Wireless Hydrotherapy Smart-Suit Network for Posture Monitoring

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Abstract—**A wireless smart-suit network for monitoring body kinetics, heart and respiratory rate during hidrocinesiotherapy sessions is presented. Sensing modules composed by 3-axis accelerometers, 3-axis magnetometers and interface electronics are used to monitor the body kinetics. Heart rate is measured using an ear clip infrared sensor and respiratory frequency is measured with inductance plethysmography. The sensor network is integrated in a swimming suit and data is transmitted in real time to a base station using a 2.4 GHz RF transceiver. Measurements of the rotation of shoulders, hips and spine are performed with a resolution of less than 2 degrees. A new MAC protocol for wireless sensing and actuation, LPRT protocol, implemented in MICAz motes is used. Some of the characteristics of the proposed protocol are low power consumption, real-time support and loss intolerant traffic. The protocol uses contention-free operation and retransmission scheme and is very flexible and has high throughput efficiency.**

I. INTRODUCTION

Body kinematics monitoring and posture analysis is an area of major importance in bioengineering and rehabilitation. Wearable health monitoring systems (smart textiles) offer non-invasive methods for diagnosis and rehabilitation monitoring [1] and they are user friendly, easy to use and comfortable.

A family of suits for hidrocinesiotherapy with textile technical materials is under development. The suit integrates floats and electronic components, such as sensors, and assures monitoring of patient posture and gesture. One particularity of the suit is the appliance in an aquatic environment. With this characteristic, innovative textiles integration techniques as textile conductors and textile based sensors can't be used in [2, 3]. Instead, sensor microsystems are stored in waterproof storage devices being integrated in the textiles. The compact size of the sensor system assures that the sensing network will not compromise the comfort and flexibility of the suit.

The posture monitor system must be able to monitor the main articulations of the human body, namely: shoulders, spine and hips, for both flexion-extension and abduction-adduction movements with a resolution of at least 2 degrees.

The use of a wireless network instead of conventional cabled networks introduce several advantages. However, the power consumption is an issue. The range of applications for reliable low-power real-time wireless sensing and actuation systems is huge, ranging from industrial process control to biomedical applications.

The IEEE 802.15.4 [4] is a WPAN (wireless personal area network) designed to be used in wireless sensor network applications. The IEEE 802.15.4 MAC (Medium Access Control) protocol uses a contention based CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance) algorithm which is unable to provide the quality of service required by loss intolerant real-time applications due to the probability of collisions.

In order to satisfy the requirements of low-power real-time wireless sensing and actuation applications the LPRT (Low-Power Real-Time) protocol was conceived and implemented in the MICAz [5] platform. MICAz motes are platforms for the development of wireless sensor networks.

The focus of this paper is on the development of a wireless sensor network system capable of measuring the body kinetics of a patient during a rehabilitation treatment. Sensing modules in a suit are connected to a station, the central processing unit, by serial interface and the data collected from multiple suits is transmitted in real-time to a base station using the LPRT protocol.

II. SENSOR NETWORK

The full system is basically a wireless network of suits with star topology. The suits send information from its sensors using
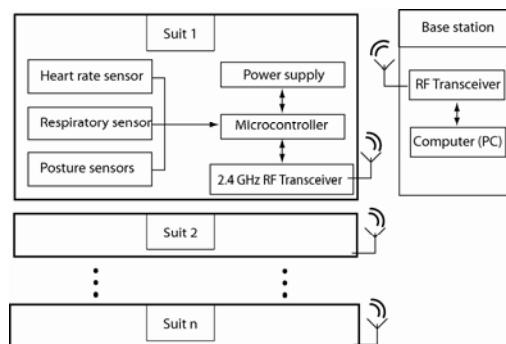

Figure 1. Schematic of the suit wireless network.

a 2.4GHz transceiver to a base station connected to a computer, where the data from suits is logged, as depicted in Fig. 1.

