REAL-TIME WALKER-ASSISTED GAIT ANALYSIS SYSTEM USING WEARABLE INERTIAL MEASUREMENT UNITS

ANDERSON S. ROSA, LAURA S. VARGAS, ANSELMO FRIZERA, TEODIANO BASTOS

Intelligent Automation Laboratory. Electrical Engineering Department. Federal University of Espirito Santo
Av. Fernando Ferrari, 514 – Goiabeiras, CEP 29075-910, Vitoria, Brazil
E-mail: sachetto@gmail.com

Abstract— Results presented in the literature indicate that IMUs (Inertial Measurement Units) are an alternative to vision systems in the analysis of human gait, not limited on monitoring patients into specific laboratories with special equipment and high cost. This work presents a study to address the viability of developing a real-time analysis tool for smart walker-assisted gait. The system consist of a graphical interface to process user gait parameters in real-time helping physiotherapists to assess the current state and/or evolution of patients during the gait, allowing immediate intervention. The system is equipped with a module for off-line data processing, in which the collected data can be stored enabling the quantitative monitoring of the rehabilitation process. Initial results demonstrate the viability of developing a system that can provide support for clinical physiotherapists. Clinical parameters will be evaluated, which will be inserted into the system in near future.

Keywords— Gait analysis, smart walker, IMUs, joint angles.

Resumo— Resultados apresentados na literatura indicam que as IMUs (*Inertial Measurement Units*) são uma alternativa a sistemas de visão na analise da marcha humana, não limitando o monitoramento de pacientes a laboratórios específicos dotados de equipamentos especiais e de custo elevado. Este trabalho apresenta um estudo de viabilidade para o desenvolvimento de uma ferramenta de análise, em tempo real, da marcha assistida por um andador robótico. O sistema conta com uma interface gráfica que recebe parâmetros da marcha do usuário, a fim de disponibilizá-los em tempo real para que fisioterapeutas possam avaliar a situação e/ou evolução do paciente à medida que ele executa a marcha, possibilitando sua intervenção imediata. O sistema é dotado de um módulo para processamento *off-line* dos dados, com o qual é possível armazenar os dados coletados e realizar o acompanhamento quantitativo do processo de reabilitação. Os resultados iniciais demonstram a viabilidade de se desenvolver um sistema que possa dar apoio clínico aos fisioterapeutas. Os parâmetros clínicos serão avaliados e suas informações serão inseridas no sistema em um futuro próximo.

Palavras-chave— Análise de marcha, andador inteligente, IMUs, ângulos articulares.

1 Introduction

Aging, conditions at birth, accidents and disorders including Parkinson's disease, cerebral palsy, stroke and spinal cord injury can alter biomechanical features that define a healthy gait pattern (Tien et al., 2010). In this context, clinical professionals and researchers resort to the use of assistive devices for the treatment and functional compensation of patients with gait impairments. Such devices can be passive or active depending on their interaction with the user. Examples include canes, crutches, manual and autonomous wheelchairs, conventional and smart walkers, prostheses and orthoses, and recently robotic exoskeletons. Considering its simplicity, walkers represent an assistive device with great potential to improve safe, efficient ambulation, balance and stability of patients (Frizera et al., 2012).

Conventionally, clinical assessment of patients' functional ability is subjective, based on experience and descriptive information about movement patterns. Thus, there is a significant need to have quantitative information making the assessment objective and precise. Moreover, the knowledge of kinematic parameters, as a fundamental part of a complete human gait analysis, helps to optimize rehabilitation strategies (Frizera et al., 2012). In addition, this quantitative information can be used to provide feedback for both physician and patient, in order to monitor the therapy evolution. Different researches about gait rehabilitation have demonstrated that feedback of gait performance takes an important role on motor relearning and improve patients' motivation (Lünenburger et al., 2007).

In gait analysis, optoelectronic systems based on cameras are considered the gold standard. However, these technologies present some limitations: they are expensive, present reduced portability, restrict the study to a controlled laboratory environment and require dedicated and experienced personnel. The aforementioned characteristics may make difficult the use of these systems in clinical routine and in conditions where the patient is performing their activities of daily living. Moreover, systems based on cameras are not a flexible and adaptable option to applications involving walkers.

