Bio-feedback System for Rehabilitation Based on a Wireless Body Area Network

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Abstract

In this paper we describe Bio-WWS, a bio-feedback system for rehabilitation based on a dedicated, wireless, sensor-network architecture. The sensor network is designed to be distributed on the user's body for balance monitoring and correction. The hardware and software architecture (communication protocols, power management policies and application-level control) have been tuned to optimize cost, battery autonomy and real-time performance required for this application. Bio-WWS is an example of complete vertical integration: the sensor network is fully integrated with processing and auditory feedback generation.

1. Introduction

Technology advances in wireless communications, miniaturized sensors and low power design have enabled the design of integrated Wireless Body Area Networks (WBANs) [1]. WBANs are strategic for the deployment of wearable systems for biomedical applications, in particular when unobtrusiveness and ubiquitous availability are critical requirements, as in daily-life monitoring and movement tracking. In the field of human motion tracking, the potentials of wearable technology are attracting significant interest in the scientific community [2], with applications that may vary from computer assisted rehabilitation [3], to motion tracking both in normal and disease-altered conditions [4] and may include monitoring of athletes performance [5] or high-risk patients [6]. Many of actual solutions in wearable systems for human motion tracking in the biomedical field are limited by non real-time data processing for operation in a feedback loop (biofeedback) and wired design (with only few exceptions [7]).

In this scenario, the present work proposes a Biofeedback Wireless Wearable System (Bio-WWS) for biomedical applications, that implements a WBAN based on inertial sensor nodes to track human movements and that provides audio biofeedback for optimization of balance and postures. Its applications range from movement rehabilitation after a damage of the motor system, to aid in case of sensory deficits, to use in sports training.

Inertial sensors (accelerometers in particular) and biofeedback have proven to be essential elements in applications for balance control, because of their small size, portability and the useful kinematic information they supply [8, 9]. Postural unbalance is a crucial aspect in many musculoskeletal, neurological and age-related diseases [10,11,12], in several sport disciplines [13], and recent studies have shown that improvement of balance may be gained by use of biofeedback, based on the principles of physiological adaptations and brain plasticity [14]. Nevertheless, biofeedback systems for balance control are usually cumbersome, expensive, mainly for ambulatory use and need specific expertise (e.g. [15]). Hence, easy accessibility (in terms of unobtrusiveness, portability and low-cost) of biofeedback systems for balance and motor rehabilitation is still a requirement.

We designed the system with low-cost off–the–shelf components, aiming at performance and ergonomics typical of consumer market products. Bio-WWS avoids any wired link among system components, resulting in a WBAN that integrates both sensors and actuators for long-term monitoring and biofeedback. The integration of a palmtop computer as a wearable, wireless, general-purpose node of the WBAN enables the implementation of dedicated algorithms for biofeedback. The audio biofeedback chosen for Bio-WWS, provided through lightweight headphones, is based on previous results where such method was proven to be effective for balance improvement in patients with bilateral vestibular loss [16,17]. The modular system architecture allows large flexibility in the diversity and number of sensors that can be included, to enable future developments in many different biomedical applications.

2. System Architecture

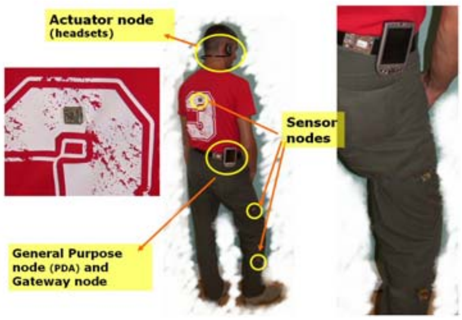

Figure 1. Bio-WWS set up

Since the primary purpose of Bio-WWS is helping the user to self-correcting her/his posture both in static and dynamic conditions, the major requirement for Bio-WWS is the ability to provide the user with all the necessary to be independent from other people intervention.