Each suit supports a body sensor network composed of a heart rate sensor, a respiratory frequency sensor and posture sensors as shown in Fig. 2. The microcontroller, power supply and RF transceiver are attached to the suit through an external float in such a way that will not compromise the patient activity while in the water.
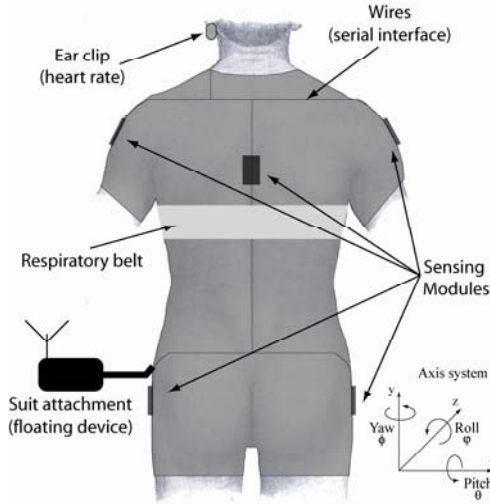

Figure 2. Location of the sensing modules in suit.

III. POSTURE MONITORING SYSTEM

The sensor system monitors the posture, orientation and movement of the human body in space, in real-time, for different types of human posture like flexion-extension and abduction-adduction movements [6, 7].

The posture monitor system is composed of five sensing modules; two located on upper-members, two on lower-member and one on the spine, as shown in Fig 2. The detection algorithm uses the gravitational force to detect inclination, and the earth magnetic field to measure the rotation of the body about the axis perpendicular to the gravity field.

The position of the accelerometers has huge importance, and in order to avoid the degradation of the system's performance due to the accelerations caused from limb motion, the accelerometers are placed on the center of rotation of the arms (shoulders) and legs (hips). This way, the linear acceleration caused by the joint rotation is zero, and the rotation angles can be easily obtained from the accelerometers readings.

Each sensing module contains a 3-axis accelerometer and a 3-axis magnetometer that are used to obtain the pitch (θ), roll (φ) and yaw (ϕ) angles (see Fig. 2). The module placed in the back measures the spine inclination and also acts as a reference module. By computing the difference of the angles measured at the shoulders and hips in respect to the reference module the angles at these articulations are found. Since the human limb motion bandwidth is at most 5 Hz for internally generated trajectories, low pass 2nd order filters with a 20 Hz

corner frequency are placed on the output of the sensors to reduce noise and improve resolution. The differential measurement also eliminates any magnetic interference on the earth magnetic field.

For a measured gravitational field, $\vec{g} = (a_x, a_y, a_z)$ and magnetic field, $\vec{m} = (m_x, m_y, m_z)$ and using the axis system depicted in Fig. 2, the pitch (θ) and roll (φ) angles for the reference module are given by:

$$\theta = \arctan\left(\frac{a_z}{\sqrt{a_y^2 + a_x^2}}\right) \quad (1)$$

$$\varphi = \arctan\left(\frac{a_x}{a_y}\right)$$

The angles can be resolved over 360 degrees by checking the signs relative to each other. The magnetic sensor readings can be projected in the horizontal plane (earth referenced) by doing:

$$X_H = m_z \cos\theta - m_x \sin\theta \sin\varphi - m_y \sin\theta \cos\varphi \quad (2)$$
$$Y_H = m_x \cos\varphi - m_y \sin\varphi$$

The angle yaw can then be computed as:

$$\phi = \arctan\left(\frac{X_H}{Y_H}\right) \quad (3)$$

Equation (2) is valid if the magnetic field vector is in the horizontal plane (earth referenced). That is not the case, since the magnetic vector points North but with a component in the vertical axis. To overcome this situation, the readings from the magnetic field are rotated to the horizontal plane using the constant relationship between the magnetic field and gravitational field vectors.

A block diagram of an individual sensor module is presented in Fig. 3. The module is a hybrid microsystem with commercially available sensors and a custom made ASIC (Application Specific Integrated Circuit).

