Unobtrusive Sensing for Gait Rehabilitation Assessment

O. Postolache
Instituto de Telecomunicações
ISCTE-IUL
Lisbon, Portugal
opostolache@lx.it.pt

M. Ribeiro, P.S. Girão
J.M. Dias Pereira
Instituto de Telecomunicações
Lisbon, Portugal
psgirão@ist.utl.pt

G. Postolache
Instituto de Telecomunicações
Instituto de Medicina Molecular
Lisbon, Portugal
gpostolache@fm.ul.pt

ABSTRACT
A set of sensing devices that wireless transmit information on gait rehabilitation are presented. Aiming an objective evaluation of patient progress during physiotherapy sessions, we implemented a set of sensing devices that are wearable, such as a smart inertial measurement unit (IMU), or are embedded in walking aids, such as a 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 and smart walker design and implementation for gait assessment, and the experimental results are included in the paper.

Categories and Subject Descriptors
J.3. [**Life and Medical Sciences**] – Medical Information Systems

General Terms
Measurement, Documentation

Keywords
Doppler radar array, inertial measurement system, gait assessment

1. INTRODUCTION
In gait-related clinical practice, as well as in applied scientific research, objective information on the forces, acceleration and velocities are very important to diagnose gait patterns and to evaluate therapeutic interventions [1]. The analysis of 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] thereby 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 for gait measurement and analysis, that can be used by physiotherapists 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 based on the usage of inertial sensors attached to the human body [7][8]. Wearable solutions were developed by Postolache et. al., a Bluetooth compatible, smart system characterized by motor and cardiac activity monitoring [9] and a flexible modular multiprocessor plug-and-play with multiple wireless connectivity [10]. The use of this kind of solutions imposes the necessity to fix the sensing module in an appropriate way, which requires that the physiotherapist has specialization in this field. In the case of remote physiotherapy, in addition to discomfort associated with long period of usage, it could require special knowledge and motor ability of the user part, limiting the usage of this type of systems. Taking into account that many patients in physiotherapy uses walkers or rollator, we designed unobtrusive solution for gait rehabilitation by embedding sensors adapted to this kind of equipment. Few authors reported the development of walkers or rollators with capabilities to sense the motion and forces that should characterize the users during the physiotherapy sessions and provide this information to the physiotherapist in appropriate way [11][12].

In the present work a description of two kinds of prototypes - an IMU body area network and a smart rollator based on microwave Doppler radar array - for gait assessment during rehabilitation are made.

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 include the 3D accelerometers and gyroscopes. A second section 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.

2. IMU - WIRELESS NETWORK
The latest developments in microelectromechanical systems (MEMS) makes possible to integrate multiple sensors, including a gyroscope, an accelerometer and a 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].

IMU applications were developed in the field of pedestrian dead reckoning (PDR). PDR technologies provide step detection, walking speed and step length; thereby they are important tools

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for gait measurements during rehabilitation sessions. In the present work, for measuring these quantities a Qk motion wireless node [14] based on an IMU board developed in our laboratory was considered.

2.1 Inertial Measurement Module

To extract the gait information during the physiotherapy session an IMU expressed by a tri-axis gyroscope, accelerometer and magnetometer was 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, the I2C communication interface was chosen. Based on this interface the data from gyroscope is transmitted to a PIC24F32KA302 microcontroller, the I2C protocol being implemented considering the functionalities of SSL (Synchrounous Serial Port) port, SDA and SCL lines of the microcontroller. The Qk motion reduced schematics including the microcontroller and the IMU board are presented in Figure 1.

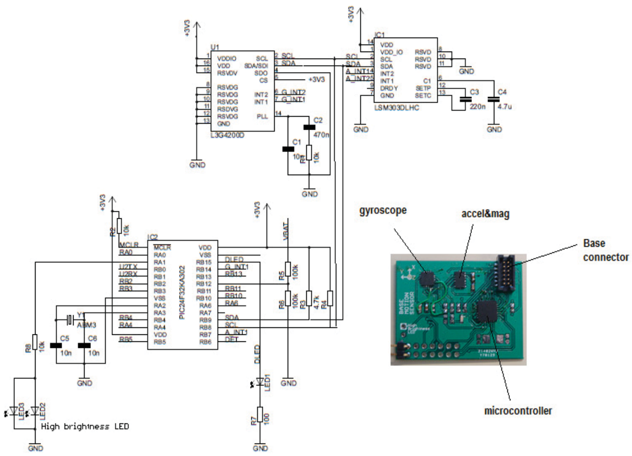

Figure 1. Qk motion: microcontroller, IMU connection scheme and IMU board

The first prototype of the IMU board, presented in Figure 1 contain a gyroscope, an accelerometer and a magnetometer but also the Base connector [10] that includes the U2RX and U2TX communication lines that allows the data exchange between the microcontroller of the IMU board and the microcontroller associated with IEEE802.15.4 wireless connectivity board (Qk nodule).