Specific requirements of the system taken into account for the design are: (i) Wearability and unobtrusiveness, thus needing light and small-sized components; (ii) Low-cost (affordable for consumer market); (iii) Low-power consumption (supporting daily continuous use); (iv) Flexibility and easy integration of other sensors/actuators; (v) Easy maintenance and components update; (vi) Mobility for ubiquitous use.

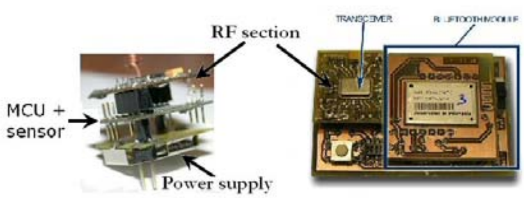

Figure 2. A prototype sensor node

Bio-WWS is composed of four kind of nodes: one or more sensor nodes, the audio actuator node, the PDA, which acts as a general purpose node, and the gateway node. At present the system has been tested with three sensor nodes, one located on the trunk for sway monitoring and the other two on a leg (thigh and calf) for distinguishing if the user is walking or standing. (Figure 1)**.**

For a simple WBAN, as the one presented here, a star topology between nodes and gateway is adequate. The gateway performs a signal pre-processing, data normalization and organizes, in packets, data retrieved from the sensor nodes, to forward them to the PDA over a Bluetooth link. Finally, the PDA processes the data from the body sensors, in order to resolve the human's posture condition and to give adequate feedback to the user.

The following sections will describe each part of the system both from a hardware and software perspective.

3. Hardware

3.1. Sensor nodes

The sensor node adopts a modular architecture (Figure 2, left side) [1]. It is organized in layers corresponding to functional blocks for reduction in node size and flexible reuse, upgrade and maintenance. The main layer is equipped with the microcontroller, an ATMEL ATmega8, a low-cost, low-size 8-bit microcontroller based on the AVR RISC architecture, providing a good trade-off between performance (1 MIPS per MHz) and low power consumption. In the same layer the sensing unit is also present. It is a MEMS tri-axial digital output linear accelerometer (LIS3L02DQ, ST-microelectronics), which measures within the range of [-2g, +2g]), equipped with internal A/D converters and a SPI serial interface for data exchange to MCU. The RF section is currently composed by a RFM TR1001 transceiver and a small antenna working at 868 MHz. Using both OOK and ASK modulation a maximum bit-rate of 115Kbps is reached.

The power consumption of this device is 19 mW in receive state and 26mW in transmission (using OOK modulation). The main disadvantage of TR1001 is the absence of protocol firmware for the access to the medium (MAC). Thus we supported the node with a proprietary MAC implementation for setting up a wireless sensor network.

3.2. Gateway

The gateway (Figure 2 right side) is a special node, without sensing element, acting as a bridge between the Body Sensor Nodes (BSN) and the mobile devices. Conceptually each sensor node can act as gateway, if equipped with a Bluetooth transceiver or another interface to connect to a general purpose device. Not needing sensing capabilities, in the present implementation the gateway is very small, non-intrusive, and the user can place it wherever he wants (e.g. in a trousers pocket). The choice of a Bluetooth access port enhances portability and deployment.

The module has a stackable design as the sensor node, hence uses both the RF and the MCU layer designed for the sensor nodes. The Bluetooth layer is equipped with a Bluetopaz module (manufactured by SmartM), to enable communication with the handheld device. It is a Bluetooth certified device with HCI and Serial Port Profile implemented into the firmware. It is a class 2 device, and it consumes 0,9mW when it is in sleep mode and requires a maximum of 150mW during the transmission. The interface to MCU is provided by two digital signals (TX and RX) implementing an UART serial protocol, consequently it is easy for ATmega8 MCU to retrieve and forward data.

