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3DCane: a monitoring system for the elderly using a connected walking stick

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Abstract—fall related injuries caused have become a leading cause of fatalities among the elderly. Lots of aging people rely on a cane as a help device to overcome such problems as balance loss and leg weakness, presumed to be at the origin of many fall incidents. In this respect, the internet of things may turn out to be critically helpful, by offering disabled people the assistance and support necessary for achieving a good quality of life and allowing them to participate in the social and economic activities. In this paper, a 3DCane design is depicted, with an implementation for the CANet project, a system whereby a comprehensive monitoring of disabled people can be maintained through the use of their connected walking stick. Actually, the 3DCane is modeled through consideration of real-time movements for a thorough understanding of the concerned person's state, including fall detection. To note, the 3DCane applies a multi-stage thresholding framework based on an accelerometer. Experiments have revealed that the fall-detection algorithm appears to be robust in term of detection rate and false positive rate.

Index Terms—connected walking stick, fall detection, multi-stage thresholding, real-time movements.

I. INTRODUCTION

Nowadays, the world has witnessed remarkable demographic changes culminating in the emergence of aging populations and life longevity phenomena [1]. The worldwide number of elderly, exceeding the age of 65, reached 760 million in 2010, and is expected to attain 1 billion by the end of 2020 [2], and 2 billion by 2050 [1]. Projections for 2150 have shown that the proportion of elderly people is expected to represent the third of the world population, which makes the goal of maintaining healthy aging a priority at the European level [3].

In this context, using sensor networks likely to help collect various measures on the persons' condition, or monitor any suspicious change in their environment, stands as a very favorable solution for many reasons. Economically, monitoring elderly persons while safeguarding their usual living environment helps greatly in reducing nursing costs by specialized staff at a hospitals or nursing care units home. A significant contribution is related to the old person's

psychological and social aspects, as it is thanks to the discreet and imperceptible monitoring, that the sense of security, respect for privacy and autonomy could be preserved. Indeed, mobility devices and personal assistance are strongly desired to ensure a certain independence of the elderly [4]. In this regard, used by a large number of old people, the cane constitute a massively versatile assisting device thanks to the simplicity and precious help it may provide.

A new discipline called e-health [5] has emerged, as a bridge between the new information-communication technology and public health [6]. In this respect, e-health has highlighted certain elderly related health problems and dependence, with the particular aim of solving the aging population relating problems. In a bid to improve the elderly living conditions, several solutions integrating new technologies within the health system have been proposed by specialist in this area. This new field of research is intended to help grant a privilege to users by facilitating life and making it rather convenient. In fact, its applications' results on the human being's life is valued and required by society as several human needs can be satisfied by means of implementing such e-health applications.

It is worth noting that there exist several e-health systems applying the cane as a critical health support device, for instance the Co-Robot cane project [7] initially designed to help the blind use the cane as a guiding element and a recognition device of the environment. We can mention also the AID project [8] that proposes to equip a walking cane with several sensors useful for measuring the user's pulse, blood pressure and body temperature when the forearm is in contact with the cane. The detected information is displayed on LCD (Liquid Crystal Display). Systems, which use sensors to detect information derived from the environment or human body. They then process the acquired information locally through dedicated applications to provide indicators on the health status and efforts amount exerted by the monitored public.

In turn, the CANet project [9] and Smart Cane [10] constitute also other projects that serve to monitor a person via sensors instrumenting a connected walking cane. These applications introduce new analysis-executing methods and the necessary remote monitoring process without the need to move. They offer safe data exchange methods likely to facilitate the sharing of digital content among a local or remote processing center as well as the sensors that help

collect the natural environment related data.

Actually, the CANet project [9] constitutes a significant evolution in terms of offered features. It proposes to integrate a multitude of sensors tracking the elderly health status. Unlike other projects [7] [8], this approach puts forward a real time vital data transmission framework. The gathered data are subsequently processed by means of specific systems. The idea of the CANet project lies in serving as a control and monitoring system. Gathering all these properties and being non-intrusive make it very scalable with respect to the proposed projects devoted to the same age group, which turns out to be very sensitive as a system. To this end, a new monitoring system is advanced through the present work, whereby a contribution to the CANet project is planned.

