A Wearable System for Measuring Limb Movements and Balance Control Abilities Based on a Modular and Low-cost Inertial Unit

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Abstract— **Monitoring balance and movement has proven useful in many applications ranging from fall risk assessment, to quantifying exercise, studying people habits and monitoring the elderly. Here we present a versatile, wearable instrument capable of providing objective measurements of limb movements for the assessment of motor and balance control abilities. The proposed device allows measuring linear accelerations, angular velocities and heading either online, through wireless connection to a computer, or for long-term monitoring, thanks to its local storage abilities. One or more body parts may be simultaneously monitored in a single or multiple sensors configuration.**

I. Introduction

Balance control is a very complex task, involving several sensory systems and motor responses which interact dynamically. As shown by several studies, postural and balance control abilities gradually decline with age. Older people affected with balance disorders typically suffer from multiple impairments, e.g. multi-sensory loss, weakness, orthopedic constraints and cognitive impairments [1-3]. Typically, balance control is assessed by means of clinical balance scales, that consist in the scoring of a set of simple, everyday-life movements executed in sequence by the patient. The most common scales are: the Tinetti test [4,5], the Berg balance scale [6], and the BEST test [7]. The subject's performance is currently evaluated by the physiatrist or the physiotherapist, who give his/her judgment by means of a numerical score on a predefined scale. The evaluation is therefore affected by subjective factors causing possible inter- and even intra-evaluator variability of judgment. The continuing development of reduced size, weight, and cost MEMS inertial sensors has offered the possibility of using them for human activity monitoring, recognition and classification through body-worn devices [8-14]. We designed and built a novel, portable, low-cost system, embedding a three axial accelerometer, a three axial gyroscope, and a three axial magnetometer, aimed at providing objective measurements of limb movements for the assessment of motor and balance control abilities (figure 1).

The developed instrument has been conceived as a modular device which can be used in different scenarios: i) single unit wirelessly connected to a PC or handheld device (laboratory experiments, short-term monitoring); ii) single unit capable of storing the acquired data on a local memory (patient's home, long-term monitoring); iii) body network , i.e. multiple units deployed on the subject's body and wired to a gateway unit which can have a local memory or a wireless connection to a PC or handheld device (full body monitoring of exercises, several scenarios). Although a number of wearable IMU devices that can be used for monitoring posture and movements are available on the market, we preferred to build our own IMU "platform" for having the possibility of adding custom features. This is hardly possible with commercial devices, as they generally come with their own software and, in particular, their firmware cannot be modified as needed. Among them, Lumoback (Lumo BodyTech, Inc., CA, USA) seems a very interesting system, but can only be connected to an Apple device with a proprietary application. Sapphire, Emerald and Opal wearable sensors (APDM Inc., OR, USA) come with a development kit allowing researchers to build their own applications; nevertheless, it is impossible to act on the firmware in both cases. This limits the possibility to add features to the system, e.g. an onboard custom processing or the capability of connecting the IMU to command external devices (e.g. electro stimulators).

II. System Description

The electronic device described in the presented work is an autonomous system able to detect and monitor the movements of the subject. In order to obtain a system capable of acquiring inertial signals generated by the activity of the wearer without impeding his/her movement, the circuit layout and the battery were designed and selected to minimize both dimensions and weight of the final device. Also the physical magnitude of the signal has been investigated to properly choose the sensors for this type of measurement. Our instrument is based on a STM32F303VC microcontroller (by ST Microelectronics) which has a high performance ARM Cortex M4 32-bit RISC core operating at a frequency of up to 72 MHz. This microcontroller is able to interact with external devices through an extensive range of peripherals, while maintaining relatively small dimensions (7x7x1.6 mm, 48 pin package). The same package hosts also a 256 Kbytes flash memory, where data can be permanently stored, and 40 Kbytes of SRAM for temporary data storage [15]. The measurement of human body movements is made possible by means of three inertial sensors: an accelerometer; a magnetometer and a gyroscope. The three dimensional angular rate is provided by the L3G4200D (ST Microelectronics), a digital low-power three-axes angular rate sensor including a MEMS sensing element and an I2C interface capable of providing the measured angular rate to

