A Wireless System for Gait and Posture Analysis Based on Pressure Insoles and Inertial Measurement Units

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Abstract - **In this paper we describe a wireless wearable system to monitor gait, based on a customized pair of commercial insoles able to collect ground reaction forces by use of 24 embedded cells for each foot. Each insole was combined with a small form factor, low-power Inertial Measurement Unit (IMU) and enabled to communicate via Bluetooth with a base station. We present here the characterization of the system both in terms of performance and in terms of functionality. The system was tested on a subject to demonstrate the usability and the features extraction during gait; this data allow to recognize walking phase in terms of swing and stance phase, step and stride duration, double support and single support duration, both using the pressure sensors and the IMU.**

Keywords: gait analysis; wireless sensor networks; pressure; inertial tracking.

I. INTRODUCTION

Technology advances in wireless communications, miniaturized sensors, sensorized garments and low-power electronics have made possible to design integrated Wireless Body Area Network (WBAN) [6]. These developments enable applications of ubiquitous computing and embedded systems for diagnostic, monitoring, rehabilitation, and training purposes [1] [2]. The potential of wearable technology for biomedical application is attracting a large interest in the scientific community. In fact, the fast-paced development in sensor technology is making possible to remotely acquire and monitor a wide variety of physiological parameters, by means of unobtrusive sensors. Applications vary from high-risk patients monitoring after surgery, to geriatric care [3] [4]; applications may include athletes performance monitoring, for example in scuba diving, mountaineering, and hiking [4]. Many of these applications aim at early detection of abnormal states and the prevention of severe consequences.

One of the most interesting biomedical domains which is benefiting by the advances in technology is the motor rehabilitation field, where low-cost low-power sensors may integrate, and under certain condition substitute, the more accurate and traditionally used systems, such as optoelectronic camera-based motion tracking systems for stereo-photogrammetry or dynamometric platforms. These systems often require large spaces and are generally expensive and adequate only for in-ambulatory use.

Recently market solutions present an extensive use of inertial systems portable (e.g. [9], [5]), in many cases low-cost and often with wireless communications (e.g. [7], [8], [10]). Researchers are working to develop new sensor fusion techniques to integrate information from different sensors located on the body. Several systems and applications have been recently proposed, such as wireless shoes equipped with instrumented insole designed for real-time multimedia interaction [26], system in the healthcare domain able to estimate stride length, walking speed, and foot inclination, in the sagittal plane during walking by means of a biaxial accelerometer and a rate gyroscope embedded in a unit on the shoe [27]. Other studies presented system able to detect gait phases with application in motor rehabilitation and evaluation, based on inertial and magnetic sensors [28] [29].

This study intends to give a contribution in this perspective, and in particular in the field of portable system for real-time evaluation of gait features for measurement and, eventually biofeedback restitution with application in the clinical and motor rehabilitation fields.

We present here a wireless wearable system able to monitor both inertial and pressure information from the feet. The system, based on the combination of a pressure insole and an IMU, targets both biomedical and fitness applications.. To this extent, we modified existing off-the-shelf sensors and combined them to capture synchronized data and enable wireless communication. Therefore, from each foot it is possible to obtain parameters related to inertial measurements and to plantar pressure distribution either in quiet stance or during gait. Thanks to the wireless transceiver, sensor data can be sent in real-time via Bluetooth to any processing unit enabled with such a widespread standard wireless interface. The system has been designed with the goal of supporting human-in-the-loop sensing and processing. Particular attention during the design of the system was given to optimize the power consumption, to maximize the system lifetime.

In the following, we describe and characterize the system in terms of general architecture, power consumption, sampling rate, sensor resolution, wireless capabilities, and throughput. Then we present some preliminary but effective methodology to extract temporal parameters of gait while using our system with a reference healthy subject.

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II. SYSTEM DESCRIPTION

The system is based on a wireless wearable plantar pressure measurement device, integrated with a 6 Degrees Of Freedom (DOF), MEMS, digital IMU, able then to provide accurate real-time measures concerning localized pressures, accelerations and rotations with a maximum throughput of 103Kbps for the whole system.