The 3D magnetic sensor is composed of three magnetoresistive sensors with full active Wheatstone bridges (aligned in the three axes) and therefore is directly connected to a signal conditioning block while the accelerometer is connected to the 2nd order low-pass filter. The signal conditioning block is composed of three Instrumentation Amplifiers (IA) that convert the changes in the magnetic resistive bridges into a voltage. The 2nd order filters are made using Operational Transconductance Amplifiers (OTA) that are very suitable to implement filters in integrated circuit design due to the small die area needed as compared to the large die area occupied by capacitors and resistors used in normal passive filters.

The signals, after filtering and amplification, are sampled with a 12-bit successive approximation Analog to Digital Converter (ADC). A control logic block controls the ADC conversion and the serial interface with the microcontroller. The full system is powered with two AA type batteries.

The customized ASIC is currently under development. It will be fabricated in 0.7 μm Alcatel-Mietec CMOS technology.
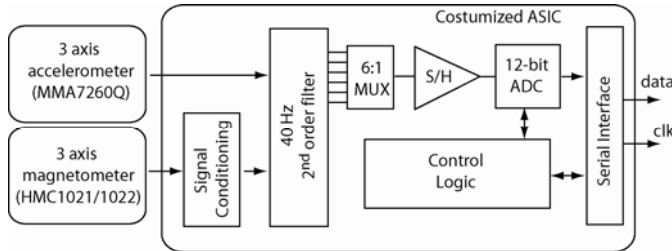

Figure 3. Block diagram of the sensor posture module.

IV. LPRT PROTOCOL

The LPRT protocol is a hybrid schedule based dynamic TDMA (Time Division Multiple Access) protocol and contention based CSMA/CA protocol. It defines a superframe structure as presented in Fig. 4.
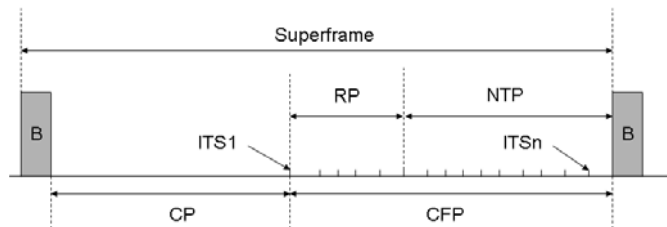

Figure 4. Superframe structure for the LPRT protocol.

Each superframe is divided in a fixed number of mini-slots (1024, in the current implementation), and starts with the transmission, by the base station, of the respective beacon frame (B), which is followed by the Contention Period (CP). During the CP any station can transmit using the rules of a CSMA/CA protocol. The CP allows the stations to associate with the base station and to request mini-slots for transmission during the Contention Free Period (CFP). It is also used to convey non-real-time asynchronous traffic. Stations must not initiate a CSMA/CA transaction if it cannot be completed before the beginning of the CFP.

The Contention Free Period is placed after the CP. Transmissions during the CFP are determined by the base station using resource grant (RG) information announced previously in the beacon frame of the current superframe. Since the transmissions during the CFP are scheduled by the base station, they are not affected by the hidden station problem, unlike protocols that rely on carrier sensing like the IEEE 802.15.4 CSMA/CA protocol.

The CFP is composed by an optional retransmission period (RP) and a normal transmission period (NTP). The rationale of placing the RP before the NTP is to allow a station to retransmit data corrupted by channel errors before new data is supposed to be transmitted, in order to allow fast data retransmission and to minimize the jitter. This division is not mandatory, however, as retransmissions can be mixed with regular transmissions during the entire CFP period. The retransmission procedure helps to increase the reliability of the protocol, which is fundamental in applications with low loss tolerance.