In recent years, fall related injuries and fractures have stood as the major causes of death amongst the elderly [11]. In this respect, roughly 30% of people aged over 65 appear to score at least a single fall each year in the US [12]. The statistics are almost three times higher for people living in nursing homes [13]. Among the common fall engendered injuries one can cite the damage of soft and connective tissues, bone fractures and head injuries [14, 15, 16]. As a matter of facts, the lack of autonomy proves to stand as a serious threat to the elderly population's health condition. In addition, the induced injuries can also lead to an average annual cost of health care of about \$ 20,000 per person [17], amounting to an estimated cost of more than \$ 12.6 billion for those aged 65 [18, 19].

It is worth noting that there exist several systems that apply subsequence matching as a fall detection tool using the cane. Noteworthy, Subsequence matching constitutes a technique to measure the similarity between two sequences to recognize human activities and positions (sitting, lying on the left side, lying on the right side, lying on one's back, walking, running etc) which are registered as signals in a special database. The SMARTFALL process [20], is an example of fall detection systems for a Smart Cane [10]. It uses subsequence matching process to distinguish a fall from out of the frequent daily activities. The system allows a fall detection rate of almost 100%, but the false positive rate for a variety of daily activities is low due to the close similarity between the fall sequences and other similar activities such as lying on one's lap. The problem attached to subsequence matching lies in the fact that a fall sequence may change depending on the surrounding environment, which makes a fall is not always detectable and recognizable. In our paper, we used a multi-stage thresholding method with multiple parameters (linear acceleration and acceleration due to gravity), which implies an ongoing comparison of sensor data versus predefined thresholds. Indeed, a multi-stage threshold determination process applies more than a single threshold. All the thresholds must be exceeded in a particular sequence over a certain period of time to trigger the final alarm.

Hence, the present paper proposes a novel method along its associated tools necessary for monitoring the elderly while using their walking stick. In this regard, we consider to propose 3DCane as a system that helps tracks the elderly movements even more visually using their walking stick in

accordance with the CANet project procedures [16], as a monitoring system for people with disabilities through their walking stick. In fact, the system allows to display a 3D model of the cane and its graphic animation based on actual movements obtained through a wireless data transmission system from sensors on the cane. The system's major function consists in detecting any potential fall through the cane by generating a voice alert within a smart home.

The remainder of this paper is organized as follows: Section 2 is devoted to provide an overview of the CANet system, including the relevant hardware and software architectures. Section 3 concern the design and the 3D sensing details along with the modeling algorithms developed and experimentally evaluated in terms of detection rate, and false positive rate in Section 4. As for section 5, it bears the major concluding remarks as well as some suggested horizons and perspectives of possible potential improvements of the 3dCane system.

II. SYSTEM ARCHITECTURE

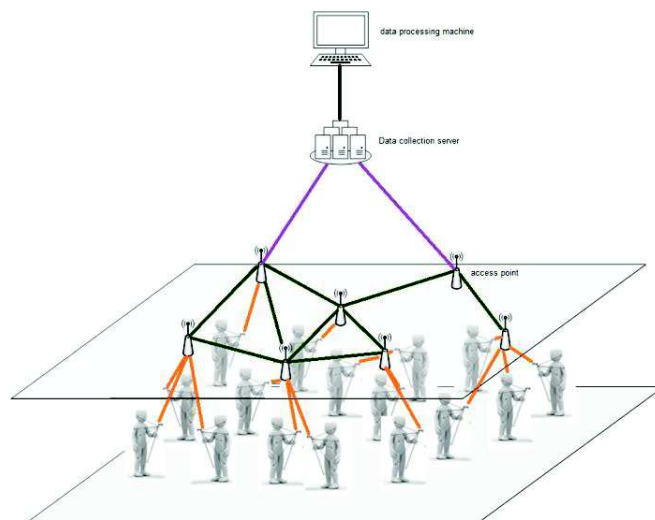


Fig. 1. The CANet Global architecture.

A novel application of the cane 3D model, along with its graphic animation and fall detection are presented. The global architecture of the CANet project is presented in figure 1 by Sabri Khsibi [21]. Every cane user sends data to the access point, while data are transmitted to a data collection server prior to treatment via a special data processing device.

With regard to the present work, the system is conceived to involve the following parts, namely: (i) a transmitter node positioned on the cane, (ii) a receiver node as well as (iii) a data analysis terminal for the 3DCane application. As illustrated in figure 1, the sensor node measures the sensor emitted data and sends them to the receiver using a Radio network processor. The software environment applied to fit for the experiment is Matlab 2014a with the fall-detection code being written in C language on a Windows XP PC.