Alternatively, wearable sensor systems (WS), such as Inertial Measurement Units (IMUs), with evident lower cost, usability and flexibility advantages may offer real-time motion analysis. Their portability and simple setups make IMUs suitable for ambulatory applications (Luinge et al., 2007).

Different approaches using smart walkers for gait rehabilitation can be found in the literature. In some of those researches different spatio-temproral parameters and gait events are estimated using gyroscopes, accelerometers and encoders but placed only on the walker and using kinematic models (Wang et al., 2014). Other authors used a combination of data from a LFR (laser range finder) and IMUs placed on both walker and user to develop control strategies based on inverse kinematic evaluated on an inclined path (Tausel et al., 2014).

Meanwhile, fall detection algorithms for smart walker are proposed in Hirata et al., 2008 e Huang et al., 2014. In Hirata et al., 2008, two LFRs were used in order to estimate the location of user's center of gravity (CoG) in real time, generating control actions on the wheels to stop the walker in an attempt to prevent the user falling. Another algorithm to estimate the CoG was proposed in Huang et al., 2014, using IMUs and anthropometric measures i.e. length of body segments.

In the previous researches, different methods were proposed to accomplish human gait assessment and control strategies for human-walker interaction, path following and fall prevention. However, practical and interactive proposals for continuous monitoring, providing feedback, localization and mapping for walkers have been little explored. Therefore, this work aims to develop a system that allows monitoring smart walker user performance, providing immediate visual biofeedback of gait parameters. In this paper, a GUI (Graphical User Interface) was developed to estimate hip, knee and ankle joint angles, also making possible to conceive an integrated system that provides a ZigBee communication channel between the smart walker and IMU sensors with the GUI in real time to assess patients' performance during walker-assisted gait.

This paper is organized as follows. Section 2 presents the methodology of this work, describing the sensors, joint kinematics, robotic walker platform, system integration and experimental protocol. Section 3 describes the experimental results obtained with the interface. Conclusions and future work are presented in Section 4.

2 Materials and Methods

2.1 Robotic walker platform

The UFES's smart walker is a 3-wheels walker with a pair of differential rear wheels driven by DC motors and a front caster wheel (Rodriguez, 2013). Control and processing tasks are executed on an embedded computer based on PC/104-Plus standard (1.67 GHz Atom N450). The application is integrated into a real-time architecture based on MATLAB Real-Time xPC Target Toolbox. The walker is instrumented with other sensors, including:

- One LRF (Laser Range Finder) sensor model URG-04LX (Hokuyo, Japan) mounted on the walker at legs height. This sensor is used to measure the distance between user's legs. The UFES smart walker has a Legs Detection Module (Figure 1) to provide the legs location every 100 ms.
- Two 3D Force sensors MTA400 (Futek, US) integrated under each forearm-supporting platform, which allows measuring six independent components of interaction forces.
- Two high resolution encoders whose signals are used at the low level control of the DC motors, which is comprised of a Transmissive Rotary Disk of one inch of diameter, and 5000 CPR (Cycles Per Revolution) working together with an EM2 Transmissive Optical Encoder Module (US Digital, US). The EM2 uses a lensed LED source and a monolithic detector in circuit to provide a better performance of signal acquisition. Data from encoders are processed on a Multifunctional Analog/Digital I/O board, named Model 526 (Sensoray, US).

