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Automated Measurement System Based on Digital Intertial Sensors for the Study of Human Body Movement

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Abstract—**An implementation of an independent recording system based on MEMS sensors controlled by a microcontroller, for measuring human body movement parameters, is presented in this paper. The developed system uses two pairs of 3D accelerometers and gyroscopes, in order to determine the exact position of a joint by measuring the relative position of the two adjoined segments. The use of such a system can provide joint kinematic information overcoming shortcomings of video based motion analysis systems. Normal and pathological gait data are presented.**

Keywords—position sensors, accellerometer, gyroscope, position instrumentation system, kinematics analysis

I. INTRODUCTION

Kinematic analysis involves the measurement of the movement of the body in space. It is excessively used in the study of human movement (sports, normal, pathological). Kinematics can be recorded using a variety of systems and methodologies. The most common is the video analysis. Using footage from single or multiple cameras (for 3D), joint angles and velocities can be measured. This method requires passive or active markers located at palpable anatomical landmarks and dedicated software involving advanced mathematics to create three dimensional trajectories from these markers. A computer model is then used to compute joint angles from the relative marker positions [1]. Video based motion analysis systems can be quite expensive and their accuracy is a complicated combination of many parameters, like high frame rate from the cameras, accurate processing algorithms, and even the operating conditions of the experimental environment like lighting conditions. Even more, the analysis can be applied for a restricted space within the view field of the cameras. Thus, the resources needed for such an analysis are quite demanding in all needed stages, recording and processing.

Most recently, inertial (cameraless) systems based on MEMS inertial sensors, biomechanical models and sensor fusion algorithms are being used. These full-body or partly systems can be used indoors and outdoors regardless of lighting conditions [2].

These sensors provide linear quantities like the linear acceleration of one location spot, which can lead to linear speed and displacement calculations. They can also provide information related to rotating quantities like the rotating speed, which can lead to calculations related to the angular displacement of one location spot, and thus its orientation status, at every moment of a movement. These sensors are integrated with an interface circuit within the same chip, thus eliminating many factors that lead to decreased accuracy (when the sensors are separate, with the sensor interfacing circuit consisting of discrete components, in custom made PCB boards). The usual case study is movements of 6 Degrees Of Freedom containing both 3-axis linear and 3-axis rotating vectors.

There is already research activity in using mostly the accelerometers for applications related to human movement. Simpler case studies are being examined, like the examination of free-fall situations [3]. Also, the usage of the combination of accelerometers and gyroscopes is already illustrated in several works [4], [5].

In this work, a system that utilizes such sensors for recording movement of the human body segments is presented. For every segment a combination of one accelerometer and one gyroscope is being used. The result is a series of accelerating and rotating speed data that are more convenient to process related to the video analysis techniques. The system that implements the kinematics analysis, provides high sampling rates, is small, portable and thus movable to the location of the subject. It is also inexpensive and user friendly related to video analysis systems as it does not need specialized personnel to contact the measurement and the analysis.

II. THE IMPLEMENTED SYSTEM

The block diagram of system that is implemented is illustrated in Fig.1. It consists mainly by three parts: the sensors, the processing part, and the communication part.

The main component of the circuit is the microprocessing unit; a convenient low power 8-bit microcontroller, with the necessary processing ability to handle the measuring procedure. The microcontroller chosen is ATMEGA168 from Atmel. It operates with an internal clock of 8MHz, it has adequate number of general input/output pins, 32 Kbytes flash memory, 512 bytes EEPROM, 1024 bytes RAM and supports several serial interfaces.

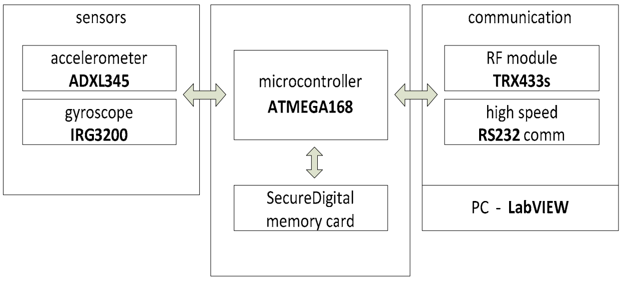

Figure 1. Block diagram of the proposed implememtation

The storage component in the proposed system is a common Secure Digital (SD) memory module of 2GB capacity. These memory modules are quite common on the market, at a real low price, with reading/writing speed adequate for low/middle acquisition speed applications. The operation of such a module is quite easy, by utilizing a typical synchronous serial interface, (SPI). The memory module comes with two main disadvantages. The first is that the writing procedure must be made each time with a buffer of 512 bytes, and not only 1 byte. So, data must be gathered first on the microcontroller in groups of 512 bytes, and when a group of data is ready, a write access to the SD card occurs. The second disadvantage is that the writing delay is quite significant, and varies in the scale of a few milliseconds. This means that the system must be smart and fast enough so that while writing to memory, no data is being lost. This delay is not of a constant value and may vary when writing to different memory modules, or even when writing to different locations of the same memory module.

