Abstract – The physiotherapy exercises for gait rehabilitation are performed by the patient under physiotherapist assistance. During successive physiotherapy sessions the patient motor capabilities is evaluated by the physiotherapist without the usage of instruments and a set of reports are fill manually in order to store the rehabilitation progress based on observed facts. To perform an objective evaluation of patient progress during the physiotherapy sessions the work presents a set of sensing devices that are wearable such as smart inertial measurement unit (IMU) or are embedded in walking aids such as microwave Doppler RADAR array. The data delivered by the smart sensing units designed for gait rehabilitation purpose are wireless transmitted to an advanced processing server that provides synthetic information to the physiotherapist that use a mobile device to access the available services. Elements of IMU sensor network design and implementation as about smart walker and the experimental results for patient characterized by different gait limitation are included in the paper.

Keywords - microwave Doppler RADAR array, inertial measurement unit, gait recovery

I. INTRODUCTION

In gait-related clinical practice as well as in applied scientific research objective information about the forces, acceleration and velocities are very important to diagnose gait patterns and to evaluate therapeutic interventions [1]. The analysis human body movement is commonly done in so-called ‘gaits laboratories’. In these laboratories, body movement is measured by a camera system using optical markers [2], the ground reaction force (GRF) using a force plate fixed in the floor [3], and the muscle activity using EMG [4]. From the body movements and ground reaction forces, joint moments and powers can be estimated by applying inverse dynamics methods [5] providing estimate of rehabilitation progress. Considering the lack of application of this kind of systems for real environments where physiotherapist and doctors assist the people under physiotherapy, an important challenge is to design and implement, reliable, easy to use, and low cost systems associated to gait measurement and analysis that can used by physiotherapist during the normal physiotherapy sessions or can be easily included as part of remote physiotherapy services [6]. At the same time the developed systems for gait measurement and analysis might be prepared for the particular case of the patients that are using walking aids during motor rehabilitation.

Frequent solutions used for objective evaluation of rehabilitation process are expressed by the usage of inertial sensors attached to the human body [7][8]. The usage of this kind of solutions imposes the necessity to fix the sensing module in appropriate way, which requires that the physiotherapist has preparation in this field and in the case of remote physiotherapy could require special knowledge and motor ability from the user part, that limits the usage of this type of systems considering also that are causing discomfort for long period of usage. Appropriate wearable solutions were developed by Postolache et. al. that were reported Bluetooth compatible smart system characterized by motor and cardiac activity monitoring [9] but also a flexible modular multiprocessor plug-and-play with multiple wireless connectivity [10].

Considering that an important group of users that are willing physiotherapy sessions using walkers and rollator and interesting solution is to have sensors adapted to this kind of equipment. Nowadays the frequently used walking aids still not provide any information to the physiotherapist about the intensity of therapy the only evaluation of the physiotherapy effectiveness being done in subjective way. Few authors are reporting the developing of walkers or rollators with capabilities to sense the motion and forces that characterize the users during the physiotherapy sessions and to provide this information to the physiotherapist in appropriate way [11][12].

Taking into account this important challenge of objective evaluation of gait rehabilitation progress the article presents two kind of prototypes: an IMU body area network and a smart rollator characterized microwave Doppler RADAR array both of them associated with gait rehabilitation estimation in objective way.

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Instituto de Telecomunicações and Fundação para a Ciência e Tecnologia (project PTDC/DTP-DES/1661/2012) supported this work.
This paper is organized as follows: we present the IMU (inertial measurement unit) body area network special attention being granted to the end-nodes that includes the 3D accelerometers and gyroscopes. A paragraph presents the microwave Doppler RADAR smart rollator followed by the software elements concerning the acquisition, data processing and communication. A preliminary approach concerning the RADAR signal processing for gait recognition and a set of experimental results are included in the paper followed by the conclusions.

II. IMU-WIRELESS NETWORK

The latest developments in the of microelectromechanical systems (MEMS) makes possible to integrate multiple sensors, including gyroscope, accelerometer and magnetometer in a compact inertial sensor module that may also include a digital processing unit associated with data fusion. This type of implementation is known as inertial measurement unit (IMU) and provides all the information needed for the detection of human movement.[13].

The usage of IMU is also related to the applications in the field of pedestrian deadreckoning (PDR). Step detection, walking speed and step length measurement are proper to the PDR and at the same time are considered as important elements to evaluate the gait during the rehabilitation sessions. In the present work to measure these quantities an Qk motion wireless node based on a IMU board developed in our laboratory was considered[14].