Concerning the transmitter, it consists in a Wino Node [22] equipped with a diversity of sensors, namely, an accelerometer, a gyroscope, a magnetometer, a temperature sensor and a radio transmitter RF22. In this application, we used initially a three-axis accelerometer of an adafruit

trademark reference LSM303 and a three-axis magnetometer of an adafruit trademark reference LSM303.

At this level, the sampling rate is set to 100Hz, a bandwidth exceeding the characteristic response of human movement. Each triaxial acceleration is statistically calibrated for the sake of correcting any possible axis tilt due to the device orientation on the subject or lower back tilt of the subject. For the purpose of implementing the algorithm that helps detect a fall suffered by an aged person, the gateway monitor the sensor node transmitted acceleration and calculates several parameters including the linear acceleration and the gravity related one.

To note, the Wino node [22] is based on the Arduino architecture, as it should be easily interfaced with real sensors. The Arduino module used in this card is a Teensy 3.1. It is based on an ARM Cortex M4 processor and offers several advantages. Unlike the majority of Arduino modules, this one has an electronic design enabling standby. It has a very favorable processing capacity ratio / consumed energy, which will allow the integration of low-consuming communication protocols such as 6LoWPAN in the future. The dimensions of a wino node are very limited as seen in Figure 2, allowing its easy integration in operational systems such as the 3D cane.

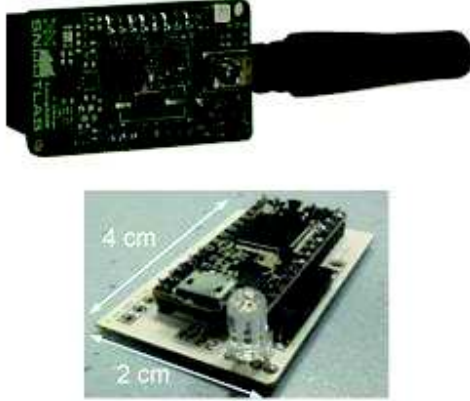


Fig. 2. A Wino node prototype and its commercial version [22].

The transmitter is positioned on the cane, as shown in Figure 3.



Fig. 3. Connected cane prototype equipped with a wino and its battery

III. THE 3DCANE APPLICATION FUNCTIONING ALGORITHM

In this section, we detail our 3DCane algorithms

functioning system such as the determination of absolute orientation and fall detection algorithm.

Prior to executing the algorithms implementation, we have to initially detail the cane orientation, with the X, Y and Z axes figuring on the cane as shown in Figure 4.

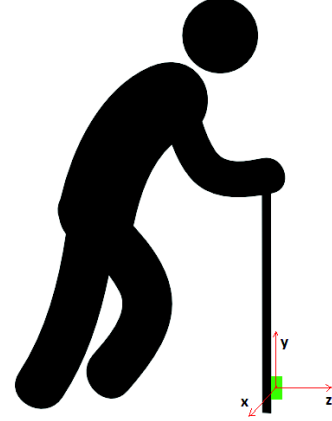


Fig. 4. representation of the X, Y and Z axes.

A. Absolute orientation

The applied orientation calculation system is shown in Figure 5. The calibrated accelerometer signal is used to obtain the roll and pitch via equations 2 and 3. As for the magnetometer calibrated signal, it is applied to compute the Yaw through equation 6.

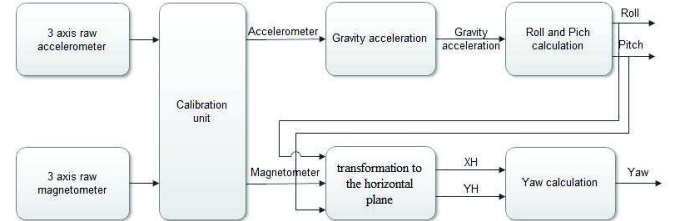


Fig. 5. Orientation calculation system

The accelerometer is intended to provide a measurement based on the linear acceleration and acceleration due to gravity [23]. Still, a major problem related to the accelerometers consists in the fact that they help measure both of the linear acceleration and that related to gravity. As it cannot distinguish between these two accelerations, it turns out to be critically necessary to separate both of the acceleration types (gravity and motion) through the use of a special filter.

On the X axis, for instance, the gravity relating acceleration can be calculated as follows:

Initially $X_g = 0$.

$$X_g = X * \alpha + (X_g * (1 - \alpha)) \quad (1)$$

With $\alpha = 0.5$ (as presented in [24]) and X is the value of acceleration on the x-axis provided by the accelerometer.