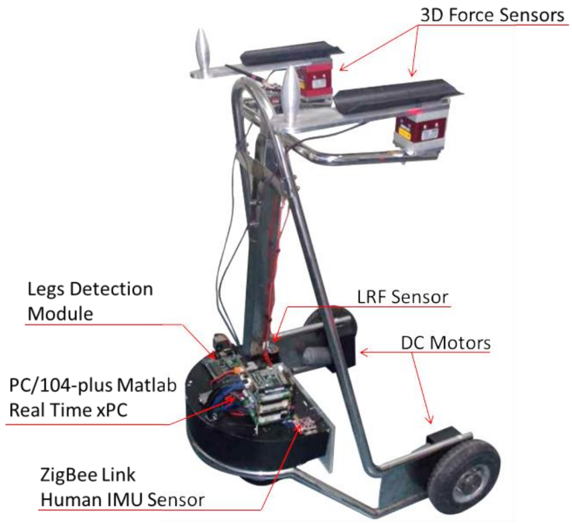


Figure 1. UFES's smart walker [Modified from: Rodriguez, 2013].

2.2 MARG sensors

Four MARG (Magnetic, Angular rate and Gravity) sensors (Figure 2), developed in a previous research (Alfonso, 2014), are used in this work. MARG sensor includes a 3D accelerometer (ADXL345), a 3D gyroscope (ITG-3200) and a 3-axial digital compass (HMC5883L). Each sensor has a ZigBee transceiver used for wireless communication. These IMUs are placed on the pelvis and right lower limb (thigh, shank and foot) in order to quantify and detect user gait features such as joint angles, walking speed and cadence. To represent the orientation of body segments, quaternion format is used.

Each MARG sensor sends a message to the concentrator every five milliseconds, which contains the sensor identifier, its gyro data and its orientation data in quaternion. The concentrator device waits for messages from all of the four sensors, and every 20 milliseconds sends a message comprising all the information to the PC. This way, all sensor data are synchronized (Alfonso, 2014).

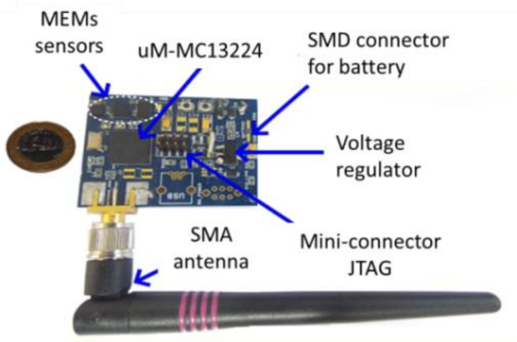


Figure 2. MARG - UFES board [Modified from: Alfonso, 2014].

2.3 Spatiotemporal and joint kinematics

Hip, knee and ankle joint angles are estimated using the body-to-sensor calibration procedure and joint angles extraction method presented in a previous research (Vargas et al., 2014). Basically, a technical-anatomical quaternion is defined for each body segment (${}^{G}Q_{B}$, orientation quaternion of the body with respect to the global system). The joint rotation is calculated as:

$$Q_{JOINT} = {}^{G}Q_{pB}^{*} \otimes {}^{G}Q_{dB}, \qquad (1)$$

where pB denotes the proximal and the dB the distal segment respect to the global system. The rotation Q_{JOINT} describes the joint angles, which can be extracted using the Euler sequence ZXY.

Kinematics of the hip, knee and ankle joint are calculated for total joint excursion throughout the gait cycle, using the initial contact (Heel Strike -HS) and Toe Off (TO) events. Total joint excursion is calculated using the maximum and minimum values for each joint angle. These discrete parameters were previously reported in a reference work by Benedetti et al. (1998), for the three planes of motion. These parameters allow making a parametric analysis, which is demonstrated to be a reliable and practical method to analyze gait data. Also, it is a useful tool for the assessment of data reliability (Benedetti et al., 1998). In Table 1, the joint excursion parameters able to be displayed in the interface which is listed, named according to Benedetti et al., 1998.

Table 1. Joint angles parameter for gait analysis.

Parameters (º)	Description	Parameters (º)	Description
H6	Total sagittal plane excursion	K6	Total sagittal plane excursion
H7	Total coronal plane excursion	A6	Total sagittal plane excursion
H10	Total transverse plane excursion	A7	Total coronal plane excursion

The procedure to extract the gait cycles consists of determining the events HS and TO. Sabatini et al. (2005) propose a method to determine these parameters using the angular velocity sensed by a gyroscope on the foot.