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the external world through a I2C or a Serial Peripheral Interface (SPI). Full scale values are selectable among the following: 250 °/s, 500 °/s, 2000 °/s. Sensitivity values are, respectively, 8.75 °/s/digit, 17.50 °/s/digit, and 70 °/s/digit [16]. The LSM303DLHC (ST Microelectronics) allows the measurement of the three-dimensional accelerations and magnetic field; it is a system-in-package featuring a 3D digital linear acceleration sensor (selectable full-scales from ±2 g to ±16 g, sensitivity from 1 mg to 12 mg, where g is the

Figure 1. The assembled device and casing: battery (left) and circuit board (right).

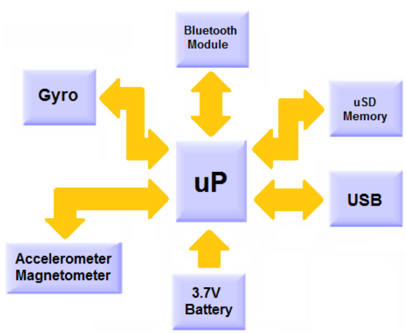

Figure 2. System architecture.

gravitational acceleration) and includes a 3D digital magnetic sensor (selectable full-scales ranging from ±1.3 G to ±8.1 G, and magnetic gain setting ranging from 1100 to 205 digit/G, where G is the abbreviation for gauss) embedded in a 14 lead, 3x5x1mm-sized package. Magnetic and accelerometer parts can be enabled or put into power-down mode separately, allowing to reduce the power consumption when one of these features is not required. An Inter-Integrated Circuit (I2C) serial bus interface is included, that supports standard (100 kHz) and fast (400 kHz) speed mode [17]. The microcontroller can manage these external sensors through two different kinds of synchronous serial communication internal interfaces: the I2C and SPI. The latter is a communication based on 3 digital lines and is used to send commands and receive data from the LSM303DLHC, while the I2C, that uses only two digital lines, allows to share data with the gyroscope. The SPI interface is also used to store data in ASCII files on a micro Secure Digital (µSD) card which can then be extracted for data visualization and processing. Otherwise, the acquired data can be sent to a remote device (such as notebook, tablet or smartphone) thanks to a RN-41 class 1 Bluetooth® radio module (by Roving Networks). This small (13.4x25.8x2mm), low power (30 mA connected, < 10 mA sniff mode) module exchanges data with the microcontroller through a Universal Asynchronous Receiver/Transmitter (UART) interface, and delivers a data rate of up to 3-Mbps for distances up to 100 meters [18]. A 4 layers, 55x30x2mm, printed circuit board allows the above listed components to work properly and to exchange data. The circuit is powered by a very small (5x25x35mm), extremely lightweight (9 g) 3.7 V Polymer Lithium Ion battery with a nominal capacity of 400 mAh, including a built-in protection against over voltage, over current, and minimum voltage. The battery can be recharged by connecting the unit via USB to a PC or a 5 V power adapter. Current consumption of the inertial unit is shown in Table I (data measured in worst case conditions). The system is currently capable of continuously acquiring and transmitting data to a PC for about 10 hours, but we are implementing power saving techniques in order to further extend the battery life. The circuit board, the Bluetooth module and the battery are enclosed in a 60x35x20 mm box, which is made in translucent plastic, in this way the LED indicators on the board are totally visible. The developed prototype is lightweight and unobtrusive, and its packaging allows to wear it on the body part to be monitored using elastic Velcro straps. and it is adaptable to different kinds of monitoring purposes: long term monitoring thanks to the µSD card and real-time monitoring through a Bluetooth wireless connection. The device can also be used as a node of a body area network in this way it is possible to monitor the activity of more than one limb.

TABLE I. DEVICE CURRENT CONSUMPTION (WORST CASE)

Components	Current Consumption (mA)
Microcontroller	27
Accelerometer and magnetometer (measuring)	0.11
Gyroscope (measuring)	6.1
Bluetooth module (peaks data transmission)	65
Bluetooth module (average)	30
uSD (Page Write[1])	60

[1] Page Write Time = 3ms

III. SYSTEM APPLICATION

As mentioned in the Introduction, we conceived this instrument for three kinds of scenarios.