Using the accelerometer output, the rotation around the X axis (roll) and the Y axis (pitch) can actually be calculated. On considering the Accel_X, Accel_Y and Accel_Z as the accelerometer measurements (gravity acceleration) in the X, Y and Z, then equations (2) and (3) below, would demonstrate how to calculate the angles Roll and Pitch [30]:

$$Pitch = \arctan\left(\frac{Accel_X}{(Accel_X)^2 + (Accel_Z)^2}\right) \quad (2)$$

$$\text{Roll} = \arctan\left(\frac{\text{Accel_Y}}{(\text{Accel_Y})^2 + (\text{Accel_Z})^2}\right) \quad (3)$$

If m_x , m_y and m_z are calibrated and normalized magnetometer outputs, and α , β and γ respectively stand for roll, pitch and yaw, the heading appears to be computable through equation (6). Equations 4 and 5 are applied to transform the magnetometer reading to the horizontal plane. Once the magnetometer data appear on the flat plane, equation 6 would then get a reliable calculation.

$$\text{XH} = m_x \cos(\beta) + m_y \sin(\beta) \sin(\alpha) + m_z \sin(\beta) \cos(\alpha) \quad (4)$$

$$\text{YH} = m_y \cos(\alpha) + m_z \sin(\alpha) \quad (5)$$

$$\gamma = \text{atan2}\left(\frac{-\text{YH}}{\text{XH}}\right) \quad (6)$$

Following the calculation of the absolute orientation we turn to representing this particular step animation. In a first place we undertake to analyze the sensors' derived data when the elderly is in the walking process (see figure 6).

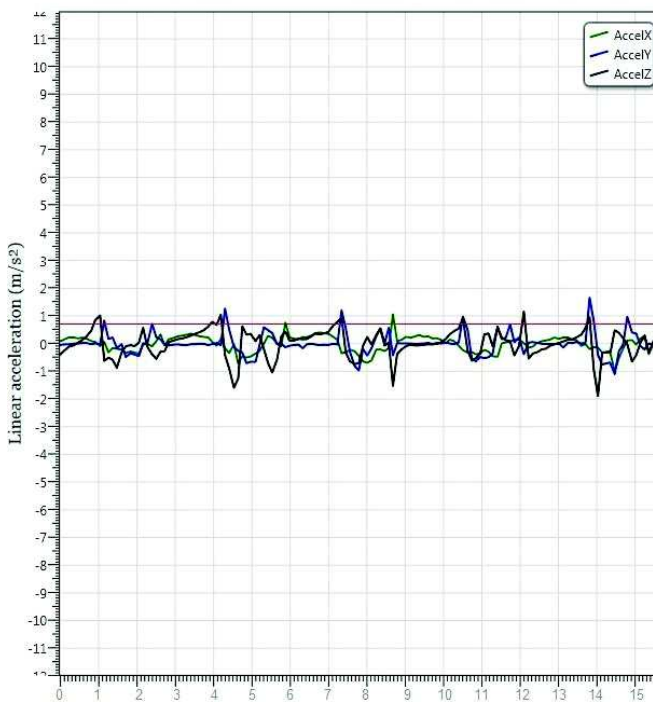


Fig. 6. Data of linear acceleration when walking with the cane.

After several walking related analyses, one is able to recognize that when the elderly is walking, the linear acceleration on the z and x axes tends to increase, exceeding 0.7 m/s^2 , with a time delay that does not exceed 0.3 second. To this end, a simple algorithm has been implemented to help detect a particular step then for representation in the graphic animation.

Through the cane graphic modeling, one might well differentiate between three activities: walking, standing and lying on lap. Yet, the related problem lies in recognizing how a fall can be depicted.

B. Fall detection algorithm

Actually, the fall relating principle must be well understood for an effective fall-detection algorithm to be constructed. For this reason, more than 200 falls have been performed with the cane at different positions (forward, backward and side falls),

while the linear acceleration as well as the gravity related data have been entirely displayed.

