An Intuitive Visual Interface for a Real-Time Monitoring System for Human Gait Using IMUs*

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***Abstract*—A Matlab Graphical User Interface (GUI) to help monitor the human gait in real time, and to enable to better understand the information of the used Inertial Measurement Units (IMUs) system is here presented. The interface not only improved the speed of data processing, but also facilitated the interaction between the user and the system, providing a clearer change of variables and information exchange. In order to ensure a clearer and more reliable data processing an algorithmic state machine (ASM) was implemented. Data from sensors can be used to estimate the orientation of each module through the use of a complementary filter (representation achieved in Quaternions and/or Euler angles), based on previous work. Furthermore, in this article it will be presented the list of requirements built initially for the interface creation as well as the Matlab GUI, its functionalities, and its assessments. Results show quality assessment of the developed interface based on an inquiry made in a group with thirty-six participants, and the assessment of the communication protocol.**

Keywords—Inertial Measurement Units (IMUs); Graphical User Interface (GUI); Motion Capture; Wireless Sensor Networks; Neurological Diseases.

I. INTRODUCTION

A. Background and Motivation

Human walking, which is one of many types of human gait, can be considered as complex and a common human physical activity that can be performed in a variety of ways and directions, and that requires muscular strength, joint mobility and coordination of the central nervous system [1]. According to [2], the normal gait can be affected by a number of neurological injuries that have been investigated in order to improve the early diagnose techniques and to develop and/or to assess the treatment procedures. Specially, from gait pathologies are highlighted: stroke; poliomyelitis (polio); spinal cord injury (SCI); Parkinson disease (PD); cerebral palsy (CP); multiple sclerosis; hip and knee osteoarthritis; muscular dystrophy; gait degeneration in elderly subjects; rheumatoid arthritis; degenerative joint disease; and myelomeningocele. Consequently, the main symptoms used to diagnose and to assess the progress of the gait impairments are disorders and abnormalities of the gait caused by walking diseases.

Thus, a detailed knowledge about gait characteristics at a given time, and monitoring and evaluating over time, will allow early diagnosis of diseases and their complications, which contributes to the decision of the treatment that should be chosen [3]. In order to quantify these gait characteristics or parameters, there is a set of several techniques [3],[4] used for gait measuring such as: Image Processing (e.g., Vicon or Optotrack); Floor Sensor or instrumented walkways (e.g., the GAITRite system); and Wearable Sensors (e.g., Inertial Measurement Units - IMUs).

Among all the techniques mentioned, wearable sensors units reveal an extreme potential to monitor ambulatory activities in the home environment, and their reliability has since been demonstrated in various studies. So, the connection between this technique for measuring gait and Ambient Assisted Living (AAL) is truly promising [5],[6],[7]. Not surprisingly, a real-time monitoring system is essential in this type of environment, because it allows the gait analysis to be continuous and ambulatory. This whole process may still be easier to understand if the information is available in a way that the user perceives intuitively. An interface can simplify the whole process, ensuring this easy understanding from those involved.

Nowadays, in some cases, commercial brands that produce IMUs systems also offers a software for motion capturing. For example, Xsens offer a software called MVN Studio and can provide real-time three dimension (3D) visualization and data integration, and playback and editing of motion capture data [8]. InterSense is also a company that provides software to monitor human motion [9]. Motion Capture Software from Technaid is also an example of GUIs in the market [10]. According to Technaid, their visual interface is intuitive, and provides real-time data visualization and recording with 3D IMU and Avatar visualization.

B. Problem Statement and Scope

Based on an IMUs system with an established communication protocol from a previous project [11], the main problem translates into a difficulty that the user has when using the system. Basically, the information that can be modified requires the user to change code for what he or she wants. To do this, it is necessary that the user is familiar and skilled with the system, and that he has spent some time studying the entire project. Besides, there is no visual interface or real-time data visualization. All the processing is done *a posteriori*, and not in real time has required in data monitoring. In order to overcome

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these problems, it is proposed the development of a Matlab GUI that meets all system requirements and is capable of facilitating human-machine interaction, making it more intuitive, appealing and working in real time. In addition, the speed of data processing has been improved, and an Algorithmic State Machine (ASM) was implemented as a means to provide for reliability and feasibility of the overall system. In order to achieve an intuitive interface the end-users' opinions were assessed and included in the GUI development since the beginning. These quality assessments about the developed system were made through enquiries to different type of users.