How proposed by Sabatini et al. (2005), finding these points comes down to identify the moment when the foot movement changes its direction; if it changes from clockwise to counter-clockwise, it’s a TO moment, otherwise, it’s a HS. In this work, a method to determine the HS and TO events was developed, which uses the derivative of the gyro signal from foot’s IMU. A data set formed by the last three acquired samples, from the foot's IMU gyro data, is stored and its derivative is calculated. If a change from negative to positive sense occurs, the center point of the data set is considered a HS or TO event. An experimental threshold was defined and used to differentiate both.

2.4 GUI and systems integration

Figure 3 shows a complete schematic of the systems integrated in this work. A GUI was developed in order to provide a visual feedback to both user and therapist. During the walker-assisted gait, the joint kinematics is plotted in order to promote a continuous monitoring of the user performance.

A coordinator sensor receives data from MARG sensors. Then, the coordinator sensor transmits the information to a PC by USART, where the GUI is installed. Using the GUI, hip, knee and ankle kinematics are calculated based on quaternions, and the angles, in different planes of movement, are plotted in a graph. Additionally, the data set can be saved in a data logger file to allow an off-line data processing.

The GUI was developed using Python programming language, along with a framework appropriated to design GUIs, the PyQt4, which is an open source library that can be used to design professional GUIs (Riberbank, 2015).

The GUI was designed and divided in three parts. The first one is responsible for communication tasks. A thread running continuously checks the PC serial port to get any message coming from the coordinator, which is connected by a USB port (Figure 3). Every time a new data is presented on the serial buffer, the thread sends it to the second part, which is the main task, where the quaternions and angular velocity are processed and the joints kinematics are estimated. The graphical interface, the third part, is responsible to show in a graphical form the parameters of interest.

2.5 Experimental protocol for preliminary test

One volunteer without gait disabilities was enrolled in this study. IMU sensors were placed on the pelvis, right thigh, right shank and right foot. The sensor placed on the pelvis was aligned to the walking direction as proposed in Vargas et al., 2014. The subject was asked to keep a straight, upright posture during five seconds before starting walking in a 10 meters walkway. This calibration posture allowed the

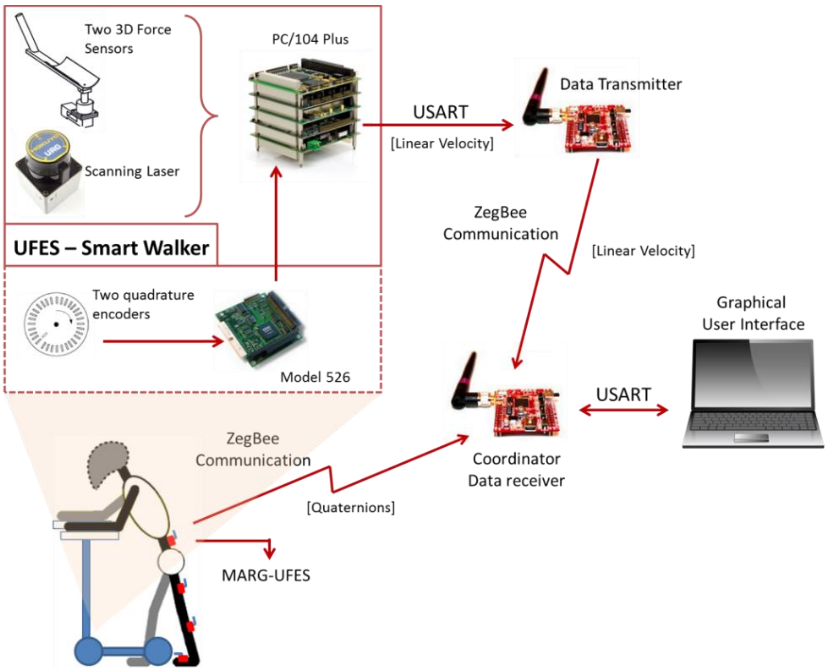


Figure 3 - Schematic diagram of the integrated system.

definition of the body-to-sensor alignment and setting the initial configuration of the GUI. Also, during this first stage the physiotherapist can check the sensor communication, and if the data are being received correctly.

