Wireless Human Motion Acquisition System for Rehabilitation Assessment

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Abstract

After having suffered an accident with major injuries and fractures, people generally have to be monitored while following physical rehabilitation therapies. The obvious aim is to recover from any undesired/weird motion pattern in order to permit restoring the normal functional capabilities. Among several ways to record patients’ activities, automatic human motion tracking systems are becoming more and more attracting because of their potential.

In this paper we describe the low-cost wireless and wearable motion acquisition system that we are currently developing. Our proposal is based on a number of small electronic modules that permit to acquire body motion with accelerometers and transmit the related information to an acquisition device using wireless communication. Automatic processing of the data can then provide objective and quantitative information to be used during rehabilitation by doctors and physiotherapists.

1. Introduction

Human motion tracking and analysis is particularly useful for a wide spectrum of applications, being physical rehabilitation a potential area of interest [2]. Its main aim is to enable patients to regain the highest possible level of motor functions and independence after having experienced a stroke [10] or other kind of accident and it is heavily based on the monitoring of body motion patterns. Many rehabilitation centres rely on classical treatments based on physiotherapy, which depends on trained specialists and their valuable previous experience. However, sometimes clinicians do not have enough standardized information for evaluating patients’ performances. This is the main reason why, since the 1980s, human motion tracking for rehabilitation has been an active research topic [9].

Nowadays, the development of miniaturized wearable sensors is of particular relevance to the practice of physical medicine and rehabilitation, as this technology allows therapists to gather data to precisely assess the performance while recovering from the impact of clinical interventions [4]. Among the many different sensors that can be used for monitoring, MEMS (Micro-Electro-Mechanical Systems) accelerometers show great potentials. They can provide reliable information as well as objective and quantitative measurements when attached to different parts of the body. For this reason, several studies about their use for body motion capture have been recently published. For example, in [7, 10] accelerometers are used for motion detection and posture sensing while in [6] they are used for gait analysis and balance evaluation.

Although the published work allow for effective body motion data collection from many multi-modal sensors, most of the proposed hardware includes interconnection cables or heavy elements that have to be worn. This usually results in not so comfortable or wearable systems, which can also limit the patient’s movements, making them unsuitable for certain therapies as, e.g., sports medicine. Creating products—in particular Wireless Body Area Network (WBAN) systems— that are comfortable to wear, easy to use, apply and re-apply as well as non-limiting for the body movements and acceptable by clinicians, will open a wide range of applications that can significantly influence our lives.

With the aim to fulfil the above requirements, we propose a low-cost and low-power wearable wireless system which allows for precise human motion acquisition for physical rehabilitation. Even if the system is still not fully developed and, hence, we are still not ready to provide complete results about the data elaboration, we are already getting encouraging results which make us willing to continue towards our current direction. We aim in the future to provide standardized information obtained from the automatic analysis of the collected data, providing real-time feedback to the clinicians during the rehabilitation sessions.

The remainder of this paper is organized as follows: Sec-
tion 2 presents in detail the system’s architecture while in Section 3 preliminary results are described. Finally, Section 4 provides some concluding considerations about the proposed system and related future work.

2. Description of the system

In this paper we propose a wearable wireless system for human motion acquisition, to be used in physical rehabilitation. The structure of the system is shown in Figure 1. It includes five low cost universal modules, one acting as a master and the other four acting as slaves. The slave boards are used to monitor the patient’s knees, which is our first scope in this field. In order to fix their location on the body, thin knee pads for easy wearability are used to hold them: each pad provides room for two slave modules, one above and one below the knee. It must be noticed that, thanks to the flexibility of the system, any other part of the body, e.g. the upper limbs, could be monitored just displacing the modules. On the other side, the main function of the master is to maintain the system synchronized while receiving the accelerometer data from the slaves and sending it to a computer via USB connection for storage. During this work, it was also developed a software application with a friendly GUI to control the system.

![Figure 1. Proposed system architecture](image)

2.1. Henesis WiModule

The main component of the architecture is a low cost universal sensor module [1] –entirely designed and developed by Henesis S.r.l. and named Henesis WiModule. The dimensions of the board are 60mm × 39mm × 11mm, which makes it small and wearable. In its basic configuration, this module contains a digital temperature and humidity sensor and a digital three-axis accelerometer, which is the high performance sensor that we use in our system to acquire human motion data. It has a precision of ±1mg with a range of ±6g and the sampling frequency has been set to 160Hz. This setting completely fulfills –and improves– the 30Hz requirement established by the clinicians consulted.