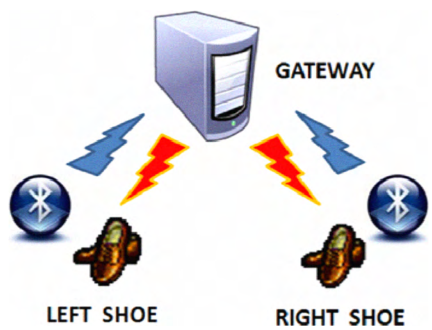

Figure 1. Wireless Network

The system (Figure 1) is based on two wireless boards equipped with Bluetooth transceiver (BT) to enable data streaming from the nodes to the gateway. The gateway is responsible for: (a) wireless networking management; (b) high performance signals processing; (c) bridge between the gateway and the remote server; (d) data storing. The PC acts as a gateway providing functionality such as start/stop data transmission, end-nodes synchronization and exceptions handling. Both nodes integrate a sensorized insole combined with an external IMU containing a 3-axes accelerometer and a 3-axes gyroscope.

A. Node Architecture

Wireless nodes are based on the following functional blocks, (Figure 2), : (i) power unit, (ii) processing unit, (iii) radio interface, and (iv) the combination of the sensorized insole and the IMU. The processing unit is based on the MSP430 microcontroller [11], which provides a serial interface, used for connecting the IMU via Serial Protocol Interface (SPI) while the 12 bit analogical to digital converter samples data from the insole. Power unit is designed to perform the maximum energy efficiency. A two stage chain was designed both to provide different voltage levels (3V and 5V) and to supply up 800mA to the whole system. Radio communication make use of Bluetooth 2.0 + E.D.R. to allow high data rate.

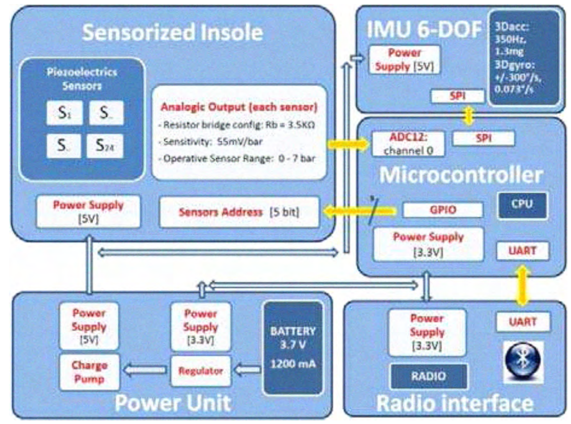

Figure 2. Wireless Sensor Node Architecture

In Figure 3, the internal task of the nodes are represented. The gateway manages the synchronization and guarantees the quality of service. After the gateway establishes the network, it sets the node to obtain the desired sampling rate and throughput. The raw data are sent via radio defining the first 24 timeslots for the pressure measures while the 25^{th} is reserved for inertial data.

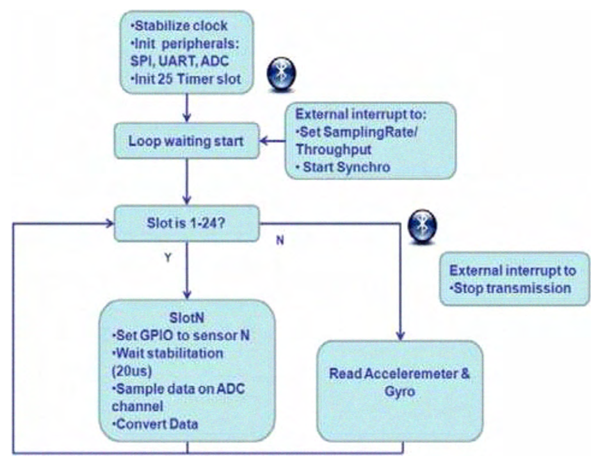

Figure 3. On board firmware

B. Inertial measurement unit

Small form factor and low power consumption are the most relevant features that motivate our choice in selecting ADIS16350 [13]. This component integrates a digital 3-axes accelerometer and a digital 3-axes gyroscope in only 22x22x22mm, with a low current absorption (55mA at 5V, in normal mode). Moreover, this device has high performance in terms of resolution, bandwidth and sensitivity. Relevant features are: (a) accelerometer dynamics: ±10 *g,* bandwidth: 350 Hz, resolution: 1.22mg, (b) gyroscope dynamics: up to ±300°/s, resolution: 0.073°/s.