The purpose of this experiment was to check the communication between sensors and GUI, including validation and verification of the programming code, algorithms, graphical library and serial communication in order to display correctly the kinematics parameters. On the screen, hip flexion-extension, hip abduction-adduction, hip internal-external rotation, knee flexion-extension, ankle dorsi-plantar flexion and ankle eversion-inversion are shown.

3 Results

The GUI was designed mainly to provide the physiotherapist on-line information, during the assistive gait, but moreover, a function able to process off-line data was also designed. During the daily life, the patient can choose saving data through the GUI and then, when assisted by physiotherapist, the progress can be evaluated.

As mentioned in section 2.2, the MARG data fusion algorithm certifies that every 20ms a new dataset is available to the GUI that will have a 20ms window to process it and display the results graphically. Even though communication is susceptible to delays in the order of milliseconds, the system usability by the physiotherapist is not affected.

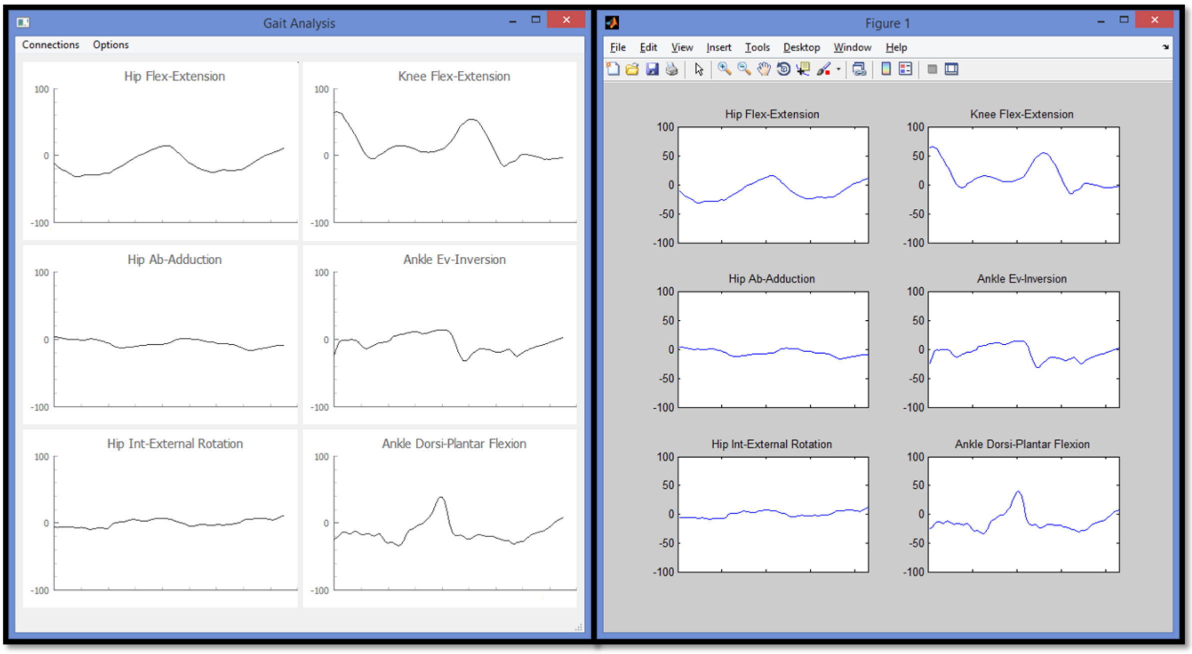
The UFES’s smart walker is used as an aid mechanism to gait, and its embedded system does not restrict the use of the gait analysis proposed in this work , allowing patients who do not make use of robotic walkers, also using our the gait analysis system.

This preliminary test demonstrates the feasibility of design and implementation of an integrated system to monitor the walker-assisted gait in real time. This was possible since data from MARG sensors were correctly collected and on-line processed without losing information. Using the same dataset, a comparison test between off-line and on-line processing was performed. Off-line processing was run at MATLAB. Both data from sensors and processed data shown on the screen were saved using the GUI.

