Design and Implementation of WiMoCA Node for a Body Area Wireless Sensor Network

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Abstract

This paper presents the design and implementation of a wireless sensor node for a Motion Capture system with Accelerometers (WiMoCA). It is composed by a tri-axial integrated accelerometer, a microcontroller and a wireless transceiver. WiMoCA nodes have been exploited to build a Wireless Body Area Sensor Network (WBASN) that allows to implement a wireless/wearable distributed gesture recognition system where nodes are mounted on many parts of the human body. We describe the hardware architecture and all the software layers supporting the recognition system. We also show characterization experiments on WiMoCA nodes that highlight how their performance and power consumption levels make them suitable to HCI applications.

1. Introduction

In this work we present the design and implementation of a wireless sensor node called WiMoCA (Wireless Motion Capture with Accelerometers) equipped with a tri-axial accelerometer. We also present the wireless body area sensor network made by WiMoCA nodes that we exploited to implement a distributed gesture recognition system for HCI applications. Furthermore, we describe all the layers needed to implement the body area network: the hardware of the nodes, the network and the application layer.

Wearable inertial sensors are a low-cost, low-power solution to track gestures and, more generally, movements of a person. The implementation of a body-centric network mounting inertial sensors has been explored in many fields. Examples are in context-aware applications [9, 10] and monitoring of patient activity in the medical domain [1]. A combination of accelerometers, magnetometers, temperature and light sensors to be worn by users has been applied to help indoor navigation [5] and infer user's location. Many research studies focus on hybrid sensor networks or sensor fusion techniques. The sensing elements are distributed along the body and data processed both off-line or in real-time [11, 8]. Even if these solutions are suitable to specific applications, they are not tailored to applications requiring high wearability and very-low power consumption.

If we refer to previous gesture recognition solutions, our system has many elements of novelty. First of all, being based upon wireless nodes, it overcomes other solutions where sensors are connected through cables. Moreover, being equipped with a single integrated tri-axial accelerometer, WiMoCA has a smaller form-factor compared to previous solutions. Our module provides better accuracy with respect to traditional orthogonally mounted accelerometers [6, 2], thus reducing re-calibration frequency.

Commercial solutions like Mica Motes [7] are designed to handle sporadic or slowly changing events (such as temperature and pressure variations) and to interface with web applications for environment monitoring. As such, they are equipped with embedded operating systems, that support a complete network stack. Comparing to these solutions, our system has been designed for real-time interactive applications with low-power requirements and for this reason we focused on minimizing software overhead by implementing our own component drivers and communication layer. Moreover, Mica are equipped with analog bi-axial accelerometers, that require additional ADC conversion and are less tailored to gesture recognition applications compared to digital integrated tri-axial devices equipped by WiMoCA.

The contribution of this paper is threefold. First, we describe and characterize (in terms of accuracy, performance and power) the hardware architecture of new sensor module. Second, we describe the software architecture developed for the node and the architecture of the WBASN that connects WiMoCA module together. Finally, we demonstrate the use of the WiMoCA WSN in a vertically integrated application in gesture recognition where nodes are mounted on many parts of the human body.

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2. WiMoCA Components

In this section we describe the main hardware components of WiMoCA nodes. We also specify the architecture of the gateway node that performs bridging functions between WBASN and the external world.

2.1. Sensing Node Architecture

WiMoCa sensing node is designed to be wearable and low-power. It has a modular architecture to ease fast replacement and update of each component. It is composed by three sections (Figure 1) namely MCU/sensors, RF and power supply. Main features of WiMoCA node are detailed in Table 1. In the first row we reported the sensibility of the accelerometers, which depends only on the sensing units. In the second row we reported the maximum sampling rate independently from the maximum transmission rate on the wireless channel, which is 1000 samples per second. Since each sample is composed by an acceleration value of 12 bits along each axis at 1K sampling rate, we have 36 bit samples. Fourth row reports on-board buffering capability in terms of number of samples. In the last we reported the maximum power consumption (i.e. at the maximum output data rate).