The source of measurements in the proposed implementation is presented on the left part of Fig. 1, and consists of two sensors. These sensors are a digital accelerometer and a digital gyroscope. The accelerometer is a 3D digital device that provides 3 numbers per sample. Each number corresponding to an acceleration vector component, related to one of the axis of the 3-axis Cartesian system of the accelerometer. It is the model device ADXL345 from Analog Devices. This device can provide a rate up to 3200 samples per second, at a supported bandwidth of 1600Hz. Each sample is a 12bit number, plus 1 bit for the sign. It can measure accelerations to a maximum range of ±16g. Many of these parameters can be changed to more relaxed values, so that this device can be adjusted to the specification of different applications, since human movement is generally characterized by small frequencies. It can communicate also with SPI, but also with I2C. The digital nature of the accelerometer is vital, since it minimizes the usage of materials on the implemented system, e.g. unnecessary A/D converters, while on the same time the provided accuracy is much better since the complete accelerometer chip is created with high quality standards.

The second sensor is the gyroscope ITG-3200 from InvenSense. This device is also digital, and provides 3 numbers, which are the rotating angle speeds along each one of the axis of the 3-axis Cartesian system of the device itself. Each sample is a 16-bit number (15bit + 1bit sign). It can measure angle speeds up to a maximum range of $\pm 2000^{o}$/sec. Again, some of these parameters can be configured at more relaxed values, according to the specifications of each application. The communication of this device is I2C. The digital nature is also an important advantage for the reasons mentioned on the accelerometer. Also, an internal programmable low-pass filter exists within the chip for filtering the provided measurements according to the specifications of each application.

The last part of this application includes the modules related to the communication of this system with the outside world of the instrumentation system. One of these modules is the RF module TRX433s by RF Solutions. This is an FM Transceiver operating at the frequency of 434MHz. It can Transmit/Receive at a rate up to 115Kbps at a maximum of 300 meters. This module is of less significance on this application, with the ability to receive start/stop recording signals from a remote control. Such signals control the measuring time window, so that the system does not record all the time, but only when needed. Also, these signals can place time marks on the measuring procedure, so that specific events can be easily spotted on the resulting data. In future use, this module will also be responsible for transferring wirelessly the recorded data to a computer.

The main communication module is a Serial-to-USB converter, being used for the intention of transferring the recorded data to a personal computer. The device implementing this conversion is the cable/converter TTL-232R-3V3 from FTDI, which includes the necessary electronic circuit, physically close to the USB jack, for the conduction of the conversion procedure. A convenient speed that was implemented is 500kbits per second, which is also a quite high speed for serial communications with a computer (approximately 50 kb/s).

As mentioned already, the serial communication is being held with the microcontroller and a personal computer. The software running on the computer is an implementation within the LabVIEW instrumentation suite. It is characterized by many abilities for the fast and rather easy creation of instrumentation systems. It has a large number of functions related to serial communication and string handling, it provides multiple ways of plotting data without the need of time consuming programming, and it gives an adequate number of file handling functions, so that the resulting data can be stored on disk, and furthermore opened by other software, for further processing.

Until now, the components being used on the system were presented. The next step is the presentation of the measuring procedure. This is illustrated on the block diagram of Fig.2.

Initially, the measuring system is resetted, immediately after getting power supply. The power supply is convenient to be a battery of a value of 3V. The reset is followed by the initialization of the various components of the measuring system. The sensors are being configured according to the necessary speed and accuracy specifications, the memory card is being prepared for proper use, and the RF module is configured for accepting start/stop signals.

After the initialization procedure, the system stands idle, waiting for a start/stop signal. The response of the microcontroller to the component devices being used is interrupt based, for creating fast responses to the requests of these devices. So, the RF module is listening for wireless requests and informs the microcontroller immediately if a request is received. When a request is available, the microcontroller initializes the necessary variables for the measuring procedure, and begins the measuring algorithm.

During this algorithm, first the microcontroller waits until one of the accelerometer has available data, according to the already configured speed and accuracy settings. The accelerometer will provide an interrupt signal when data is available. Upon the receipt of this signal, the microcontroller requests the data from this accelerometer. After that it requests data for the other three sensors. For every sensor it does first an initial check that data is ready from them too. When the four sensors are read, then the system returns to the waiting state of the interrupt signal from the first sensor, and this acquisition procedure is being repeated, until a new start/stop signal is received.