The WiModule operates as a component of IEEE 802.15.4 wireless sensor networks. Supporting wireless communication is a very important characteristic in this field, as it makes it easy to retrieve data while performing the rehabilitation exercises without having wires interfering or limiting the patient’s movements. This is a key aspect in our system, as it allows for outdoor use as well as inside the rehabilitation centre facilities.

It must be pointed out that the Henesis WiModule has been previously used in [5] and [8] for fall detection and classification of other body movements, showing its advantages for acquiring motion information due to its size and precision.

2.2. Protocol and synchronization

The design of the synchronization between the different modules has been one of the most important and studied issues of this work. The structure of the system, using distributed sensors for acquiring data, brings up to a design where there is not an implicit synchronization of the sensor nodes, as all of them have independent clock sources [3]. Even more, considering the transmission medium, there is a high possibility of losing packets or having collisions between them if there is not a protocol defining the behaviour of the system. But, due to the target application, it is very important to receive all the data packets from every slave board—or at least most of them– and in the correct order. For this reason, the synchronization between all the boards has been carefully studied. The protocol that has been implemented, which follows a TDMA (Time Division Multiple Access) approach, is described below.

The master board sends periodically, every 100ms, a beacon packet, which is received by all the slaves, to request their accelerometer data. To avoid collisions, all the slaves have an ID number, and depending on it, they have assigned a determined time slot to send their packets. During these time slots they send their data packets and wait till an acknowledge (ACK) packet from the master arrives. If the ACK is not received, it forwards the packet up to a maximum of three times. Having the configuration of the ACK request permits to assure the data reception and increase the robustness of the system. On the other side, when the master receives a data packet from a slave, it sends back the corresponding ACK packet and transmits the data through the serial port so that the accelerometer samples are stored in the computer. However, to get to this established situation the system has to be synchronized first.

When the system is powered on the first time, the master starts an internal synchronization process to set the ideal timing interval for sending the beacon packets. This is done by acquiring its own accelerometer samples and calculating how much time does it take in average to complete a data
packet, which is formed by 16 samples. When this process finishes, it uses the obtained value to program a timer. The interrupt service routine (ISR) of this timer will be responsible for sending the beacon packet periodically. Using this strategy permits to reduce the jitter in this part of the system as the time base that activates this ISR is generated by a crystal oscillator, which is very precise.

On the other side, when a slave board receives the beacon packet for the first time, it also starts its own synchronization process calculating the average time between beacon packets. After receiving a certain number of them, the synchronization process finishes and this time base is used for programming a timer to start saving the data acquired from the accelerometer. The accelerometer ISR works independently getting the samples every time one of them is ready, so the mentioned timer is in charge of copying the last sample acquired from the accelerometer in the buffer. It is necessary to point out that a double-buffer structure is used, as it permits to use one buffer for sending a full packet while new data is being stored in the other one. In this flow, the possibility of the beacon packet being lost must also be controlled. This is another task of the timer. In case the beacon has been lost—or if there is a large delay—and the packet is full, the buffers are exchanged and it is indicated that the packet is ready to be sent. If not, this is normally done by the transceiver routine when a beacon is received.

It is necessary to make a difference between the situation where a beacon is lost, but the master is still awake, or when it has been powered off. To consider this situation, the slaves have a mechanism implemented that permits to continue sending their data packets until a threshold of lost beacons is reached. If this happens, they enter into the synchronization mode again, which requires receiving a certain number of beacons before starting to send new data to the master.

The implemented synchronization process, where data is sent under request with the mechanisms described above, permits to save energy while maintaining a low-power scheme, as the transceiver is not continuously used, but only when it is necessary.

### 3. Preliminary results

The initial experiments performed have been focused on the study of the data synchronization and the timing characterization. Data has been analysed from two different points of view. On one side, all the packets—beacon, ACK and data packets—were captured using a packet sniffer. On the other side, the master board stored in the computer all the data packets received from the slaves. With this double-check system we had the possibility of acquiring data from different sources and therefore using more available information about the system performance.