C. *Study Importance and Objectives*

Concerning the literature in the scientific community, although there are some studies that focus on the monitoring of events through the aid of a GUI [12]–[14], none of them aggregates in the same article the real-time gait monitoring by using a GUI through a inertial measurement units (IMUs) system. So, the purpose of this paper is to gather all information regarding gait analysis, IMUs system, and a Matlab GUI. Thus, the article intends to demonstrate the extension of previous work [11], the developed Matlab GUI, and the quality assessments of several users about it. The remainder of this paper is organized as follows: in Section II the system used by the authors, the communication protocol established between system elements, the explanation of the implement ASM and the human gait are presented; Section III presents, respectively, a list of needs identified from the system to build an interface, and explains in detail the built GUI; Section IV provides methods for assessing the quality of the GUI and to validate the communication protocol; Results and discussion of the quality assessment and the validation of the communication protocol methods are presented in Section V; and Section VI contains the conclusions and future work.

II. System Overview

The overall system, able to monitoring human gait, is shown in Fig. 1. A personal computer (PC), a base station, and sensory modules are the three main elements of the system used [11]. A MPU-6000 [15] from InvenSense, which contains a three-axis MEMS accelerometer (Acc), a gyroscope (Gyr), and a temperature sensor, allowed an integration with a Honeywell three-axis Digital Compass IC HMC5883L (Mag) [16]. This sensor board is connected to the CC2530EM module (Evaluation Module) from Texas Instruments which is a System-on-chip solution to IEEE 802.15.4 applications (IEEE Std 802.15.4, 2006) through two 20-pin header connectors. Thus each sensory module is formed.

The Evaluation Module is used to establish communication between sensory modules and base station SmartRF05EB (Evaluation board) via wireless. Data received by the base station is routed to the PC via serial port (RS-232). Subsequently, the data are properly processed. Moreover, each sensory module can be firmly attached to one body segment to be monitored. Sensors from each sensory module were calibrated as mentioned in [11] before a gait monitoring. Thus, there is a system capable of monitoring human gait. The entire system is controlled by the developed GUI. In the following it is presented the use of the communication protocol, the proposed ASM, and a brief explanation of the human gait. The sampling frequency is at least 0.63Hz, and 160Hz is the maximum value. However, 30Hz is the minimum value used to monitor gait.

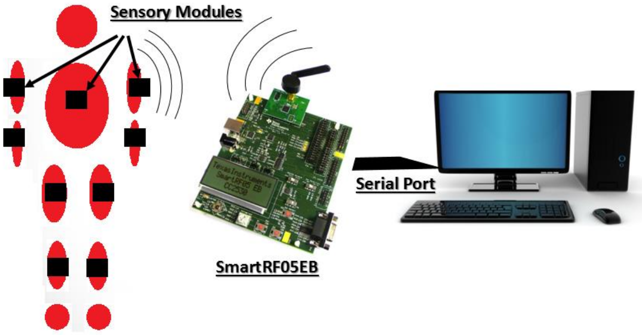

Fig. 1. Magnetic/Inertial Measurement System Elements.

A. *Communication Protocol*

The communication through the wireless medium is controlled through the Enhanced Low Power Real Time (eLPRT) protocol that was designed to optimize the quality of service (QoS) support and the bandwidth utilization efficiency [17]. After the information from the sensors has been collected, it is necessary to form a multi-byte message to transmit the multiple sensor readings between the sensory modules and the base station. This message will be designated from now on as frame (Fig.2.a). At this point, the user can set both the frame period and the number of sensor readings (n) in each period. Each reading is expressed in two bytes for each axis of each used sensor. For example, in Fig. 2.b, "S1 Acc_X1" represents the first byte from the first accelerometer reading, and "S1 Acc_X2" the second byte from the same reading.