2.2. 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. Its architecture is presented in Figure 2. The IMU network is a ZigBee network where the coordinator is USB connected to a PC or tablet, the end-nodes that include each of them an IMU board and a ZigBee communication board with a Digi Zigbee modem. Each of the boards 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. Considering the current supported technologies, ZigBee boards are the only ones that require the use of a Qk 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 board such as USB, Bluetooth or WiFi. In other words, the gateway transmits the data from all the network sensor nodes to the computation device (e.g. smartphone, tablet).

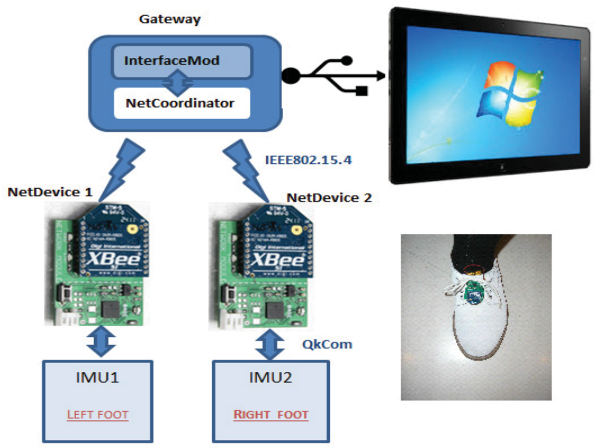

Figure 2. IMU wireless network architecture (QkCom – Qk communication protocol) for gait rehabilitation

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.

3. SMART WALKER

The walker's users are usually persons with limited motor activity caused by neuromuscular disorders, pain arthritis, poor balance or join stiffness, among others. The walker could be without wheels, or with two or four wheels (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 radar array was designed and implemented. Together with the radar array that allows acquisition of gait signals, 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.

3.1 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 3). The used Doppler Radar sensor IVS-162 DRS, also shown in Figure 3 is of the frequency modulated continuous wave (FMCW) type and includes a transmission antenna and a receiving 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 of 5V or by a 10kHz triangular signal of 6V pk-pk amplitude and 3V DC offset. 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 are delivered. During the gait rehabilitation procedure or during the normal usage of the walker, the motion of the user's legs is captured by the array of radars characterized by azimuth angles. The I1 and I2 in phase intermediate frequency 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 and also to perform the gait recognition.

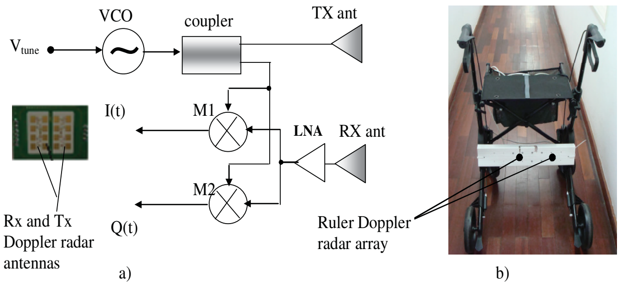

Figure 3. The smart four wheel walker based on Doppler Radar sensor array a) Doppler Radar sensor unit implementation and block diagram b) smart walker implementation including the ruler of Doppler Radar array the multifunction board and the embedded PC

3.2. Acquisition, Signal Processing and Communication

The acquisition of 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 PC, mounted also on the walker. Gait features are extracted trough signal processing - Short Time Fourier Transform (STFT) - and used for gait recognition. The values of features and the motion waves captured by the Doppler radar array are Wi-Fi transmitted to a client application installed in tablet used by physiotherapist.

4. PERVASIVE COMPUTING

Software for a Windows 10 Tablet materialize the human machine interface (HMI) used by the physiotherapist to visualize the signals coming from IMU wireless network or from smart walker using ZigBee or Wi-Fi wireless communication protocols.

Qk Viewer software was developed using the Qt creator for IMU wireless network management and data visualization. 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 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 4 are presented the acceleration and angle variation associated with gyroscope's output values.