The acquired data is not written immediately on the SD memory module. As already mentioned, data must be written on this module in groups of 512 bytes. So, the measurement data is being stored temporarily on a buffer on the memory of the microcontroller, and when 512 bytes are gathered, and then they are sent on the memory module. Also, the SD writing procedure is quite slow compared to the rate that new data is being gathered. So, while the writing procedure on the SD card lasts, the measuring system is still collecting data, but with a temporary storage on an alternate memory buffer on the microcontroller. The result is two alternative buffers, with one collecting data and the other one sending its stored data to the memory card. Even, with this collecting technique, the memory card must be fast enough so that the writing procedure is finished faster than the time needed for filling the alternate buffer. Not all SD memory cards are fast enough for such a procedure, so a proper SD card research is needed before selecting it.

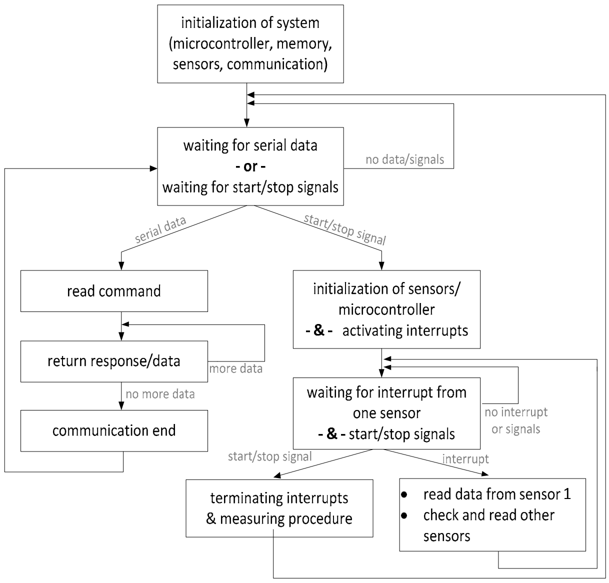

Figure 2. The measuring procedure

This measuring algorithm is being executed repeatedly, until a new start/stop signal is received from the wireless module. If a new start/stop signal is received then, the microcontroller terminates the interrupts related to the sensors, and turns again to the initial idle state, for accepting new data from the wireless module, or the serial port.

III. Experimental Data

The proposed system was used in a case study from the orthopedics field. More specifically a woman (65years old) with a partial caseation of her left ankle was asked to walk for several steps (>15). A gyroscope and an accelerometer were mounted on her shank along the longitudinal axis of the tibia. The second pair of sensors was mounted on the 3rd tarsal of the foot. The gait cycle step markers were calculated for the accelerometer data while the angle joint ankle was derived by integration of the gyroscope data. Results of the left and right ankle joint angle are illustrated in Fig.3.

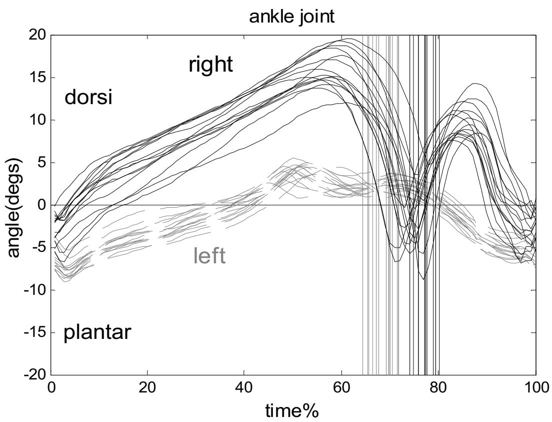

Figure 3. Gait cycle of angle joint-angle

They clearly indicate the deterioration of the range of motion of the left ankle. The reduced mobility of the left ankle is also imprinted in the angular displacement – angular velocity plot of the shank and foot segment Fig.4.