In Fig. 2.a, the "Type" byte indicates the function of the frame, i.e., if it is a command message or a sensors data message. The "Length" byte gives information about the size of the payload. The CRC (cyclic redundancy check) values (CRC1 and CRC2) are used to detect accidental changes to raw data. If they do not match, then the block contains a data error.

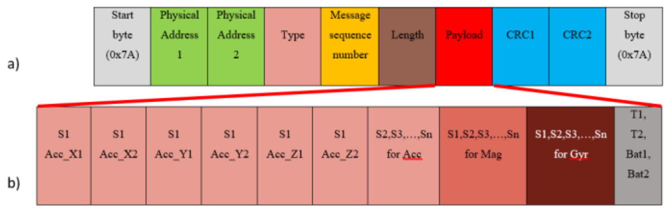

Fig. 2. a) Constitution of the frame; b) Constitution of the payload (S-sample/reading, T1 & T2-temperature byte 1 and 2, Bat1 & Bat2-battery byte 1 and 2).

B. *Algorithmic State Machine*

As the data is received by the base station, it is necessary to process the bytes in order to obtain the relevant information from the sensory modules. To this end, it must be ensured that the frame is received correctly, and two equal frames are not processed. Thus, an ASM was made in order to improve the reliability of the data processing (Fig. 3).

As soon as the user clicks the "Start" button, a start command is sent through the selected serial port to all activated sensory modules to start sending data. At the same time, frame size (blocksize) is set. Then, the serial port starts to be read. In order to start information processing at least one frame has to be constituted. From Fig. 2.a, it is possible to retain that the start byte and the stop byte have the same value. Thus, the byte position corresponding to the decimal value 122 is collected to the array "str_byte_pos". So, a "for" loop sweeps this array through a count variable "i". While "i" is less than the number of possible start bytes, the CRC bytes will be checked, and if "CRC state" variable is one, it means that the frame is valid for processing.

When "i" is one, the frame is immediately checked. Otherwise, the frame is checked if there are as many or more bytes between possible start bytes than the size of the "blocksize", or even if there are fewer bytes between possible start bytes than the "blocksize", the "CRC state" variable must be 0 in this particular case. If "CRC state" variable is one, the stop byte corresponding to the checked frame is eliminated from the array "str_byte_pos" except for the first position of this array. Thus, it is possible to shorten the number of iterations of the "for" loop.

Sequence number of the frame is compared to the last received. If the frame is equal to the last one, the last frame received is not processed. So, two consecutive processed messages are necessarily different. Taking into account the payload structure shown in Fig. 2.b, the data is then separated, processed, displayed, and saved in real-time. With the aid of a complementary filter to estimate the orientation, it is possible to obtain the angles of each sensory module represented in quaternions and/or Euler Angles. Another feature is the detection of human gait events, namely foot flat, toe off, swing phase, and heel strike by using sensory modules on the upper foot or on the heel. When the "for" cycle ends (Stop states), the whole process will repeat itself again when the number of bytes received by the serial port is enough to constitute a new frame. This process occurs while the selected modules are activated. After several uses of this ASM, its operation is considered exemplary, since it never had problems of operation. It showed an efficiency of 100% for a use of 500 times. This ASM was used in [18] to quantify the wireless communication losses.

C. *Gait analysis*

Depending on the subject anatomy/physical condition and the ground, gait is the movement pattern of the body from one place to another [19], and a gait cycle is the time interval in which one limb performed a single sequence of limb movements [19], [20]. Each gait cycle is divided in two major periods as depicted in Fig. 4: the stance phase (0-60%), period during which the foot is on the ground; and the swing phase (60-100%), period during which the foot is in the air for limb advancement [21]. Stance phase can be subdivided into three separate phases, namely, First double support (0-10%), Singlesupport (10-50%), and Second double support (50-60%) [21]. Both stance and swing can be further divided into five and three phases, respectively. The sub-phases are also represented in Fig. 4 and are as follows: Initial Contact (0-2%), Loading Response (2-10%), Mid Stance (10-30%), Terminal Stance (30-50%), Pre-Swing (50-60%), Initial Swing (60-73%), Mid-Swing (73-87%), and Terminal Swing (87-100%) [1], [19]–[21]. However, the classification of marching events does not stop here. There are events that are responsible for the transition of gait phases, and Fig. 4 describes this relationship. Four events are considered: Heel-Strike, Foot-Flat, Heel-Off, and Toe-Off [1], [19]–[21].