In the first one, a single unit is exploited in a typical laboratory or clinical environment: the instrument is attached to the limb of interest or to the trunk and connected via Bluetooth to a PC, notebook, tablet, or smartphone on which the researcher can visualize in real time the acquisition signals when the subject performs a set of movements (e.g. exercises included in a clinical balance test).

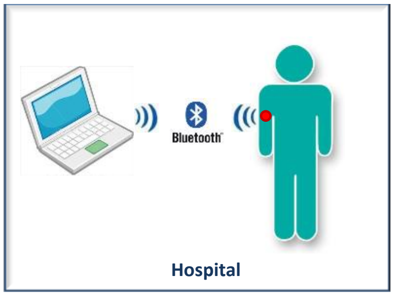

Figure 3. Application Scenario 1: the subject wears a single unit during a trial performed in a clinical environment; data are transmitted via Bluetooth to a PC/tablet/smartphone.

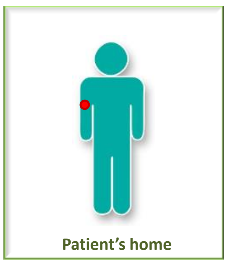

Figure 4. Application Scenario 2: the subject wears a single unit at home, the Bluetooth module is switched off and data are stored on the local memory.

In the second scenario, the basic unit is used for long-term monitoring, while the patient is at home, for instance. In this case the Bluetooth® module is not necessary, therefore it is simply switched off. Data are recorded on the local µSD memory, where they are arranged in text spreadsheet files. When the device is returned back to the laboratory/clinic, the µSD is extracted so that the files can be downloaded to a PC for further processing.

In the third, and most complex, scenario many basic units are positioned on the body of the subject, e.g. one at the level of L3, two on the thighs, two on the wrists or arms and one on the head. One of these devices, typically the one on L3, acts as a gateway and relay node, so that it is wired to all the other devices and collects their data. It then extracts parameters of interest if needed, and then it either stores data and computed figures on the µSD or transmits them wirelessly to a PC. The peripheral units are connected to the gateway unit by means of a multiprocessor serial communication, implementing a single master – multiple slaves system. With our design, the body network can be composed by up to ten (9 slave and 1 master) units, with 9 signals (3 accelerations, 3 angular velocities, 3 magnetic field signals) provided by each unit, sampled at 400Hz per channel.

IV. EXPERIMENTAL TRIALS

In order to carry out preliminary tests of the system's performance, we have recorded a population of 10 control subjects performing exercises, i.e. items, drawn from the Tinetti test for balance control assessment, with the single sensor configuration attached to the subjects' back at the level of L3-L4. With this setup the sensor's data were acquired at 100Hz sampling frequency through the Bluetooth connection to a laptop computer and saved in a text file. Subjects were simultaneously recorded using a Microsoft Kinect (30 fps recordings) system positioned at about 2.5 m in front of each subject, through a custom developed C++ application.

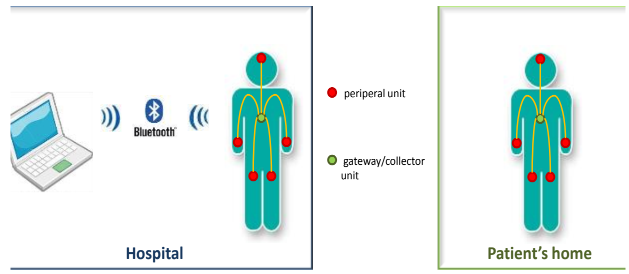

Figure 5. Application Scenario 3: the subject wears a body area network of inertial units. In a clinical environment, the gateway unit collects all units' data and transmits them wirelessly to the remote station. While the subject is at home, instead, data are gathered by the collector unit and stored locally in its µSD memory card.