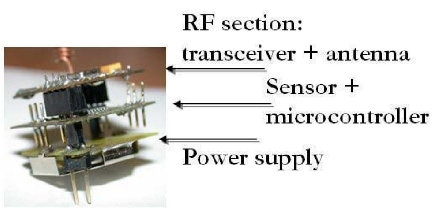

Figure 1. WiMoCa system structure

Sensibility	0.001g
Max sampling frequency	1000 Hz
Max throughput (bit/sec)	36000
On board sampling memory	300 samples
Power consumption 3.3V)	68 mW

Table 1. WiMoCA features.

Microprocessor. The core of the WiMoCa node is the ATmega8 8-bit microcontroller based on the AVR RISC architecture. The choice of this MCU has been driven by its low-cost and low-power characteristics coupled with a throughput of 1 MIPS per MHz, which is suitable to our purposes. In our system the MCU is set to operate with an internal 4MHz clock to reduce board area occupation.

Sensing Unit. Acceleration measurements are performed with LIS3L02DQ sensor, a tri-axial digital output linear accelerometer manufactured by ST-Microelectronics. The device includes a MEMS sensing element, three $\Sigma\Delta$ analog-to-digital converters (one for each axis), and a SPI serial interface from which the external MCU reads acceleration values.

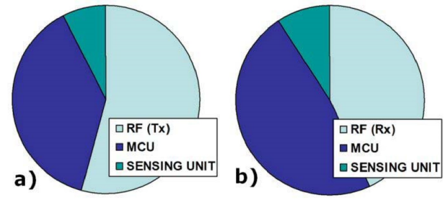

Figure 2. Node power contributors when transmitting (a) or receiving (b).

The LIS3L02DQ has a programmable full scale of 2g or 6g. It is capable of measuring accelerations with 1 mg resolution and provides a maximum sample rate of 2 KHz for each axis. The maximum power consumption is 5mW in active mode and 1 μW in sleep mode (at supply voltage of 3.3V).

RF Transceiver. The RF section is a TR1001 transceiver by RFM that operates in the 868 MHz European free bandwidth. It uses OOK or ASK modulation with a maximum bit rate of 100kbps. At this rate, multipath fading effects can be completely neglected up to distances of 50m.

The RF section has three active states and one sleep state.

Power Supply. The system power supply is realized with charge-pump integrated devices to stabilize voltage at 3.3V and by three NiMH rechargeable, serially connected 1.2V batteries.

The power contributions of node's components are shown in Figures 2 when the RF section is respectively in transmit (OOK) and receive state. A complete power characterization of the node is given in Section 6.

2.2. Gateway Node

As explained later in this paper, we designed a special node that takes care of interfacing the WBASN with an external processing unit, e.g. a PC or workstation. This node, namely a gateway, uses the same MCU and RF transceiver but it is not provided with a sensing unit. The gateway interfaces with the external processing unit (PU) through a Bluetooth wireless link. As a consequence, a complete Bluetooth protocol stack has been ported on the gateway node.

3. Sensing and Acquisition Software

The software support of WiMoCA nodes performs preprocessing of acceleration data and coordinate acquisition and transmission tasks initiated by an application running on a remote PC. Depending on the type of movements to be recognized, each sensor can be programmed to provide the required output data rate. The user application configures the acquisition cycle through a set of APIs that interface with the software running on the gateway node. The APIs implements a device driver of the whole acquisition system.

3.1. Sensor Data Conditioning

The sensing element of the wireless node provides 16 bit acceleration data for each orthogonal axis. The accelerometer can measure both dynamic acceleration (e.g. vibration and in general acceleration due to movements) and static acceleration (e.g., gravity). In steady-state conditions we can assume that gravity is the main acceleration component, thus acceleration value can be easily translated in tilt through simple trigonometric rules. Using a geometrical approach as in [3], inclination can be computed without the need of integration that introduces errors.