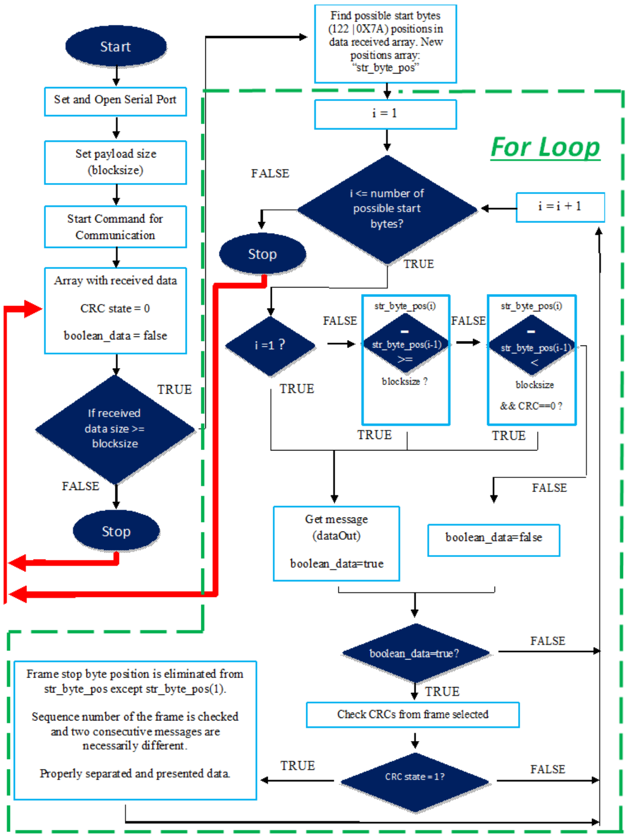

Fig. 3. Data acquisition process flowchart.

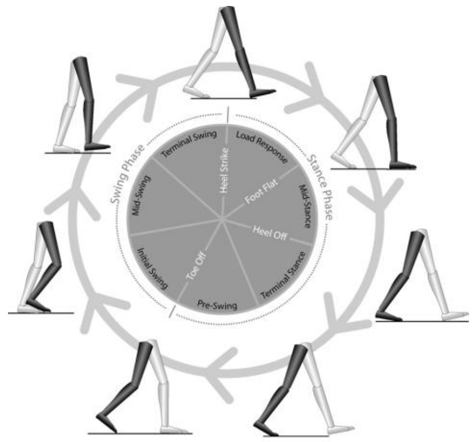

Fig. 4. Normal gait cycle formed by stance and swing periods and respective gait phases [1].

III. System Requirements and Matlab Interface

Data acquisition can be facilitated by the development of a GUI. A logical and intuitive man-machine interaction can be achieved as long as all the necessary variables and requirements of the system are known. Moreover, the GUI can display relevant information in a simple and easy-to-understand way, which would be more difficult if only the command line was used to display the information. As already mentioned, for this project it is intended a real time human gait monitoring. As such, there is a lot of information to be processed and displayed instantly. The GUI will provide for an intuitive visual interface and real-time data visualization and recording.

A. System Requirements

In order to properly develop the GUI, it is necessary to establish a list of requirements based on the user and system needs. The requirements are as follows: a) an easy way to select the serial port; b) an interactive way to choose which sensory modules to use and where to place them; c) from the selected modules choose a module of interest; d) must provide information about the battery status of the selected sensory modules; e) should display the temperature from the temperature sensor of the sensory module of interest; f) should count the time from start to finish; g) allow real time data visualization of the sensors data and the calculated angles of the module of interest; h) allow recording the data to files; and i) count total frames, lost frames and their percentage over real-time monitoring.

B. Matlab Interface

Once the system requirements were defined, a Matlab GUI that fulfilled the previously mentioned requirements was developed. Thus, each requirement has been evaluated and structured in such a way to be represented in the Matlab GUI with simplicity, so that the user can interact with the interface intuitively and easily.