3.3. Mobile Device and bio-feedback actuator

As general purpose data-processing node we chose the HP iPAQ 5550 with Bluetooth and WiFi capabilities. It is equipped with an Intel XScale 400 MHz, 32+32 KB data and instruction caches, and 128 MB SDRAM. We use Microsoft Pocket PC 2003 as operating system whereas the Bluetooth protocol stack is provided by Widcomm.

To reach a fully wearable system, we adopted also a wireless link through PDA and the headphone using Hewlett Packard Bluetooth Stereo Headphone as actuator node to provide the audio bio-feedback.

4. Software

The software architecture is organized in four main sections, which are responsible for data acquisition from the BSN, communication processing and restitution of the bio-feedback to the user.

The firmware running on end-nodes and gateway is developed on AVR assembler for ATMega platforms. Data acquisition is the main task of a node, whereas the gateway module is committed for pre-processing. On the PDA, a C/C++ application is based on the SDK API for Pocket PC 2003. Furthermore, a graphical user interface (GUI) support setup and adjustment of main parameters (e.g. Bluetooth port parameters, sound biofeedback frequency, volume range).

Data acquisition. As first release of the system, we adopted only a tri-axial sensor accelerometer as sensing unit for all the nodes, because an accurate positioning of the sensor is coarsely enough to determine an alert on incorrect posture. In future we plan to integrate this information with other data, collected from other body sensors and related to other aspects of posture and movement.

As we formerly described, the output data of the accelerometer is already converted in digital form and represented in two's complement encode in a range between 0 and 2^{16}. Since in steady state conditions, the main contribution is the gravitational acceleration, a geometrical approach for measuring tilt is used [18]**.** Currently, data are sampled at 60Hz, but the system can provide a higher data rate and the firmware is arranged to share MCU resources between other sensors.

Communication. The WBAN has a star topology. Nodes worn by user are end-points of the star and they are responsible for sensing and acquiring data from the environment and for sending them to the gateway. Coordination among transmissions of various nodes to the gateway is performed at the MAC-level [1].

A typical non obtrusive WBAN does not exceed a maximum of a dozen of nodes placed on the user body, each node working at data rate ranging from a few Hz to 30/60 Hz. Therefore the data rate of the transmitted information is not critical. As a consequence, a real-time collision free (CFRT) MAC protocol is adequate for the purpose. The protocol implemented basically divides time into frames in which only one node is allowed to transmit. The scheduling order is derived from a message table stored in each node. The table, identical for each node, contains entries specifying source, destination nodes, message length and message period for each node allowed to transmit or receive in a frame, so that each of them knows when it has the right to transmit. This protocol has been optimized for energy saving, switching transceivers and sensors in sleep mode during time frames in which they are idle.

The main drawback of a collision-free protocol is that synchronization among nodes is necessarily required. We get through this problem, adopting a phase of synchronization between all nodes. A row at the end of the table is reserved to the purpose and executed periodically. In this special slot, all sensor nodes switch in receiving mode and wait for the synchronization data sent by the gateway. During this phase the gateway can also send control command such as re-transmit the table. This solution does not present critical problems because the network has small size and the nodes are not far from each other (within the range of typical body distances).

Processing and audio biofeedback generation. Bio-WWS consider trunk planar accelerations (in the forward-backward and left-right directions), both gravitation and dynamic, and determines an estimate of sway of the user's center of mass. The gateway collects all accelerations retrieved by the BSN. All accelerations are coupled with a timestamp in order to have a screenshot of all sensors placed in the human body at the same time. Then, the integrated accelerations are sent to the PDA using a Bluetooth link. We have chosen a transceiver with a serial port profile (SPP), to map the connection to the gateway as a simple serial connection. From the application side, it is easy for a developer receiving data using the serial API provided by the Pocket PC 2003 SDK.

The accelerations are then coded into a stereo sound using an algorithm already tested in previous studies [16,17,19], where it was shown how this audio biofeedback algorithm is able to provide a high comfort level to the user and to improve the user stability while standing.