A. Inertial measurement module

To extract the gait information during the physiotherapy session an IMU expressed by a tri-axis gyroscope, accelerometer and magnetometer were employed. The L3G4200D gyroscope from STMicroelectronics was considered to measure the angular velocity. It includes a sensing element and an IC interface capable of providing the measured angular rate to the external world through a digital interface (I2C/SPI). Considering the necessity to assure the digital communication with a 3D accelerometer and 3D magnetometer too, the I2C communication interface was chosen. Based on this interface the data from gyroscope is transmitted to the PIC24F32KA302 the I2C protocol being implemented considering the functionalities of SSL (Synchronous Serial Port) port, SDA and SCL lines. Referring to the accelerometer and magnetometer they are embedded in a single integrated circuit LSM303DLHC from STMicroelectronics. LSM303DLHC has linear acceleration full-scales of ±2g / ±4g / ±8g / ±16g and a magnetic field full-scale of ±1.3 / ±1.9 / ±2.5 / ±4.0 / ±4.7 / ±5.6 / ±8.1 gauss. The Qk motion reduced schematics including the microcontroller and the IMU are presented in figure 1. The first prototype of the IMU is presented in Figure 2 where it can be observed the gyroscope, accelerometer and magnetometer but also the Base connector [10] that includes the U2RX and U2TX communication lines that permit the data exchange between the microcontroller of the IMU board and the microcontroller associated with IEEE802.15.4 wireless connectivity board (Qk nodule).

B. Wireless network

Taking into account the necessity to receive the information related to the feet motion during the gait rehabilitation an IMU body wireless sensor network was designed and implemented. The implemented architecture is presented in Figure 3. The IMU network is expressed by a ZigBee network where the coordinator is connected USB connected to the PC or Tablet and the end-nodes that including each of them a IMU board and a ZigBee communication board characterized by a Digi Zigbee modem. Each of the boards it contains a microcontroller that implements a common protocol stack (the Qk protocol) that allows the data exchange between coordinator and end-nodes that are disposed on the foot level.
All boards can be remotely configured enabling different functionally without requiring firmware updates. For example, a sensor can be configured to send raw data or processed data. Taking into account the current supported technologies, ZigBee boards are the only ones that require the use of a 6k network board. This is the main element of a gateway since it allows collecting data from all networked sensor nodes being used. However, the final objective is to access its data from a computer, smartphone or tablet, which have limited connectivity options. Zigbee or IEEE 802.15.4-based protocols are currently not supported on these devices (without using external adapters), so other connectivity technologies have to be used in order to interface with sensors. USB, Bluetooth or WiFi are possible options. In other words, the gateway transmits the data from all the networked sensor nodes to the computation device (e.g. smart phone, tablet). This is a very important abstraction feature because the computer does not need to distinguish data coming from different network addresses and possibly carrying different information; instead it is all contained into a single structure, sent in a (not addressed) packet. The packets are addressed and computer will know that they come from different sensors.

III. SMART WALKER
The walker’s users are usually persons with limited motor activity caused by pain arthritis [ref], poor balance or joint stiffness while the walker types that are usually used include the classical no wheel walker, two-wheel walker and the four wheel walker or the rollator. All of these models commercially available can be used as walking aids but also during the gait rehabilitation process. In order to perform the unobtrusive monitoring of the user gait during the walker usage a modular sensing, processing and communication unit based on microwave Doppler array was designed and implemented. Together the RADAR array that assures a reliable capture of the performed gait motion the modular unit includes a multifunction board MyDAQ that is USB connected to a compact computer characterized by Wi-Fi connection capabilities and battery as power supply.

A. Microwave Doppler RADAR array
The smart walker used for rehabilitation includes the sensing module characterized by two microwave Doppler RADAR sensors mounted in line and oriented properly to catch the gait (Figure 4). The used Doppler RADAR sensor IVS-162 DRS presented in Figure 4.b. is of the frequency modulated continuous wave (FMCW) type and includes a transmission antenna and a receiver antenna connected to an I/Q receiver.

A FSK/FMCW-capable K-Band VCO-transceiver controlled through a tuning voltage (Vtune), assures a transmit frequency in the 24GHz-24.250GHz interval, according to the applied Vtune voltage that was expressed in the present application by a continuous DC signal VtuneDC=5 VDC or by a triangular signal characterized by 6V Vpk-pk amplitude, fVtune=10kHz frequency and 3 VDC offset value. The signal coming from the receiving antenna is demodulated and a set of intermediate frequencies signals, which correspond to signal in phase I and signal in quadrature Q. During the gait rehabilitation procedure or during the normal usage of the walker, the legs motion of the user is captured by both RADARs of the array, characterized by azimuth angles. The I1 and I2 signals are acquired and used to calculate features that can highlight the evolution of the gait during periodic physiotherapy sessions that can be used to evaluate the effectiveness of the applied training exercises but also can be used to perform the gait recognition.