3.2. Sensing/Transmission Cycle

The software running in the microcontroller drives the acquisition/transmission process in each WiMoCA node. It also implements a handshaking protocol needed to communicate with the gateway node. To start an acquisition session, a user application sends a start message to the microcontroller of gateway node and a stop frame to cause the system to stop the session. The start message contains also information regarding nodes involved in the acquisition session (such as the number of samples for each node and the required data rate). The gateway is then responsible for propagating the command to the interested nodes on the network.

The software running on WiMoCA node can be configured in two modes of operation:

Normal Mode. Normal mode operations are described as a state diagram in Figure 3.a. During the beginning phase, nodes are listening (RX state) for control messages (start/stop) from the gateway. Upon reception of a start command, each node involved in the acquisition session begins the acquisition/transmission cycle. During this cycle, a node switches between three states:

- **Acquisition (ACQ).** Node software samples data from sensing unit and perform data conditioning.

- **Communication (TX/RX).** Node software prepares the data packet and drives the transceiver to transmit (TX) the packet towards the gateway. Before the actual transmission takes place, the node can experience a delay during which the transceiver waits for the channel to be free. The node can also receive data (RX) from the gateway during the beginning phase.

- **Waiting (WAIT).** After transmission/reception, the node can be idle for a while before to begin a new acquisition. The duration of this waiting state depends on the acquisition rate that can be programmed by the user.

The cycle is broken upon reception of a stop message from the gateway.

Low-Power Mode. In low-power mode, described in Figure 3.b the transceiver can be turned off when it is not communicating (i.e. out of TX/RX state). The time needed to turn it on and off is negligible compared to the duration of the cycle. We called *sleep state* (SLEEP) the state in which the transceiver is shut-off and the MCU is idle (e.g. WAIT state in Normal mode). As shown in Figure 3.b, the transceiver is off also during ACQ state.

As regards the accelerometer, since its wake-up time is not negligible, it can be shut-off to save power only under certain conditions. If these conditions are verified, the state diagram is as depicted in Figure 3.c. Here, also the accelerometer can be powered off when idle. In particular, in the SLEEP state both transceiver and the sensing device are powered off. The accelerometer is off also during TX/RX state.

Conditions to apply power control on the accelerometer are related to the acquisition rate and for this reason they depend on the user application. In fact, the model we used is characterized by a wake-up time (T_{wu}) of 50ms. As a consequence, in order to shut-off the device without impacting acquisition performance, the minimum time interval between two acquisitions must be greater than $min(T_{wu} + T_{ACQ}, T_{BET})$, where T_{ACQ} is the acquisition time and T_{BET} is the *break-even time*. T_{BET} is defined as the time that the device should remain in low-power state to compensate the additional power spent during wake-up. In our case, T_{BET} is zero, since, as shown in Section 6, wake-up power is lower than active power for the accelerometer. As a consequence, we just need to compare T_{wu} with the acquisition period, which is decided by the user.

4. WBASN Characteristics

The WBASN is organized with a star topology. It can be applied to a human body as schematically shown in Figure 4. WiMoCA nodes are end-points of the star and they are responsible for sensing and acquiring data from the environment and send them to a gateway node. The gateway performs bridging functions and has not sensing device. It is used to form the backbone of the system by connecting the WBASN to a host machine or to connect an external network. Coordination among transmissions of various nodes to the gateway is performed at the MAC-level. WiMoCA

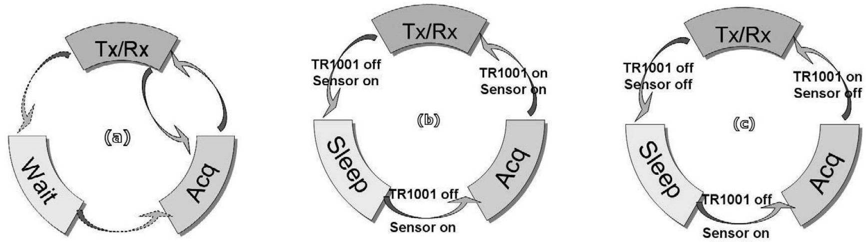

Figure 3. State diagram of WiMoCA node in Normal mode (a) and Low-Power mode with high acquisition rate (b) and with low acquisition rate (c).