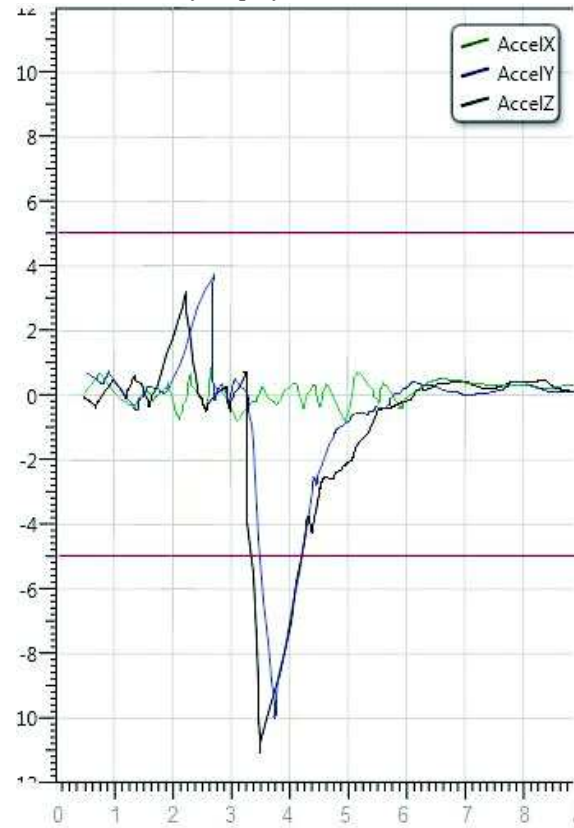


Fig. 7. linear acceleration data with a backward fall.

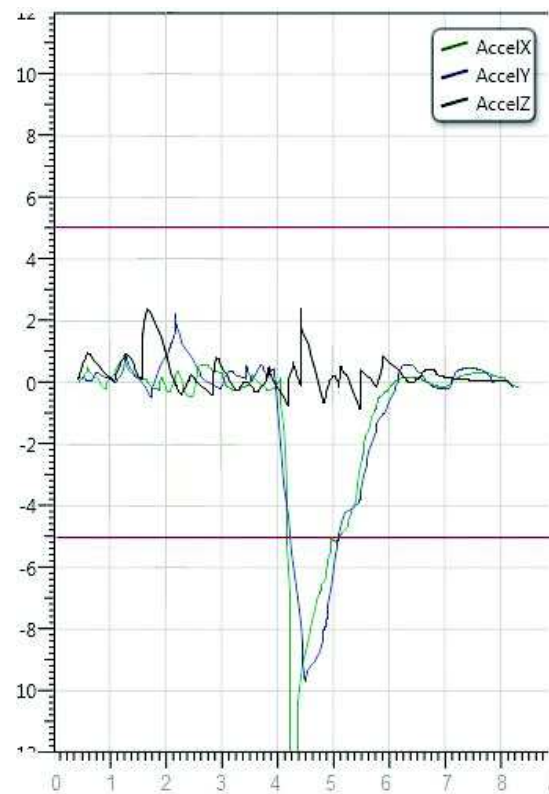


Fig. 8. linear acceleration data with a left side fall.

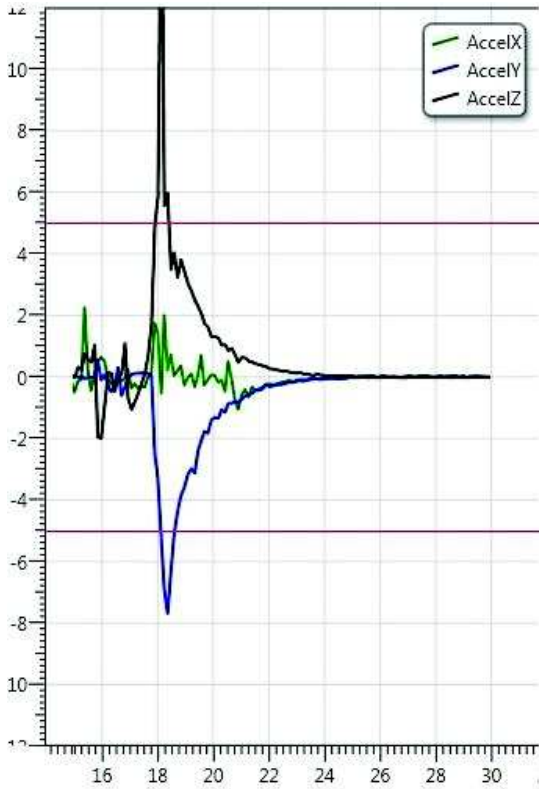


Fig. 9. linear acceleration data with a forward fall.