The interface acts as follows. When the interface is initialized (Fig. 5), it is displayed: i) a representation of the human body appears displaying the body segments where the respective sensors can be allocated (only body segments are considered); ii) a control panel where there is a "Start" button (disabled at the beginning), a time display, a panel that assesses the communications quality by displaying the lost frames/packets and the total packets received, and two displays (battery and temperature) of the module of interest; and iii) a settings panel, where it is possible to select the serial port, the module of interest, which information to visualize in graphs from a dropdown list (e.g. accelerometer, gyroscope, magnetometer, sensory module angles and the gait event detectors) and the state of the batteries of all sensory modules.

As a first step, the user must start by indicating the location of the sensory modules in the body segments shown in the representation of the human body in the interface, inserting the physical address of the sensory module in the textbox of the respective segment. Each module has its number recorded and in view of the user.

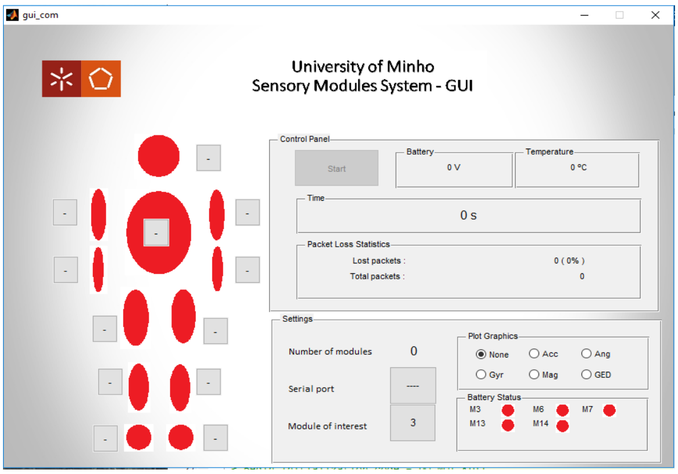

Fig. 5. Matlab GUI when initialized (Ang – Angles; GED – Gait Events Detection).

The representation of the human body in the interface contemplates the following segments and parts of the body: i) head; ii) trunk; iii) (right and left) upper arm and forearm; iv) (right and left) upper and lower leg; and v) (right and left) foot. When a segment or body part is selected, the red colour is replaced by green. For example, Fig. 7 shows an example when the trunk segment was selected and the physical address was the number 7.

Subsequently, the user must select the serial port by clicking on the button to the right of the respective text, and must select the module of interest that is where the temperature, battery and graphics information comes from. In order to achieve real time data visualization, the user may also select which graphics to display. With all these steps done, the "Start" button becomes enabled and changes its colour to green. Once the base station and sensory modules are activated, a click on the "Start" button starts the monitoring process. Fig. 6 provides an example of system operation with only one sensory module. In this particular situation, only the graphs of the three axes of the Acc were selected. All the mentioned information is available and is displayed in real time. Special highlight for battery states panel, where the green colour means that the sensory module has a battery value higher than 3.40 Volts; the orange colour means that the battery has a value less than 3.40 Volts but the sensory module is connected; and the red colour indicates that the sensory module is not active.

While the sensory modules are activated and the monitoring process has been initiated, the gait monitoring process is taking place. When the modules are switched off, the data acquisition process is interrupted and consequently all the information is saved and available in text files. To safeguard the occurrence of possible errors the data coming from the IMUs are constantly stored in text files. Only at the end of the process is the information separated by sensory modules, and the statistics of losses are also saved. This provides for recording which is essential in any system aiming for real time gait monitoring.

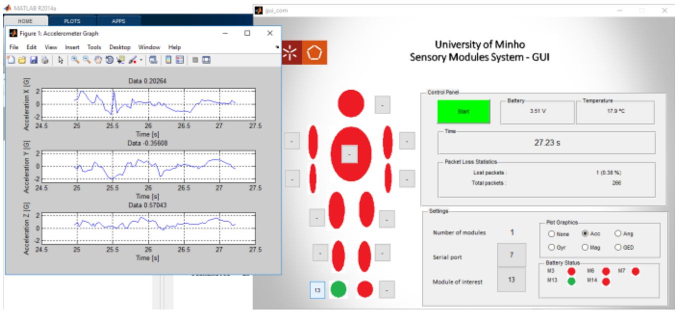

Fig. 6. Matlab GUI when the system is in the operational state.