software implements a collision free real-time MAC protocol [4]. This protocol is suitable to handle real-time traffic, since it avoids the overhead imposed by collision detection packets by allocating a time frame to each message. In fact, the typical usage of the body area sensor network imposes a periodic sampling of acceleration values from a subset of nodes. The CFRT (Collision Free Real-Time) protocol basically divides time into frames in which only one node is allowed to transmit. The scheduling order is derived by applying the EDF (Earliest Deadline First) algorithm to a message table stored in each node and identical for all the nodes, so that each of them knows when it has the right to transmit. The table contains an entry for each node allowed to transmit or receive in a frame. Fields in the entry specify source, destination nodes, message length and message period. To improve energy efficiency of WiMoCA system, we implemented a low-power version of this protocol where transceivers can sleep during time frames in which they are idle.

5. Application Example

To assess the capability of the wireless body area sensor network, a test application was implemented equipping a user with three sensing modules placed along the body, precisely on the trunk, on the shinbone and the thigh-bone as shown in Figure 5. The axis relative to each module are also shown. In the leftmost part of this figure the user is represented equipped with sensor A on the trunk, sensor B on the thigh-bone and sensor C on the shinbone. If we refer to the plane defined by the direction of gravity and the ideal line between the shoulders, the projection onto this plane of the axis relative to each sensor module is shown in the right part of Figure 5.

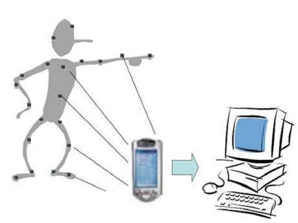

Figure 4. Example of body network

In Figure 6 we show the inclinations data coming from the three accelerometers corresponding to the following sequence of movement: 1) seated; 2) standing; 3) seated; 4) seated with legs extended (as laying on a table). The plot reports computed angle degrees versus time (expressed as number of samples). Acceleration values are collected from the 3 modules shown in Figure 5 and elaborated in order to obtain the angle of each axis with respect to the gravity.

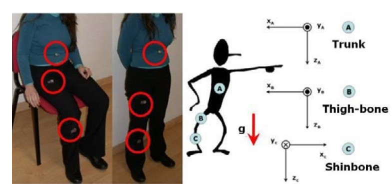

Figure 5. Picture and schema of the user and the module setup and orientation along the body

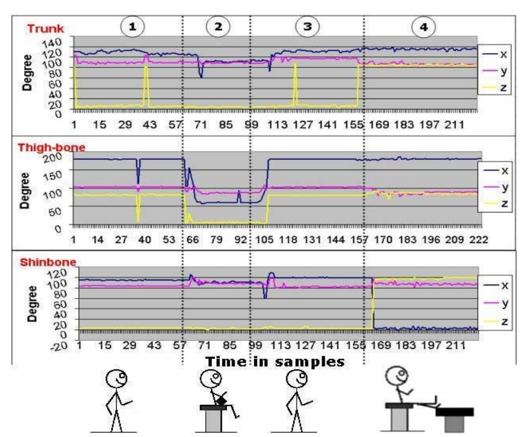

Figure 6. Sequence of movements

6. Characterization Experiments

Performance. A first set of experiments have been made to characterize WiMoCA nodes both in static and dynamic conditions. For static measurements the device was mounted at the end of a pipe with two degrees of freedom in the plane orthogonal to the ground. Cartesian reference system is schematized in Figure 7. During static measurements, shown in Figure 8.a,b and c, α was changed from 0 to 180 degree with 5 degree step. The acceleration measured (e.g. along X', Y' or Z') is the projection of the gravity acceleration along the axis. Plotted values were obtained as an average of 200 measurements. The axis of the accelerometer sensor which is parallel to the ground is Z, Y and X, for Figure 8 a, b and c respectively. Characterization has been performed at a speed of 9600 bps.