B. Acquisition, Signal Processing and Communication
The acquisition of the signals from the Doppler RADAR sensors and the Vtune generation was performed for the smart walker prototype using a multifunction board NI MyDAQ that is USB connected to the embedded computer. The acquired signals are processed in order to extract the gait features during the rehabilitation period that can be later used for gait recognition. The values of feature but also the motion wave captured by the Doppler RADAR array...
are Wi-Fi transmitted to a client application installed in Tablet that is used by the physiotherapist.

IV. PERVERSIVE COMPUTING

Software for a Windows 10 Tablet materialize the HMI that is used by the physiotherapist visualize the signals the signals coming from IMU wireless network or from smart walker using ZigBee or Wi-Fi wireless communication protocol.

Referring to the IMU wireless network software Qk Viewer software was developed using the Qt creator. The software allows adding many plots as needed to the plotting area and each plot has its own waveforms selected according with the gait monitoring needs. Each waveform corresponds to a single sensor output data and the sensor manager allows selecting data from a given IMU node (e.g. right foot node). The Waveform Manager can be used to set the plot’s time window and it enables other features such as auto scale, stop plotting when the values reach the end on the chosen time window (e.g. 30s time window was considered during the experimental tests). In Figure 5 are presented the acceleration and angle variation associated with gyroscope delivered values.

![Figure 5. The GUI associated with Qk Viewer software](image)

V. RESULTS AND DISCUSSIONS

In order to extract information concerning the smart walker Doppler RADAR array sensing channels, different tests were done in the laboratory conditions using a NI MyDAQ module characterized by differential analog inputs (AI0 and AI1) and a set of two analog outputs that work as outputs of virtual signal generator output channels connected to the Vtune RADAR input. The GaitRadTest software was developed in LabVIEW and permits to generate the Vtune signals and to acquire the Ii (direct), Qi (quadrature) IF signals delivered by i-th sensor of the Doppler RADAR array. The acquired signals are stored in a embedded PC that materialize the server component of the implemented client-server architecture the acquired and processed data by the server application being accessed through the LabVIEW “Shared variable” technology on the level of mobile devices (smart phone or Tablet) running Android OS or iOS used by physiotherapist or by the accompanying person to assess the rehabilitation process.

The tests were done using as volunteer physiotherapists that can perform regular gait and also analgesic gait, hemiparetic gait and arthrogenic gait. The evolution of the direct IF RADAR output signals for Vtune =5V is expressed in Figure 6 that represents the acceleration signal acquired using a smart Qk motion device that wirelessly transmit the values of captured by 3D gyroscope and 3D accelerometer to the computer.

![Figure 6. The evolution of acceleration measured by Qk Motion with ZigBee communication module during usage of rollator for a regular gait user (ax-black line, ay-green line, az-green line).](image)

By its turn, Figure 7 represents the evolution of VI1_n and VI2_n normalized voltages acquired from the DRad1 and DRad2.

![Figure 7. The evolution of VI1_n and VI2_n normalized voltages acquired from the DRad1 and DRad2 mounted in the rollator level.](image)

Spectral analysis of the VI1_n and VI2_n normalized voltages, associated with the Doppler RADAR signals, is performed using Short Time Fourier Transforms (STFT), being possible to analyze the frequency contents of the gait kinematic parameters. Regarding the main drawback of STFT operator it
is important to refer that the right compromise between spectral resolution and time resolution [xx] that must defined according patient gait speed. As an example, Figure 8 represents the evolution of the STFT spectrogram associated with VI1_n and VI2_n normalized voltages for a time window of 33 s.

Figure 8. The evolution STFT spectrogram associated with VI1_n and VI2_n normalized voltages for a time window of 33 s.

VI. CONCLUSION AND FUTURE WORK

This work presents a smart walker architecture based on a 24GHz FMCW Doppler RADAR array that capture the gait information during physiotherapy sessions permitting an objective evaluation of rehabilitation progress through gait recognition. The proposed system also includes elements of an IMU sensor network design that captures Kinematic parameters related with patients' walking improvements. The experimental results confirm the expected performance of the implemented measurement system.

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