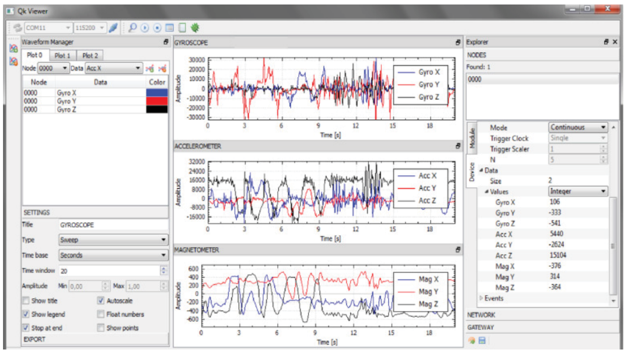

Figure 4. The GUI associated with Qk Viewer software

5. RESULTS AND DISCUSSION

In order to extract information from Doppler Radar array sensing channels from the smart walker, different tests were done in laboratorial 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 an embedded PC that materializes the server component of the implemented client-server architecture. The acquired and processed data by the server application are accessed through the LabVIEW "Shared variable" technology on the level of mobile devices (smartphone or tablet) - running Android OS or iOS - used by physiotherapist or by the accompanying person, to assess the rehabilitation process.

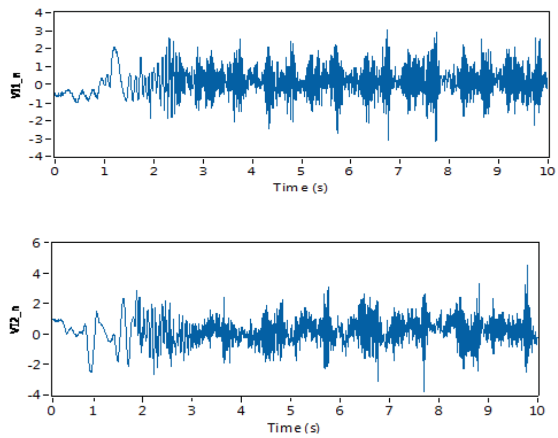

Figure 5. The evolution of VI1_n and VI2_n intermediate frequency signals normalized voltages acquired from the DRad1 and DRad2 radars mounted in the rollator level.

A physiotherapist simulated regular gait and also analgesic gait, hemiparetic gait and arthrogenic gait in order to test the implemented systems for gait assessment. Figure 5 represents the evolution of VI1_n and VI2_n normalized voltages acquired from the DRad1 and DRad2 radar sensors. Spectral analysis of the VI1_n and VI2_n normalized voltages, associated with the Doppler radar signals, is performed using Short Time Fourier Transform that allows analysis of frequency contents of kinematic parameters. Regarding the main drawback of STFT operator, is important to refer that the right compromise between spectral resolution and time resolution [15] must be defined according to the patient gait speed. As an example, Figure 6 represents the evolution of the STFT spectrogram associated with VI1_n and VI2_n normalized voltages for a time window of 10 s. Could be observed the possibility to differentiate healthy gait from an dysfunctional gait through analysis of power and band frequency in time-frequency domain. In the following example the maximum power of healthy gait is more localized in high frequency band (50-100 Hz) than dysfunctional gait characterized by higher power in low frequency band.

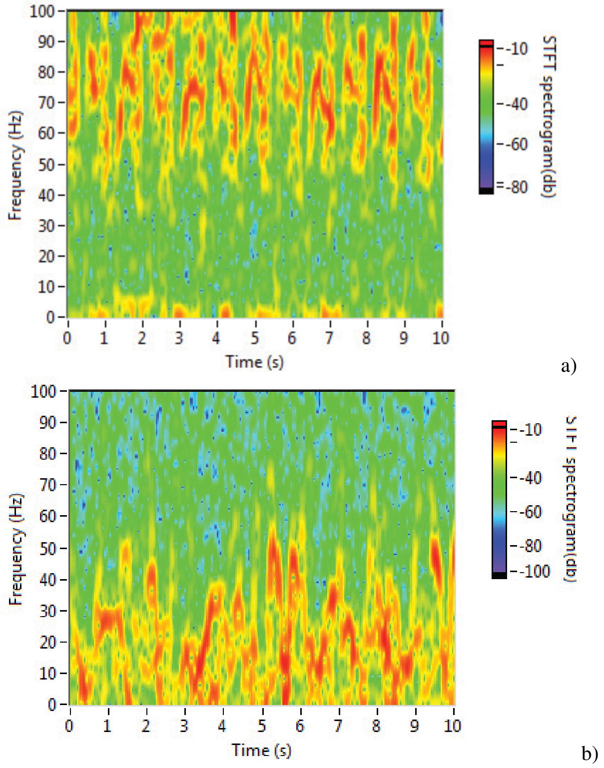

Figure 6. The STFT spectrogram associated with VI1_n (a) and VI2_n (b) normalized voltages for a time window of 10 s.