Fig. 6 is an example of the situation mentioned above. When the user disconnects the sensory modules, the process will be interrupted and a message will appear in the Matlab GUI saying «Communication finished and data saved! ». In the end of the process, there is no reset in the information displayed in the interface, however as soon as the user starts the process again by clicking on the start button, the interface itself resets the available information and returns everything to the beginning.

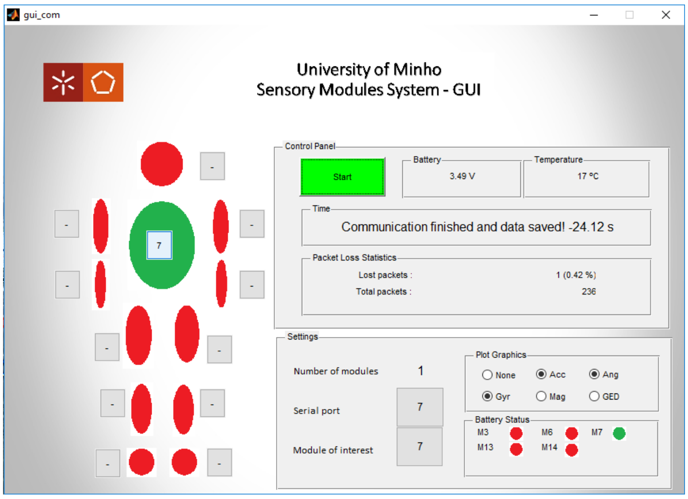

Fig. 7. Matlab GUI when the system was stopped.

Finally, just note that when the user wishes to visualize the graphs of the sensors, angles, and/or even the gait event detection, only the graphs corresponding to the module of interest are displayed. Moreover, the gait event detection graphic only gives one of four stages at a given time with a predefined value (Foot-Flat – 0; Toe-Off – 1; Swing-Phase– 2; Heel-Strike– 3). In order to visualize in real time other locations, the user just has to select a different module of interest.

IV. Methods

A. Quality Assessment

During the development of the GUI, some potential end-users were contacted in order to collect their feedback and include it in the development. After the interface was completed, the human-machine interaction was evaluated based on an inquiry made in a group with thirty-six participants (25 males, 11 females; mean age of 27.4±4.9 years old, range from 22 to 35 years old; 7 health technicians, 29 with engineering knowledge). The idea was to perform some usability tests that would indicate the easy-to use and intuitiveness of the developed GUI.

Previous to any contact with the developed Matlab GUI, the system was explained to these users as well as the aim of the overall system. They interacted alone with the GUI for five minutes. In addition, users were informed where the modules and the base station are activated, that the connection between the base station and the PC is established via serial port, and that each sensory module has a physical address.

When users finished working with the GUI, they answered five questions that are as follows: 1 - Do you think the background is simple and enjoyable? ; 2 - Do you consider that the sequence of steps is intuitive? ; 3 - Do you find it easy to choose and allocate the sensory modules in the virtual respective segment? ; 4 - Do you consider that the information obtained from the graphics, battery status from sensory modules and lost data is sufficient? ; 5 - Did not you need help during the process?

In order to evaluate the overall methodological quality of the Matlab GUI, any criteria or question on the quality assessment were assigned a score of zero point if the criterion was not met. As there are five questions, it was considered that one point corresponds to twenty percent, and thus, it is possible to have a percentage scale. The Matlab GUI is considered “Good” if it has 60% or more of the criteria. “Fair” is the second classification, and the percentage of criteria is between 40% and 60% (≥40%; and <60%). Finally, “Poor” is the last classification with less than 40%.