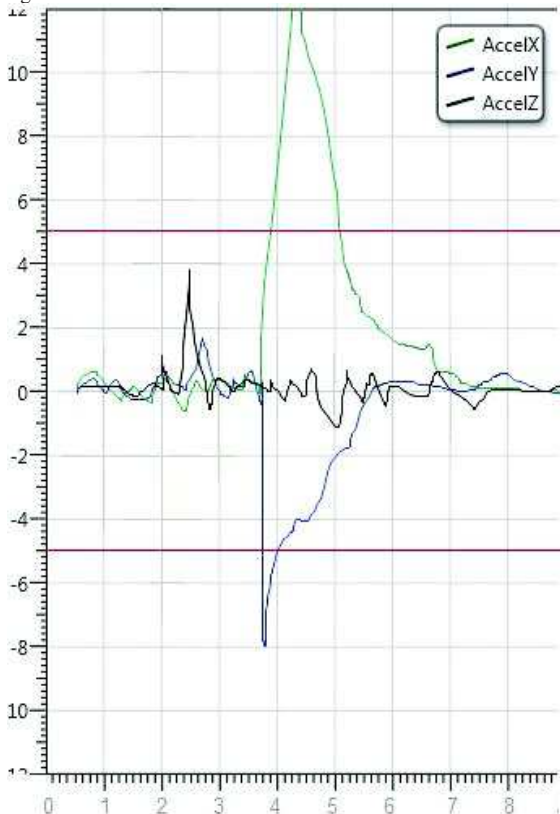


Fig. 10. linear acceleration data with a right side fall.

An analysis of the linear acceleration data reveals well that for the entirety of falls made by the elderly, the linear acceleration value appears to perpetually remain superior to 5

ms. So, for the fall validation purposes, the gravity data related acceleration, and the reached findings prove to reveal that following each fall, the acceleration on the y axes appear to remain close to zero as depicted in figure 11.

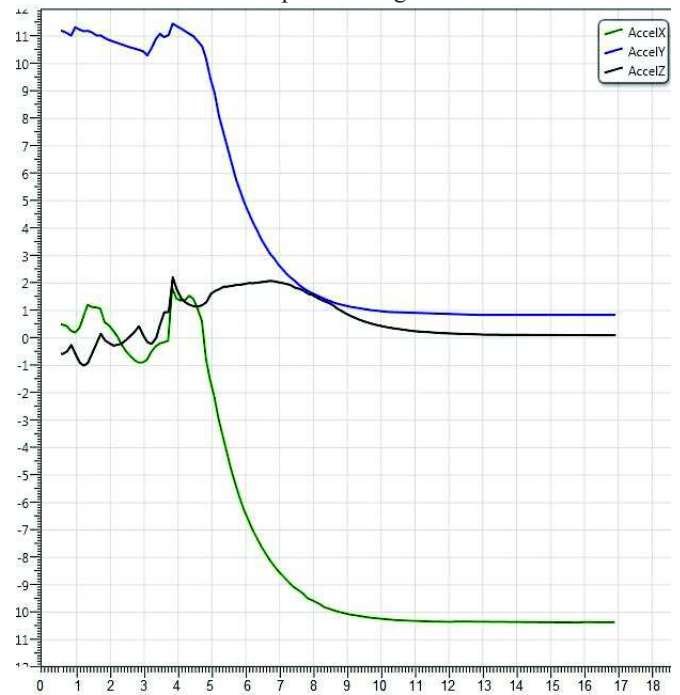


Fig. 11. acceleration due to gravity data when falling with the cane.

It has been assumed and checked that the cane would follow a similar process as that of a free fall, even in case the user loses control of the cane. The free fall case has been modeled, with the maximum acceleration level being computed. Following the linear acceleration data analysis, it has been discovered that for all free falls, the linear acceleration value does not seem to exceed 5 ms, as displayed in figure 12, below.

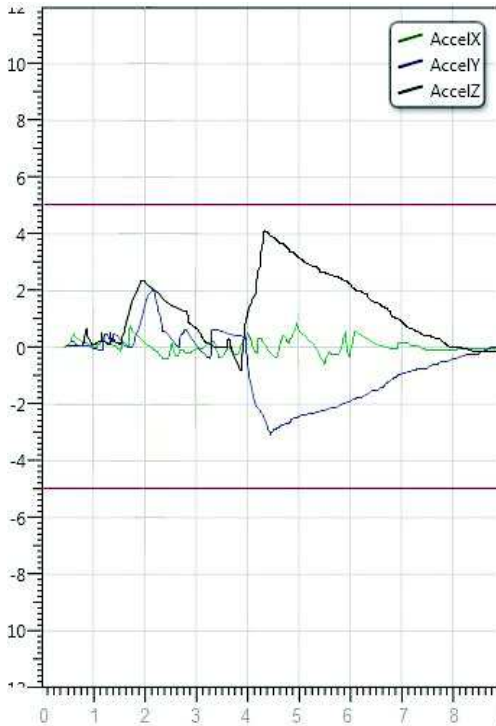


Fig. 12. linear acceleration data with a free fall.