The user's accelerations in the forward-backward direction are coded by frequency and amplitude (volume) modulation of the sound (Figure 3A); the frequency codes the value of the instantaneous acceleration while the volume increases with the distance from he Target Region (TR). The TR is a range of accelerations values which are safe for the user. The task of the user while using the audio-biofeedback is to remain inside the TR. When the user's accelerations are inside the TR range the sound volume and frequency are fixed [19]. The user's accelerations in the left-right direction are coded by Left/Right balance modulation of the sound (Figure 3B).

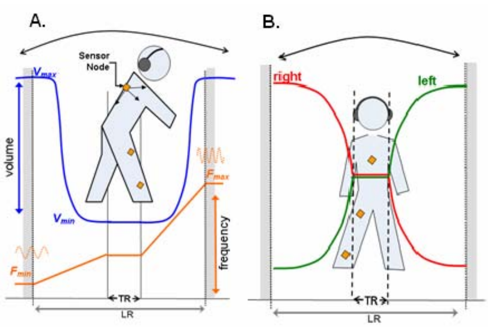

Figure 3. Audio biofeedback sound dynamics. A. Forward-Backward direction B. Left-Right direction

Every 50 ms, the biofeedback sound is updated according to the specific functions represented in Figure 3 and discussed in detail in [19]. The dynamics of the sound generation is determined by the TR and by the Limit Region (LR). TR reflects small ballistic-like movements typical of the postural control system [20]; it is subject-specific and is set in the first 10 seconds of each trial; LR is set consequently. Previous results and experimental sessions allowed us to set TR as 1.50 the standard deviation of the acceleration in the calibration time, and the LR as 10 times the standard deviation of the same value. TR (and consequently the LR) may be changed according to the specific use of Bio-WWS (e.g. smaller for applications in sport discipline or larger in severe damage of the postural system). On the PDA a GUI was implemented to support easy setting of parameters of the biofeedback algorithm.

At present, the sensors on the leg are included in the biofeedback code as quiet standing on/off sensors. Imminent developments of the system will include also the leg sensor nodes, to provide an audio biofeedback during movements (in particular during walking), and the 3D acceleration will be considered (including the vertical one).

5. Discussion

Mobility, Usability and Costs The small form factor both of the sensor nodes (size 20x20x18 mm) and the gateway (4x6x1.5cm, battery included) is suitable for easily wearing the system without experiencing obtrusiveness. Moreover, for the range of applications here presented for WBAN a small number of nodes is needed. Palmtop computers are decreasing their size while increasing computing capabilities (e.g. HP IPAQ example size is 7,5 x 1,9 x 11,9 cm) and they can easily be worn in pocket or carried in bags as it happens for mobile phones.

From a cost perspective, the proposed solution is extremely interesting, considering that the prototype node has a cost of 35€, the gateway of 50€ not including batteries. These costs can decrease significantly, since they are computed for small volume prototyping. Bluetooth headsets cost around 80€, but they can be easily replaced with cheapest wired one. For the application tested the WBAN, using low-cost headsets, has a cost ranging around 160€ (excluding the palmtop computer). Our system architecture is suitable for consumer market and widespread diffusion, e.g. as a potential partial substitute of expensive optical motion tracking systems (initial cost can easily reach $50,000), which do not allow outdoor acquisition and require high-cost maintenance during their lifetime.