6. CONCLUSIONS AND FUTURE WORK

This work presents two solutions for gait rehabilitation monitoring, one based on IMU sensor network as wearable solution and the second one expressed by a smart walker architecture based on a 24GHz FMCW Doppler radar array. This system captures the gait information during physiotherapy sessions permitting an objective and unobtrusive evaluation of gait rehabilitation progress. A time frequency analysis of radar delivered signals was carried out for feature extraction, necessary for gait assessment and gait recognition.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

[1] Wittwer, J., Goldie1, P., Matyas, T.A. and Galea, M.P. 2000. Quantification of physiotherapy treatment time in stroke rehabilitation - criterion-related validity, *Australian Journal of Physiotherapy*, 46, 292-298.

[2] Campores, C., Kallmann, M., and Han, J.J. 2013. VR solutions for improving physical therapy. *In Proceedings of IEEE Virtual Reality*, Orlando, Florida, on line at http://graphics.ucmerced.edu/papers/13-vr-pt.pdf,

[3] Prosperini, L. and Pozzilli, C. 2013. The clinical relevance of force platform measures in multiple sclerosis: A review. *Multiple Sclerosis International,* Volume on-line at: http://www.hindawi.com/journals/msi/2013/756564/

[4] Biswas, K., Mazumder, O., and Kundu. A.S. 2012. Multichannel fused EMG based biofeedback system with virtual reality for gait rehabilitation. *Proceedings of International Conference on Intelligent Human Computer Interaction (IHCI)*, 1-6.

[5] Western, D.G., Ketteringham, L.P., Neild, S.A., Hyde, R.A., Jones, R.J.S. and Davies-Smith, A.M. 2013. Validation of inverse dynamics modelling and correlation analysis to characterise upper-limb tremor. *Converging Clinical and Engineering Research on Neurorehabilitation Biosystems & Biorobotics,* 1, 697-702.

[6] Chen, S.L., Lai, W.B., Lee, T.H., K. and Tan, K.K. 2008. *Development of an Intelligent Physiotherapy System*. Mechatronics and Machine Vision in Practice, Springer.

[7] Dunne, A., Do-Lenh, S., Laighin, G.O., and Shen, C. 2010. Upper extremity rehabilitation of children with cerebral palsy using accelerometer feedback on a multitouch display. *International Conference of the IEEE on Engineering in Medicine and Biology Society (EMBC 2010)*, 1751 – 1754.

[8] Higashi, Y., Sekimoto, M., Horiuchi, F., Kodama, T., Yuji, T., Fujimoto, T., Sekine, M., and Tamura, T. 2001. Monitoring rehabilitation training for hemiplegic patients by using a tri-axial accelerometer. *in Proc. 23rd Annual International Conference of the IEEE Engineering in Medicine and Biology Society, (EMBS 2001),* 2, 1472 – 1474.

[9] Postolache, O. and Girão, P.S. 2011. Mobile solution for air quality monitoring and respiration activity monitoring based on an Android OS smartphone, *Proc IMEKO TC19 Symp*, Cavtat, Croatia, 1, 1 - 4.

[10] Ribeiro, M.R., Postolache, O. and Girão, P.S. 2014. *A novel smart sensing platform for vital signs and motor activity monitoring*. Chapter in Sensing Technology: Current Status and Future Trends I, Mason, A.; Mukhopadhyay, S.C.; Jayasundera, K.P.; N. Bhattacharyya,, Springer, Heidelberg.

[11] Postolache, O., Girao, P.S., Dias Pereira, J., Pincho, J., Moura, C., Postolache, G.. 2011. Smart walker for pervasive healthcare. *Fifth International Conference on Sensing Technology*, Palmerston North, New Zealand.

[12] Chan, A.D.C. and Green, J.R.. 2008. Smart rollator prototype. *In Proceedings of IEEE International Workshop on Medical Measurement and Applications.*

[13] Lin, J.F. and Kulić D. 2012. Human pose recovery using wireless inertial measurement units. *Physiological Measurements*. 33, 12.

[14] Ribeiro, M.R., Postolache, O. and Girão, P.S. 2013. Modular platform architecture for fast prototyping of vital signs and motor activity monitors. *Proc IEEE International Instrumentation and Technology Conf. - I2MTC*, Minneapolis, United States, 1, 1 – 6.

[15] Allen, J.B. and Rabiner, L. 1977. A unified approach to Short-Time Fourier analysis and synthesis. *Proc. IEEE*, 65(11), 1558-64.