Fig. 5 shows the structure of the payload of the beacon frame. The superframe duration field gives the duration of the current superframe in multiples of a minimum superframe duration time. It is followed by a list of resource grant (RG) fields, whose quantity is expressed by the RG list length (RLL) field. Each RG is composed by a transmission direction (TD) bit, the association ID (AID) field and an initial transmission slot (ITS) field. The RG allows the scheduling of data transmissions either to or from the station identified by the AID, depending of the value of the TD bit: "0" for downlink and "1" for uplink direction. More than one RG can be granted to a station in the same superframe. The total transmission period granted by a given RG goes from the beginning of respective ITS until before the beginning of the ITS of the next RG on the list.
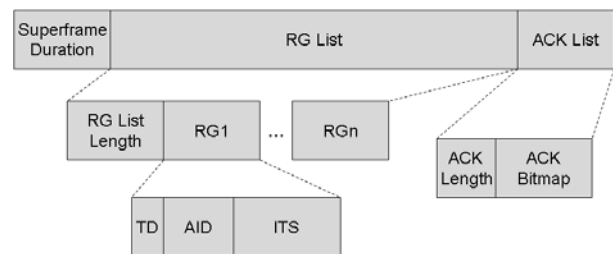

Figure 5. Structure of the beacon frame payload.

For downlink transmissions the ACK frame follows the data transmission, while for uplink transmissions the acknowledgment is made using the ACK list of the next beacon frame. The piggybacking of acknowledgments in the beacon frame eliminates the power consumption and overhead associated with the reception of individual ACK frames for each uplink data frame. The ACK list is composed by an ACK length (AL) field and an ACK bitmap field containing one bit for each uplink RG of the previous superframe. A successful transmission is indicated by a "1" in the respective bitmap position, while a lost or corrupted transmission is indicated by a "0" [8].

Each station has its own fixed ID. When the base station receives a connection request of a new station, it attributes to the station a smaller dynamic ID (association ID), which is used to identify the station in the beacon messages.

The sensor network uses a 2.4GHz RF transceiver. This is a "free" frequency band which is used by several applications, and therefore our transmissions can suffer interference by other sources, leading to a loss ratio increasing. The MICAz

platform defines 16 different operating channels. The base station monitors the packet loss ratio of connections in real-time. When a high loss ratio is detected, the base station automatically orders the stations to switch to another transmission channel, in an attempt to decrease the loss ratio.

V. EXPERIMENTAL RESULTS

The posture monitoring system has been implemented at the PCB level to check its feasibility. Measurements of a right shoulder movement and steady-state operation are shown in Fig. 6. Measurements of a right shoulder movement are shown in Fig. 6a. Fig. 6b shows that the noise floor is well bellow 0.5 degrees for the roll and pitch angles (computed with the readings from the accelerometer only) and about 1 degree for the yaw angle (the successive calculations increase the uncertainty). The overall system resolution is therefore 1 degree which makes it suitable for the application.
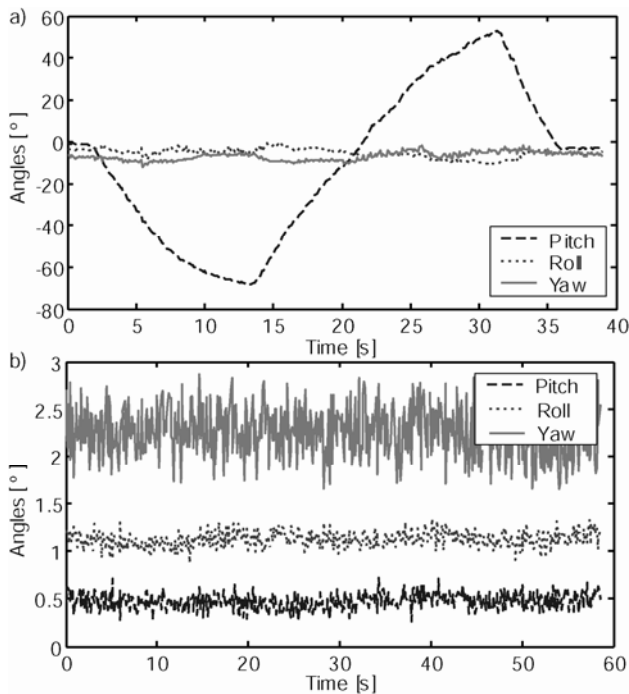

Figure 6. Posture monitoring system measurements. a) During abduction-adduction of the right shoulder and b) steady state operation.