Hence, based on the sensor data analysis derived from figures 6 and 7, one can well state that a cane user's typical fall turns out to consist of a three step process: (i) falling, (ii) horizontal position, (iii) inactivity.

During the fall phase, the user appears to lose balance and fall on the ground in an accelerated motion. An extensive experimentation leads us to discover that the minimum threshold proves to be 5 m/s^2 .

Following the fall phase, the identifiable stage is reached by tilting the cane. The latter's position turns out to be almost fully horizontal, and the gravity related acceleration figuring on the Y axis is almost 0 m/s^2 .

The inactivity step is obviously the easiest step to model and detect. A thirty-second period has been selected, during which the cane stands still, lie motionless, for the actual fall to be confirmed. Otherwise, it means that the person has resumed his cane to keep walking, the fall is less serious, or it is simply a control loss of the cane by the person.

After identi

The implemented fall detection algorithm is depicted in Figure 13, below.

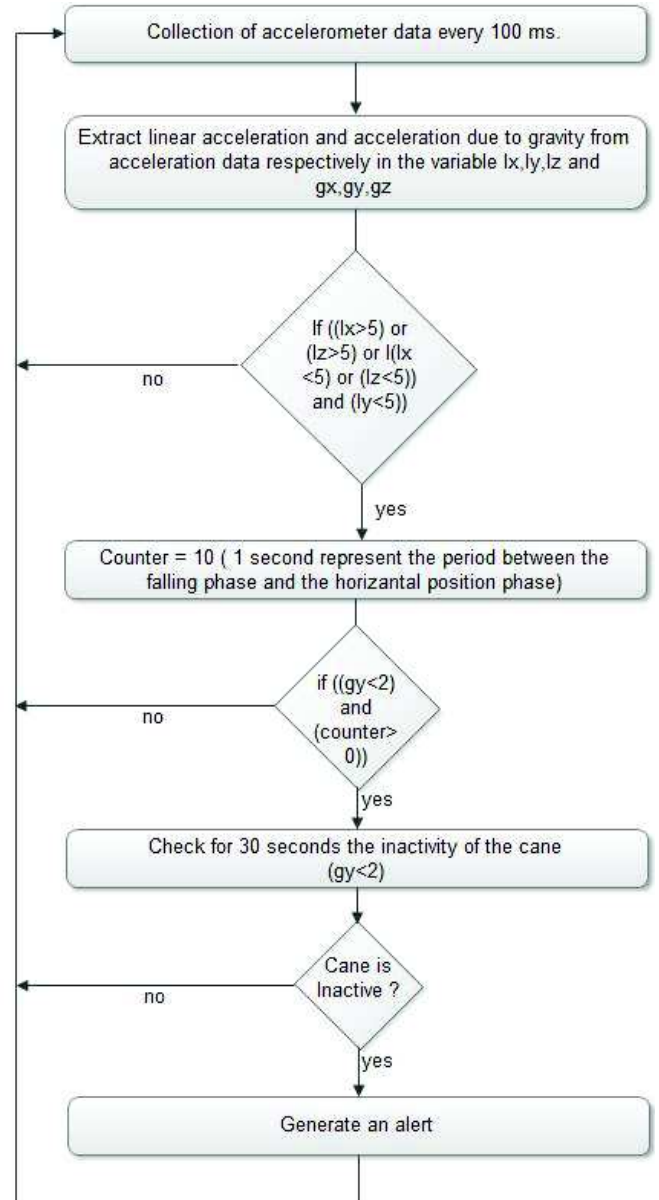


Fig. 13. fall detection algorithm.

IV. RESULTS AND PERFORMANCE ANALYSES

In a first test, the application GUI has been assessed in various situations prior to testing the fall detection algorithm.

A. Activity recognition

The 3DCane GUI resulting application allows a visualizing of the real time Cane status using a 3D display representing its absolute orientation. It also helps recognize the number of steps. The interface representation interface is shown in Figure 14.