#### 3.1. Synchronization

To assess data synchronization, the so called “wooden bar experiment” was used. After having fixed the four slave boards one next to each other on a wooden bar to assure rigid mechanical connection, a hammer was used to hit the bar with the aim to simulate a impulse which could be easily found among the data. The data sequence in Figure 2—just the Z axis, for the sake of clarity—shows the beginning of the vibration produced by the hammer, sampled by all slave boards at the same time. It was also checked that the maximum de-synchronization among the four modules is one data sample, i.e. 6.25 ms. This was expected since the accelerometer sampling process relies on its own internal clock, which cannot be synchronized with the board’s one.

![Figure 2. Data synchronization](image)

#### 3.2. Data loss

Another important factor to be studied during the experiments was the number of time slots skipped by the slaves. These can be considered as lost packets, as they correspond to intervals of time where there is no data when reconstructing a sequence. To assure the best performance of the system we performed the experiments with and without CSMA-CD (Carrier Sense Multiple Access—Collision Avoidance) in order to later choose the configuration that suits better depending on the results—see Table 1—. Comparing both configurations, it can be seen that using CSMA-CD reduces drastically the amount of lost packets, therefore helping to increase the system robustness.

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<tr>
<th>Statistic</th>
<th>Without CSMA-CD</th>
<th>With CSMA-CD</th>
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<tbody>
<tr>
<td>Average</td>
<td>0.12%</td>
<td>0.00%</td>
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<tr>
<td>Median</td>
<td>0.00%</td>
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<td>σ</td>
<td>0.23%</td>
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3.3. Jitter measurements

The other experiments were focused on the data packets transmission for measuring the time jitter, both with and without CSMA-CD. After each experiment, the jitter was obtained for every slave. The measurements are shown in Table 2. The average jitter is zero, which is the reason why it is not included. \( \sigma_{\text{jitter}} \) represents the deviation from the expected value of the timing between the data packets, while Max\( _{\text{jitter}} \) corresponds to the maximum jitter. Both of them permit to infer the minimum duration of a time slot and hence, the maximum number of slaves in the system. Giving it a wide margin to be safe –bigger than the maximum jitter plus two times the standard deviation–, which is having a time slot of 15ms, determined that the maximum number of slaves that could be included in the system is five.

<table>
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<th>Table 2. Jitter measurements</th>
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<td>Statistics</td>
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<td>Average</td>
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Results have been presented with different kind of statistics for both methods. In order to have more information to decide which configuration fits best, with CSMA-CD or without it, the Wilcoxon signed-rank test has been applied. Being the typical significance level \( \alpha = 0.05 \), it has been obtained that the null hypothesis is rejected for the standard deviation, being then demonstrated that not using CSMA-CD is better for this statistic. Even if this is not relevant for data synchronization—which is governed by the master’s beacon–, it could be interesting in other scheme fitting more slaves but trading data loss statistics.

Considering the results related to the data synchronization, it must be pointed out that when using CSMA-CD no time slots were skipped. And, as it has been said before, it is very important for this application to receive all of the data packets, or at least, as many as possible. For this main reason, in order to assure the correctness of data, CSMA-CD was selected to be used in the communication protocol.

4. Conclusions and Future Directions

In this paper a system for human motion acquisition to be used in rehabilitation has been proposed. It is formed by low cost small modules with wireless communication, being therefore ideal for patient monitoring as it is easily wearable and it does not interfere with the movements. The resulting system operates in real-time and in a wireless network with correctness of data, it is easy to manipulate and portable, which are crucial factors for the target application.

To proceed with the completion of the system, a fifth slave will be included in the waist area, close to the centre of mass of the body. The acquired data will be used as a reference in the subsequent correlation and analysis.

Afterwards, experiments will be performed in a real environment, i.e. in the rehabilitation centre with a patient wearing it while doing the exercises, analysed and classified to check if the patient is performing the physical therapy exercises correctly and in the most efficient manner. In this step the assessment of the clinicians will be needed.

Finally, a feedback will be provided to the physicians, so they can contrast these objective results with their own diagnosis in order to let the patient know if the exercises are being conducted properly or should be improved in a certain manner.

References