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C. *Insole*

Several sensor technologies were developed with the goal of enabling plantar pressure data monitoring in a wearable setup. Load cells, force sensor resistor (FSR), strain gauges and piezoelectric sensors are often employed covering at least the lateral and medial heel, metatarsal heads and the toe footprint locations. In the present study we encompass a foot pressure system based on hydrocells by Paromed [12], that employ discrete piezoresistive sensors contained in a fluid-filled cell and then embedded into a flexible insole. Both compressive and shear forces are summed to produce the pressure measurement output. The fast transition time, 20usec, characterizes the sensor allows high sampling frequency. The pressure measured by each sensor is referred to the geometrical centre of each cell and thus considered to be uniformly distributed over the sensor area.

Each insole is based on 24 hydrocells different in form factor (2.84 and 1.75 mm^2) and orientation to perform pressure detection on the higher pressure footprints. Considering the layout as in Figure 4, the 41,8% of the plantar surface is covered. We are referring to a pair of insoles of sizes 39/40.

Pressure sensors are directly connected to an acquisition board equipped with an amplifier and a multiplexer circuit. The amplifier circuit converts the analog output signal of the hydrocell (55mV/100KPa) to the [0-5]V range.

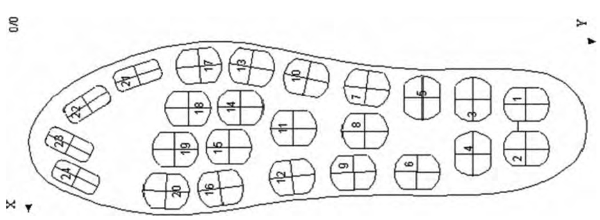

Figure 4. Hydrocells insole placement

The multiplexer interface provides individual cells access. Pressure data are sampled and converted by 12 bit ADC allowing a resolution of 2.2KPa/bit. Sampling time is configurable via radio. The digitalized pressure values are then sent to the gateway and a calibration procedure for each sensor, as provided by the manufacturer, is applied. Local pressure data and location of the center of pressure of each foot [14] are features accessible in real-time.

III. System tuning for gait analysis

The typical bandwidth to analyze the kinematics of normal subjects gait is between 4 and 6 Hz, over a range of different speeds. In particular it was reported a different frequency upper value of 3 Hz for rib and of 6Hz for heel markers [17].

Results regarding spectral power analysis from barefoot walking across a force plate were reported from Antonsson and Mann [20]. They showed that the 98% of the spectral power is below 10 Hz and over 90% was below 5 Hz. Similar results can be found for in-shoes plantar pressures in [21]. Time domain analyses were investigated in [22], where no significant differences are identified between signals sampled at 20 Hz and at 200Hz. Work such as [23] and [25] select 40Sps as sampling rate.

In our work data are sampled at a rate of 80Sps. Such rate also allows an appropriate sampling of inertial data, frequently sampled at around 100Sps [30] . The system can be adapted also for applications requiring higher sampling rate (e.g. in sport or for further motor tasks than gait) fixing the sampling frequency of the entire system up to 250Hz.

IV. Experimental session

Preliminary experiments were performed on a healthy young subject (27 years old, height 1,75 m) who was equipped with the wireless system (insole + IMU), as shown in Figure 8. The subject was asked to walk normally (at self-selected speed) along a hallway for approximately 10m. Before beginning of walking, 20 seconds of quiet stance were acquired to get the baseline of the system and to acquire information about user's balance. The subject initiated to move always with the right leg. Four trials with such characteristics were performed.

A. *Insole pressure data*

In this preliminary study the pressure data during gait were considered with the primary aim of identifying the phases of gait (stance phase and swing phase of each leg). From the phase of gait was then possible to compute the temporal parameters of gait (step and stride duration, double support and single support duration). Such parameters are of frequent use in gait analysis [16]. Insole pressure data were low-pass filtered at 10Hz and then processed.