Power consumption. Measurement of power consumption was performed in all the states of the system, setting sampling frequency at 60Hz (to obtain a useful bandwidth of 30Hz, adequate for capturing human movements). Communication speed was set at 32kbps from node to gateway on OOK transmission at 868MHz, and at 230kbps from gateway to PDA, transmitting via Bluetooth at 2,4GHz. Power consumption when all components are active and transceiver is continuously sending data corresponds to 200mW for the gateway and 45 mW for a single end-node. In idle state (only reception mode is active) the power lowers respectively at 25mW and 20 mW. When active, gateway battery (500mAh) and single node battery (100mAh) have a lifetime of 8 hours. Sleep mode corresponds to having all devices in the minor consumption state (1,5mW for gateway and 10 μW for end-nodes). For a 20% duty cycle the lifetime reaches 40 hours for the gateway and 38 hours for the node. This is a possible real situation, because typically it is not needed or it is not possible (e.g. the channel must be shared with other nodes) to send data continuously. The major limitation can be the palmtop computer lifetime. We tested the IPAQ transmitting a continuous data stream to a desktop PC through Bluetooth link. The evaluated duration of the 3,7 V battery (1000 Ah) in this worst case is of 12 hours, having that when on the PDA consumes 350mW. Thus we can conclude that WBAN lifetime is adequate for the applications we have in mind.

System performance. The STMicroelectronics accelerometer sampling frequency used in our application is 560Hz, while its accuracy corresponds to

0-7695-2520-2/06 $20.00 © 2006 IEEE

1 mg. As already described, data collected by the accelerometer are processed by the microcontroller and transferred to the wireless interface. Accuracy of the overall node is 2mg for the acceleration measurement. The maximum packet rate for each node is 300 Hz. Thus, using three node as in our case, the data rate corresponds to 100 Hz.

Packet loss measurements were performed changing the distance between gateway and end-nodes. In a WBAN this distance between two nodes is usually enclosed under 2 m. Thus, taking into account a WBAN of 3 nodes and a gateway working in real-time at 100 Hz, measurements demonstrated that within a distance of 0,5 m all packets are received; when distant 1m one from another, only 2% of packets are not successfully received by the gateway, at 2m, 3 m and 4 m the packet loss is 3%, 12% and 18% respectively.

Validation tests on users. Accelerometers accuracy and data transfer rate of the nodes abundantly matches the requirements of the specific application of Bio-WWS, even in case of data packet loss to the gateway, since human movements are below 50 Hz (even below 10 Hz in quiet standing) and trunk accelerations range from 5-10 mg [21] to 40-50 mg in condition that simulates a sensory alteration at foot level.

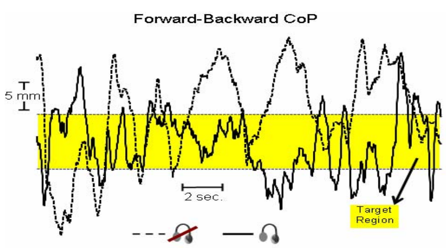

Figure 4. Results on a representative subject: BioWWS decreases the CoP excursion.

Several experimental trials were performed on 5 young healthy users as preliminary validation procedure. Users were required to stand with eyes closed on a foam-rubber surface that simulates sensory alterations at foot level. Sway during quiet standing, that indicates the level of achieved balance, was measured by means of a force platform (Bertec 4060-08), that quantified movement of the center of pressure (CoP) [20], i.e. the application point of the ground reaction force. Subjects performed three trials without Bio-WWS and three trials with Bio-WWS. Preliminary results are exemplified in Figure 4, where CoP displacement for a representative subject is shown, without BioWWS and with BioWWS (after the calibration time). Efficacy of the system for this representative trial is proved by the minor CoP excursion with the use of BioWWS, than without it, in the same sensory-altered conditions. Future development of the system will include further investigation and experimental sessions to complete the system validation and to optimize the sound modulation parameters.

6. Conclusion

A low-cost and low-power audio biofeedback system for postural rehabilitation based on a WBAN. has been proposed. Bio-WWS can support the user at any time in any place without the need of expert assistance or ambulatory infrastructure. Further, by integrating Bio-WWS with a general purpose computer, the system is ready to be connected for remote supervision.

Bio-WWS design flexibility offers the unique chance to adapt the system in more than one context, through the integration of heterogeneous sensors and algorithms in the WBAN.

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