Using custom developed Matlab functions we then exploited the 3D accelerometer as an inclinometer by low-pass filtering its data with a 1Hz cutoff frequency and computing its pitch and roll angles in an gravity-referenced coordinates system. These data were then compared to the roll and pitch trunk inclination angles computed based on the 100Hz-resampled Kinect data. An example of such comparison on a representative subject performing the "Stand Up" and the "Reaching" exercises is shown in Figure 6, where the pitch angle computed from the sensor mounted on the subject's lower back is shown together with the trunk inclination computed based on the Kinect data. Table II presents the correlation coefficients between the two signals for the 10 subjects while performing the Stand Up, Sit Down and Reaching exercises.

V. CONCLUSION

The acquired data show very good correlation coefficients between the sensor's data and the Kinect, which was used here as a control instrumentation. These preliminary experimental tests prove the reliability of the proposed sensor in such configuration. The system (single unit for short-term acquisition, first scenario) is being used in an experimental campaign where both its quantitative measurements, and expert examiners' judgments are recorded while a group of patients and controls carry out motor tasks included in the most common balance scales exercises (e.g., Tinetti test, Berg Balance Scale, BESTest).

In these tests the instrument has proven to be very comfortable to the subjects and easy to use by the operators. A proper computational framework is being devised for processing the acquired signals which will provide, at the end of the experimental session, a quantitative assessment of a subject's performance in carrying out the exercises prescribed by the various clinical scales for the assessment of balance and fall risk.

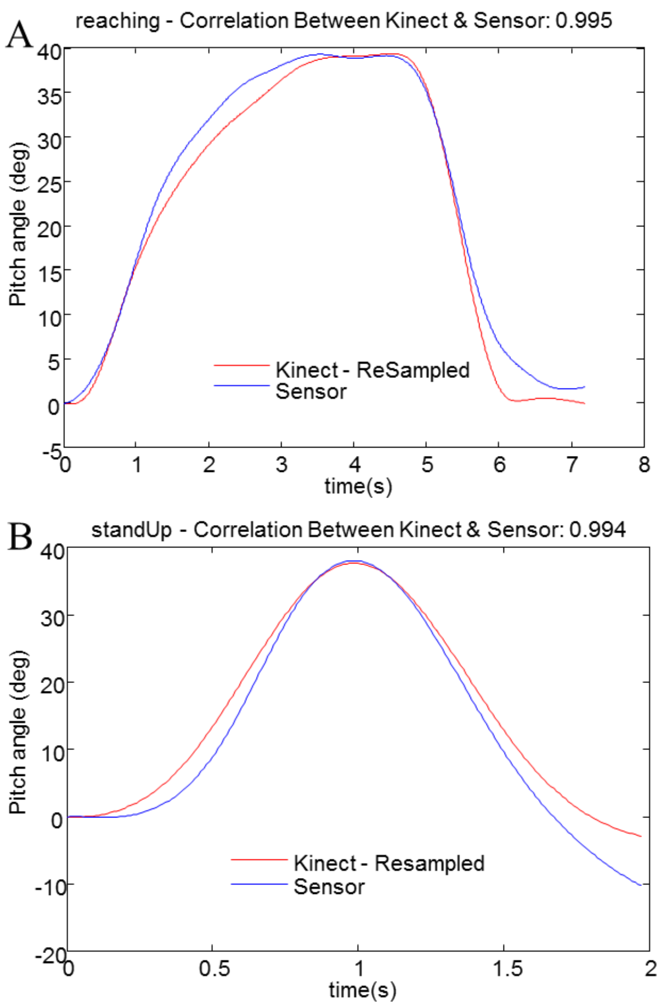

Figure 6. Comparison of trunk pitch inclination measurements performed with the developed sensor wirelessly acquired throught the bluetooth connection and simultaneous Kinect recordings. Panel A: data from a representative subject performing a reaching forward exercise; Panel B: data from a representative subject performing a stand up exrcise.

TABLE II. EXPERIMENTAL CORRELATION COEFFICIENTS (*r*)

Subject	Stand Up	Sit Down	Reaching
S1	1.000	0.894	0.989
S2	0.993	0.995	0.986
S3	0.989	0.995	0.997
S4	0.988	0.857	0.998
S5	0.995	0.976	0.998
S6	0.972	0.907	0.993
S7	0.993	0.963	0.941
S8	0.999	0.847	0.996
S9	0.986	0.988	0.987
S10	0.972	0.945	0.993

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