From the 24 sensors beneath the sensing insole, a correlation analysis was implemented to detect the most informative sensors. In particular, the period of gait was isolated and the correlation matrix computed on such signals. From the correlation matrix 4 groups of sensors were detected. Each group, illustrated in Figure 5, includes signals reciprocally highly correlated (correlation coeff. > 0.9) and with an important dynamic during gait. Other sensors were not so highly correlated or did not highlight important dynamics during gait.

Such groups of sensors are proposed as the most representative, and their pattern of activation may be useful in further experiments on different subjects to identify different strategies or characteristics of walking.

Sensors beneath the heel (lower panel of Figure 5) and beneath the toe (upper panel of Figure 5) were considered in the data analysis to detect heel-strike and toe-off during gait. The identification of such time instants was essential to detect stance, swing phases and then the temporal parameters of gait. Instead of considering a single sensor signal to identify heel-strike and toe-off instants, an average of signal within the groups were performed and then the averaged signal considered as representative of heel and toe pressure distribution. Such signals will be referred in the following as s_{HEEL} and s_{TOE}, with a representation in Figure 6A.

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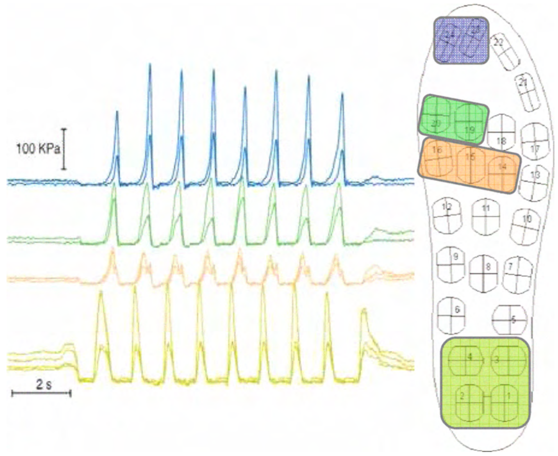

Figure 5. Groups of highly inter-correlated (>0.9) sensors of the pressure insole and corresponding representing signals during gait and during few seconds of baseline acquired during quiet stance. Right insole is represented

Considering s_{HEEL} and s_{TOE}, an automatic method to identify ON/OFF for the corresponding sensors was studied. A simple way to identify "ON" and "OFF" of sensors is that of thresholding them. However such approach may be not enough robust to spurious events or to different behavior or weight of subjects or to changes in the offset of the insoles or to baseline level of the sensors that may depend on user or on the shoes in which the insoles are inserted. Consequently, a method based on the derivative of the averaged sensor signals was implemented since considered more robust and adequate for an automatic detection of the events. The algorithm to identify ON and OFF of sensors on the heel and toe, starting from the signal s_{HEEL} and s_{TOE}, is presented in the following.

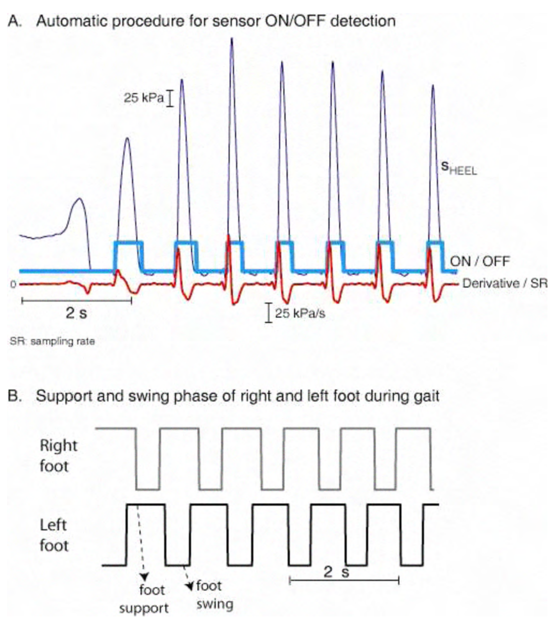

Figure 6. ON/OFF detection algorithm

Considering s_{HEEL}, its activation was identifiable by the numeric derivative that presented a peak in corresponding of its activation. The peak was detected when the derivative values were over a threshold equal to 10 times the standard deviation during quiet stance. Deactivation of the corresponding sensors, was instead identified as the return to values equal to the values of s_{HEEL} activation. This procedure was implemented during the entire trial, identifying ON/OFF of the signal for each gait cycle. ON instants of s_{HEEL} and OFF instants of s_{TOE} were used as start and end of the stance phase of the corresponding foot. Results of the algorithm from a single sensor, for a single trial are represented the following.