B. Communication Protocol Validation

In order to quantify the loss of frames during gait, one subject performed two different trials: i) stand upright for 20 seconds at one meter from base station; and ii) stand upright for 5 seconds and then walk forward 5 meters (inside a laboratory) and 10 meters (in the other two environments) at two different paces (normal and fast). These trials took place in three different environments: i) inside a laboratory; ii) in a corridor; and iii) in an outdoor environment free of any ferromagnetic influence or other wireless communications. In [18], failures of the developed system to electromagnetic interferences such as with wireless communications are presented.

V. Results and Discussion

A. Results and Discussion of Quality Assessment

Twenty-five people described the background as simple and enjoyable (≈69.4%). Fifty-six percent, approximately, (20 people) defined the process as intuitive. Only two people (≈6%) did not describe as easy to choose and allocate the sensory modules in the virtual respective segment. Thirty-two people considered the information from IMUs system sufficient. Eleven subjects needed help during the process. Information is resumed in Fig. 8.

In general, the majority of the people considered the Matlab GUI as “Good”. In a total of 180 answers, 136 were positive (75.6%) which means that the quality assessment reveals that the Matlab GUI is able to be used by a common person. Main comments from the respondents are: a) the inclusion of a “Stop” button; and b) an explanation of how it works through images or video before using the interface. As an immediately outcome of this quality assessment, this last suggestion was already implemented.

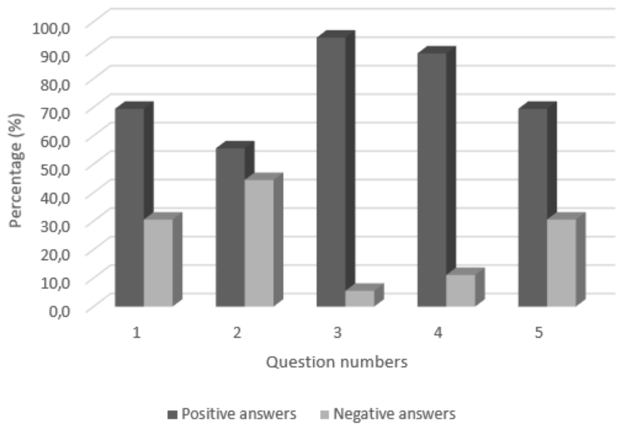

Fig. 8. Inquiry results in percentage per question. Positive and negative answers per question number.

B. Results and Discussion of Communication Protocol

As results, for normal pace the subject performed a mean velocity of 3.24±0.17 km/h, and for fast pace the trials mean velocity was 6.04±0.34 km/h. Concerning the frames losses, at a normal pace, the average percentage of lost was 4.90±1.81% inside the laboratory, 4.21±2.65% in the corridor, and 1.99±1.05% in outdoor environment. At a fast pace, for the same environments, the average percentage of lost was 5.05±2.40%, 3.38±1.77%, and 2.71±1.06%, respectively. When the subject was at stand upright position for 20 seconds, the percentage of lost was 3.40±2.59% inside the laboratory, 2.03±0.97% in the corridor, and 0.28±0.07% in outdoor environment. In an outdoor environment, the percentage of losses is lower than in any other environment. The absence of ferromagnetic materials and other wireless communications with the same frequency band are the main reasons why the Radio Frequency transmission had better results in an outdoor environment. For further details verify [18].

VI. Conclusions and Future work

The proposed work addressed the development of real time monitoring gait system, able to provide for an intuitive real time visual interface and real-time data visualization and recording with 3D IMUs. The first and most important conclusion to be drawn from this article is that in fact the use of an intuitive interface greatly facilitates the interaction between the user and the presented system. In addition, the interface created has all the proposed requirements obtained from a previous analysis of the system. Consequently, the use of this system is much more practical and interactive. The intervention of a large group of survey participants also greatly helped to understand the strengths and weaknesses of the interface, and in general the participants considered the Matlab GUI as "Good", which reaffirms that the objectives initially proposed were achieved. Based on these assessments some changes were delineated and included in the proposed GUI. As a future work, the group intends to: i) perform a fast and consistent on-body calibration of the system; ii) add a fall forecasting system related to topics such as machine learning; and iii) add a real-time virtual 3D visualization of the monitored subject without all the problems that it entails.

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