. Available: http://www.istsec.fi

[4] H. Inookal, Y. Ohtakil, H. Hayasaka, A. Suzuki, and R. Nagatomi, “Development of Advanced Portable Device for Daily Physical Assessment,” in *SICE-ICASE International Joint Conference 2006 (SICE-ICCAS 2006)*, 2006.

[5] M. Popescu, Y. Li, M. Skubic, and M. Rantz, “An Acoustic Fall Detector System that Uses Sound Height Information to Reduce the False Alarm Rate,” in *30th Annual International IEEE EMBS Conference*, 2008.

[6] R. Salomon, M. Lüder, and G. Bieber, “iFall - a New Embedded System for the Detection of Unexpected Falls,” in *Eighth Annual IEEE International Conference on Pervasive Computing and Communications*, 2010.

[7] M. Lüder, R. Salomon, and G. Bieber, “StairMaster: A New Online Fall Detection Device,” in *2. Ambient Assisted Living Kongress (2. AAL Kongress)*, 2009.

[8] Atmel Corporation. [Online]. Available: http://www.atmel.com

[9] Stollmann Entwicklungs- und Vertriebs-GmbH. [Online]. Available: http://www.stollmann.de

[10] *Data Sheet and Operating Instructions SMB380*, Bosch Sensortec, 2006.

[11] *BMP085 - Digital pressure sensor, Data sheet*, Bosch Sensortec, 2008.

[12] Vitaris GmbH. [Online]. Available: http://www.vitaris-gmbh.de

[13] Tunstall GmbH. [Online]. Available: http://www.Tunstall.de

[14] M. Mathie, J. Basilakis, and B. Celler, “A System for Monitoring Posture and Physical Activity Using Accelerometers,” in *23rd Annual Int. Conf. IEEE Engineering in Medicine and Biology Society*, 2001.

[15] J. Hwang, J. Kang, Y. Jang, and H. Kim, “Development of Novel Algorithm and Real-time monitoring Ambulatory system using Bluetooth module for fall detection in the elderly,” in *Proceedings of the 26th Annual International Conference of the IEEE-EMBS*, 2004.