For a wireless sensor network, the evaluation scenario is composed by a base station and four stations. Each station collects 36 byte samples periodically, with a sampling rate of 5 Hz, which corresponds to a packet inter-arrival time of 200 ms. The current consumption of the MICAz motes as a function of time, which include both the consumption of the transceiver and of the microcontroller, was measured, as a function of time, for the LPRT protocol. The superframe size (200 ms) was chosen to be equal to the packet interarrival time. Fig. 7 shows the current consumption of one of the stations for a timeframe slightly larger than a superframe. A first beacon can be seen

where the base station announces the allocation of resources in the current superframe and also when the next superframe will start. After receiving the beacon, the station sleeps until the moment scheduled for its transmission. After the transmission, it returns to the sleeping state, waking up again in the next superframe to receive a new beacon containing the acknowledgement of the previous transmission and new allocations.
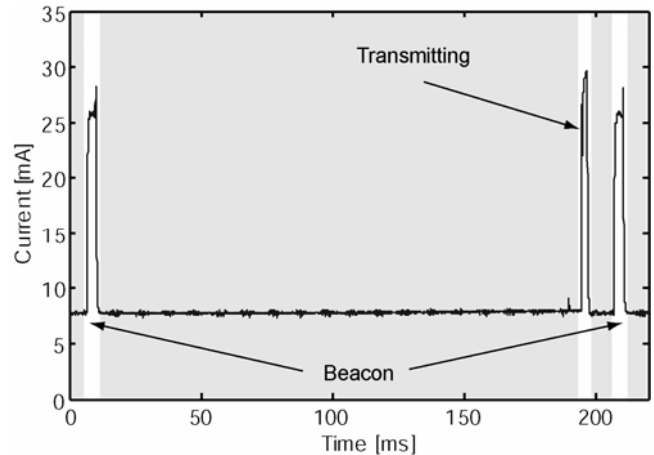

Figure 7. Current consumption of the LPRT protocol as a function of time for one particular station.

Fig. 8 presents a closer look to the current consumption charts of the four stations in the RG list, superimposed, where the transmission of each station and the reception of the beacon of the next superframe are shown.
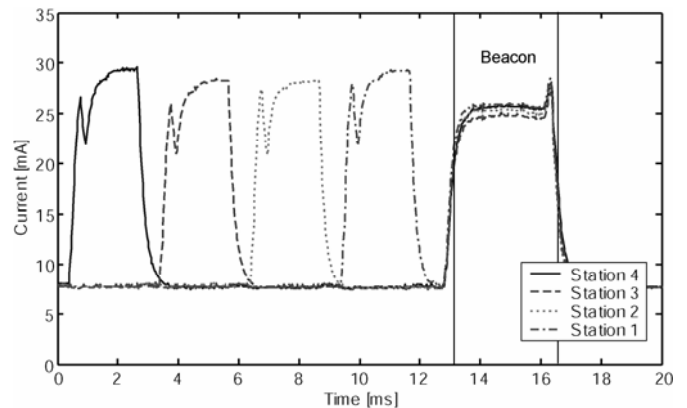

Figure 8. Current consumption of the LPRT protocol as a function of time for four stations.

Transmission position for the first station that associates with the base station is closer to the end of the CFP, and so on, in order to minimize the jitter when a new station associates. With these evaluation parameters, the proposed protocol allows more than 60 stations per superframe (disregarding a minimum CP period).

CONCLUSIONS

A wireless smart-suit network for body kinetics, heart and respiratory rate monitoring is presented. The low size of the sensor modules makes it a very good system for textiles integration, without compromising the body activity. First measurements show that the system can detect rotation of the monitored articulation. With a resolution of 1 degree, which makes it suitable for the application.

The LPRT protocol enables low power consumption and the contention-free scheduled transmissions provide low latency to a high number of stations operating simultaneously. Realibility is provided by the acknowledgement of all data frames and the provision of a fast retransmission mechanism.

ACKNOWLEDGMENT

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