B. *IMU signals*

The IMU integrated in the system is able to acquire data along the three directions, both for the accelerometer and for the gyroscope. However, only signals representing the movement in the sagittal plane were considered, since they are the most informative on gait. Considering the reference frame of the IMU box, accelerometric data along the x (vertical) axis and along the z (antero-posterior) axis were considered. Data from the gyroscope were considered along the y axis, representing angular velocity of rotation in the sagittal plane.

The goal of this approach was primarily that of identifying gait phases form the inertial measurements. We decided, in this early development phase to postpone more advanced data processing on the IMU data, such as those needed to detect kinematic information and spatio-temporal parameters, primarily along the direction of gait.

Accelerometers values were filtered at 20 and 5Hz. 5Hz filtering, even if does not divide dynamic from gravitational contribution, mainly includes gravitational information and hence is more related to foot inclination. Temporal evolution of the accelerometric signal is related to insoles pressure and they can also be considered to detect the gait phases coming from the insoles signals.

During initial quiet stance indeed accelerometer measures –g along the vertical direction, and such value decreases because of inclination of the foot. Trend of accelerometric signal along the anteroposterior direction had indeed a contrary behavior. Quiet stance acquisition was confirmed to be important to calibrate the sensor, in case they are not exactly aligned with respect to the vertical direction. This may depends both on the mounting of the sensors or on the kind of shoes the user wears.

Angular velocity in the sagittal plane showed a pattern that clearly identified the periodicity of the phase of gait. The position where the sensor was mounted amplified the dynamic of its values, with angular velocities also reaching 300degree/s.

In Figure 7 representative signals for accelerometric signals and angular velocity were shown. Algorithms with the aim of automatic detection of phase of gait, based on inertial signals, will be developed in further advancement of the present study.

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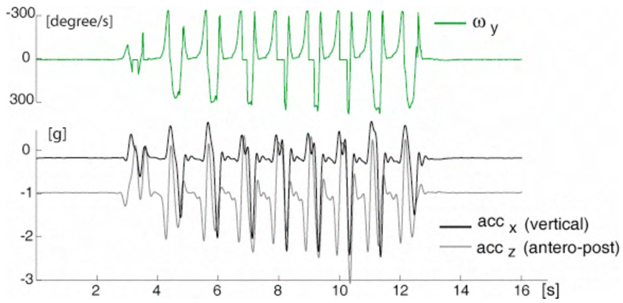

Figure 7. Representative acceleration and angular velocity acquired from one of the IMU sensors included in the system

C. *System lifetime*

Table I summarizes nodes power consumptions when sample rate is fixed to 80Hz. Different measures were made acquiring data from a single sensors and both. Since in the latter case the maximum current absorption is 275mA.the lifetime of the system is 5 hours of continuous operation with 3.7V, 1200mA, Li-Ion battery.

	INSOLE	IMU	INSOLE& IMU
Max Sampling rate [Hz]	340	700	80
Max Throughput [Kbps]	16.32	67.2	52.5
Mean Current Absorption (BT connected) [mA]	93	96	220
Max Current Absorption (BT connected) [mA]	143	146	275

TABLE I. NODE CHARACTERISTICS

V. DISCUSSION AND FURTHER DEVELOPMENTS

We presented a wireless wearable system to capture both inertial and pressure information from the feet. The system is ready to be used in gait and posture analysis both alone or integrated with other systems. The use of Bluetooth for the wireless communication enables easy interfacing with many common devices and in particular with laptops and palmtop computers facilitating applications both in indoor or limited environments and in mobile settings.

Future work will target rehabilitation scenarios where the analysis of gait in mobile settings or at home will serve as input to provide bio-feedback [15] to enhance user independence and continuity of training. We will target extraction of temporal and spatio-temporal parameters thanks to the use of IMU and of biomechanical models.

Figure 8. Setup of preliminary test on a healthy subject

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