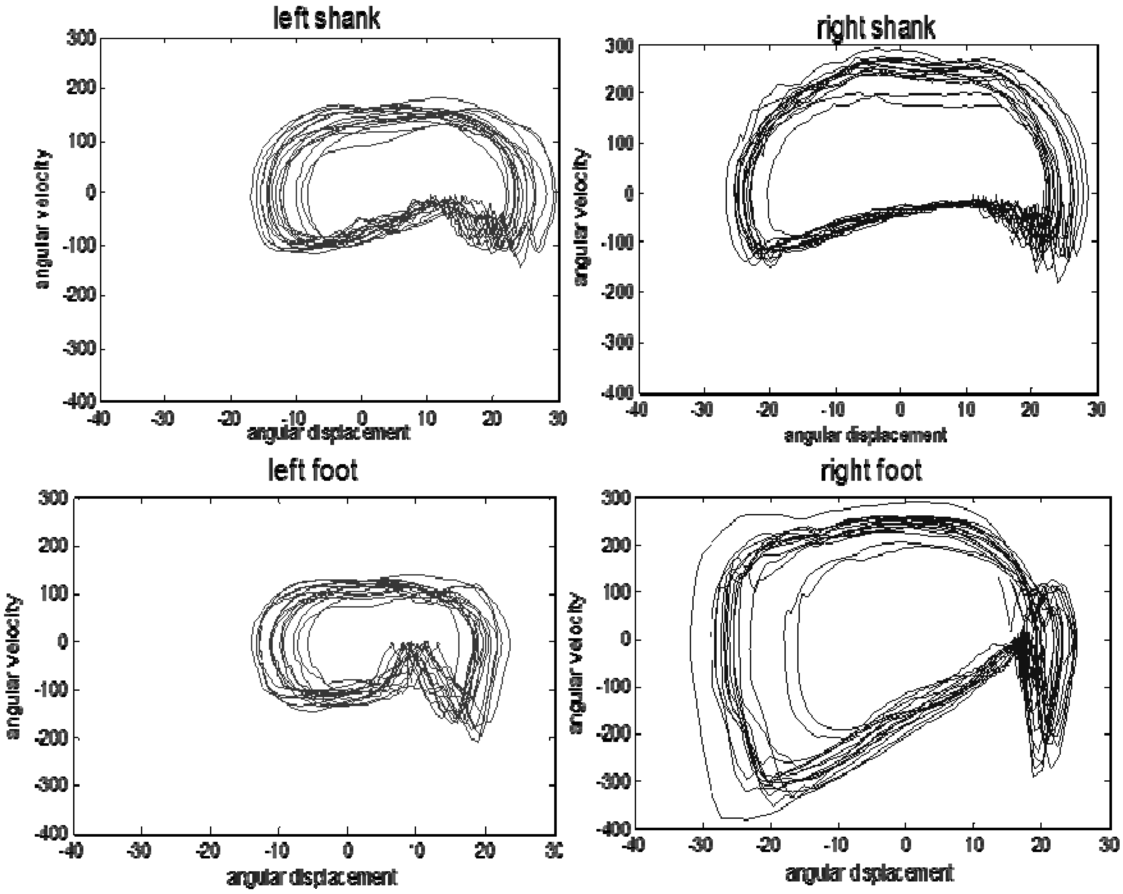

Figure 4. Measurements indicating the reduced mobility on the left ankle

Both segments of the affected side have reduced range of motion and reduced angular velocity. Those data are very useful for orthopedics as they quantitatively reflect the underlying pathology though a simple data processing method for the user. Even more they serve the purpose of "evidence based medicine" the lack of which is a short come in many pathological cases on orthopedics [6]. At the present case the doctor of the patient studied the curves before deciding to operate the patient. Both the patient and the doctor will be able to evaluate the result of the surgery not only subjectively but also objectively, based on a post-surgery measurement with the proposed system.

IV. LIMITATIONS

One of the limitations of the presented system, as far as the measurement procedure is concerned, is the need of a global reference. The system is able to record movement but is unaware on any initial orientation. This can be solved by the usage of the accelerometer and the direction of the gravity's g acceleration, but this is accurate for static initial conditions. A magnetic sensor that can provide an absolute reference, regardless of set up or movement characteristics can resolve this matter in the future.

Also, the alignment of at least one sensor's axis to an anatomical axis of the body segment is necessary in order to provide comprehensive kinematic data of the segment's movement. This is an issue that can be improved slightly by implementing smaller sized systems, but it relies mostly on the proper setting of the experiments.

As far as more technical matters are being addressed, there is an increased difficulty that occurs in case that more modules must be used, due to the increased data and the need of synchronization. In this situation, a higher level control unit must be developed, with the ability to organize and to supervise the different modules being used. This is part of the future work that is already scheduled.

Also, the ability to store data on a memory card is convenient but a more real-time approach would enhance the system's possibilities. This can be realized by adding wireless communication to the system and having the data sent directly to a personal computer. Some preliminary work has been made in this way, indicating that this approach is possible to the future.

It should be pointed out that the sampling frequency that someone would suspect as possible limitation is not an issue in such applications, because biological signals of the human body (and especially of people with pathological issues) are characterized by low frequencies in general. Thus the current sampling frequency is adequate for such applications.

V. CONCLUSIONS

An implementation for the accurate recording of quantities related to the movement of body segments has been presented. It combines one accelerometer and one gyroscope, in a small portable implementation, in order to determine the exact position of one specific location of the human body. The implemented system is used in a medical case study from the orthopedics field. Measurements are successful, indicating differences between the left and the right foot, while the patient is asked to walk. The resulting data indicate the ability of the system to provide quantitative information regarding the medical condition of a patient, in such a situation.

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