The capture screen of the GUI presenting angles related to fragment gait cycle is shown in Figure 4a. Results of off-line data-processing are shown in Figure 4b, which are also consistent with those presented in the literature (Vargas et al., 2014), where a commercial system was used and data were processed off-line. Thus, it is possible to ensure the use of IMUs as an alternative tool in gait analysis in addition to a user interface to facilitate online monitoring during the therapy.

So far, six discrete angular kinematic parameters are being computed online in the system, with total joint excursion at three planes (H6, H7, H10, K6, A6, A7) (Benedetti, 1998). Table 2 shows these parameters obtained from the volunteer, with mean and standard deviation.

The angular velocity from the IMU placed on the foot was analyzed, and from the information on sagittal plane, the events TO and HS were calculated. This information is very important as the HS and TO events represent the beginning of the stance and swing phases, respectively. Also, these data allow extracting gait cycles, understood as the period between two HS instants (Whittle, 2007). In Figure 5, the processed waveform is shown, where the estima-



a) b)

Figure 4. Graphical results for: a) on-line; b) off-line processing.

tion of HS is indicated with an asterisk and TO with a square.

Table 2 - Discrete angular kinematic parameters from the volunteer, where Cn identifies the cycle number.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	Mean	± STD
H6 (º)	47,8	47,0	40,2	41,0	44,0	40,0	41,3	42	44,2	43,1	2,7
H7 (º)	16,1	18,4	20,1	16,1	18,3	19,0	21,1	17,2	20,2	18,5	1,7
H10 (º)	18,5	20,0	20,0	19,7	19,8	20,1	18,7	19,0	18,9	19,4	0,6
K6 (º)	59,5	68,5	62,7	67,4	60,8	69,7	64,6	63,2	66.5	64,6	3,44
A6 (º)	39,8	41,2	40,1	42,0	39,8	44,3	41,8	39,9	41,7	41,2	1,4
A7 (º)	31,3	37,9	33,4	35,1	33,0	32,1	32,8	37,4	33,2	34,0	2,2

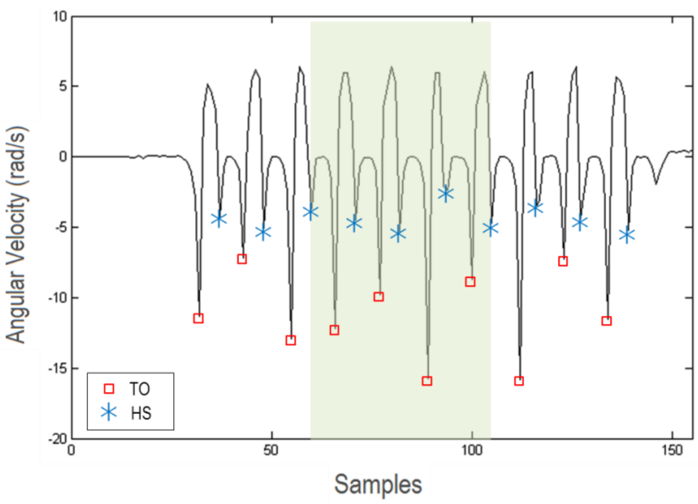


Figure 5 - Detection of Heel Strike (HS) and Toe-Off (TO) events.

4 Conclusions

This work shows the viability of designing and implementing a real-time system to analyze the human gait assisted by walker, which will allow physiotherapists improving its diagnostics and making treatment decision, also making possible a continuous monitoring of the patient.

Using this system, it will also be possible to generate a data log of patient's gait information in near future. The complete integrated system can be used in ambulatory applications and the patient will be able to use it at home during its daily life. In addition, physiotherapists will be able to save the parameters during each test, allowing analyzing the patients' evolution.

Future investigations will be focused on providing other clinical parameters, like maxim flexion at loading response, maxim flexion at swing phase, and cadence, allowing physiotherapists improving the diagnostic based on joint angle parameters.

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