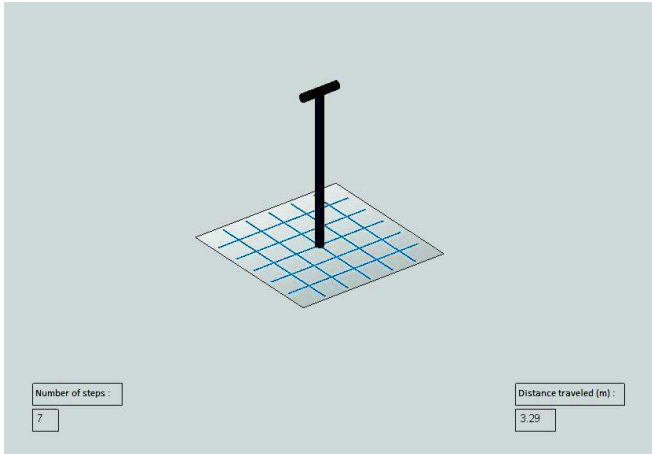


Fig. 14. GUI 3DCane application

The cane 3D modeling, together with its movements, appears to be helpful in identifying its condition as well as the user's status. Once a fall is detected, the application triggers a voice alert. In addition, such an interface enables us to recognize whether the user is walking or in a standing still position.

B. Fall detection experimental platform

A secure fall reserved platform has been constructed for experimental purposes. It consists in a soft cushion for the person to fall over without damage, and a harder surface for the cane. The cushion positions and orientations are adjusted for different fall positions ways. An elderly person has been selected to perform all the fall types.

TABLE 1
THE FALL DETECTION RATE (30 TRIALS) FOR DIFFERENT TYPES OF FALLS.

Project	Cane3D	Smart fall
Forward	100%	100%
Backward	96.7%	93.3%
Side	100%	100%

Forward: simulates a face down fall due to trip over.

Backward: simulates a fall on the back or bottom due to a slip.

Side: simulates a sideward fall due to balance loss.

The table 1 figuring results prove a detection rate of almost 100% for the three fall types, as performed by the elderly.

TABLE 2
THE FALL DETECTION RATE (30 TRIALS) FOR DIFFERENT TYPES OF FALLS.

Project	Cane3D	Smart fall
Slow walk	0%	3.3%
Fast walk	0%	0%
Swing	0%	0%
Sit and Stand	3.3%	16.7%
Lay on lap	3.3%	10%
Free fall	0%	0%

Slow walk: walking with the cane at a pace of less than one step per second.

Fast walk: walking with the cane at a pace of around two steps per second.

Sit and stand: standing up with the help of the cane from a

sitting position.

Swing: swinging the cane back-and-forth at around 1Hz with an angle less than 30^\pm from the vertical axis.

Cane on lap: picking up the vertically oriented cane and placing it horizontally on the lap.

Free fall: simulates an unobstructed topple of the cane due to loss of control. The subject does not fall with the cane in this case.

The results, listed in table 2, appear to indicate well that the algorithm is robust in terms of false-positive rate while perfectly solving the sit and stand as well as lay on lap problems. Indeed, the applied system seems to be more accurate than the Smart-fall one.

V. CONCLUSION

In the present work, a novel method has been developed whereby a real-time monitoring process of disabled people is advanced using through the use of an accelerometer and a gyroscope equipped walking cane. Real time data have initially been displayed to analyze the accelerometer and the magnetometer movements for a fall detection algorithm to be conceived. Then, a 3DCane application has been carried out for the walking stick state real-time visualization to replace, so as to control the elderly movement. Noteworthy, the proposed monitoring system will be soon ready for real tests in homes exclusively inhabited by old people. Several experiments simulating various fall types have been conducted to evaluate the 3DCane performance. The findings prove to indicate that the algorithm turns on to be able to detect almost all the experiment related falling cases while achieving low false-positive rates for the entirety of the non-falling activities.

One of the future research perspectives is to implement an algorithm through which the number of steps can be computed by means of the cane. As the cane is equipped with other types of sensors, such as temperature and gyroscope, we are planning to investigate the accuracy based inference possibility with regard to these sensors. We also envisage conducting large-scale clinical trials to further validate the 3DCane application effectiveness. Finally, we plan to implement a special architecture likely to help ensure interoperability persistent between the cane and other items or devices connected to the smart home or to the Internet in general. For instance, we intend to trigger a remote alarm, open the house doors to facilitate the arrival of relief, and send Smartphone messages to the emergency operating medical personnel whenever an elderly person falls and an alert message is emitted through his / her smart cane sends an alert message.

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