Measured data are compared with expected data that is equal to zero with the accelerometer parallel to the ground and has a sinusoidal behavior in other cases. It can be observed that the tri-axial accelerometer we use shows an excellent linearity for each axis and each plane.

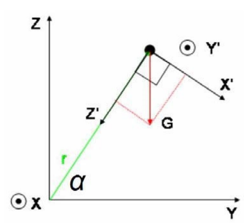

Figure 7. Cartesian representation

Dynamic tests were also performed to verify the response time of WiMoCA modules. Figure 9 shows a 360 dynamic rotation at a rate of 120 degree/sec realized with a DC stepper motor. As for static measurements, the acceleration curve has a sinusoidal shape for the components non parallel to the ground. Signal noise was produced by the vibration of the stepper motor. This kind of noise is similar in amplitude to the one produced by rotation of a human hand and it is low enough to clearly detect the target movement.

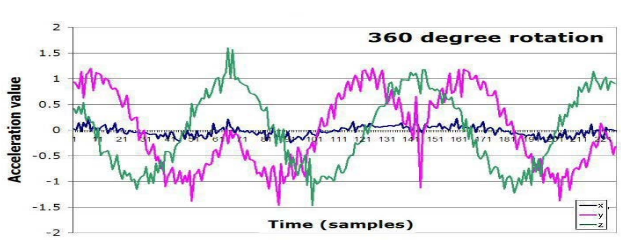

Figure 9. Static plot - YZ plane

Power Consumption. Measurement of power consumption was performed in all the states of the system (Table 2). To compute power consumption of each node, let us consider a sensing/transmission cycle as shown in Figure 3. If T is the time period to complete a cycle, the total energy consumption is:

$$E_T = T_{Acq} \cdot P_{Acq} + T_{TX} \cdot P_{TX} + T_{sleep} \cdot P_{sleep}$$

Where T_{Acq} and T_{TX} are constant while T_{sleep} depends on the acquisition rate. In the worst case for energy consumption (e.g. max sampling frequency) T_{sleep} is null and the energy spent in one hour is equal to 99.58mW. Considering the battery model used in the prototype (20 mAhour), WiMoCA upper bound on lifetime is 40 minutes. However, considering a more practical case, as the acquisition rate used in the recognition application described in Section 5 which was 30 Hz, the lifetime becomes 3 hours.

Status	Power Consumption	Time
RX state	48,10mW	2,2msec
TX state	59,40mW	21,2msec
ACQ	30,02mW	0.5msec
SLEEP	25,14mW	-

Table 2. Power consumption and Time requested per operation in the best case

Referring to Table 2, sleep time that depends on the programmed data rate, can be computed as:

$$T_{SLEEP} = T_{ACQ} - T_{TX}$$

In Figure 10 the current is plotted during an acquisition/transmission cycle. The maximum current absorption is reached during TX mode. Transceiver and accelerometer wake-up and shut-off transitions are also shown. It can be noted that the accelerometer has a negligible wake-up current (marked with a circle in the plot) and shut-off time.

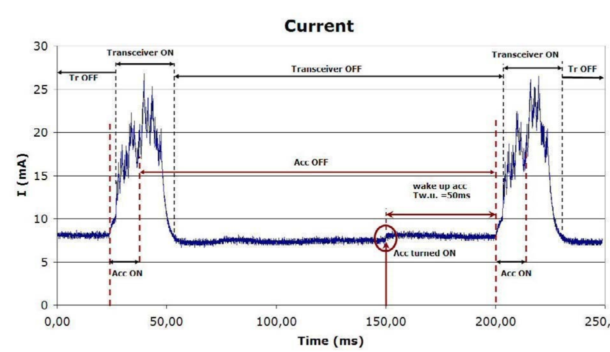

Figure 10. Current as a function of the node states

The plot in Figure 11 shows the power as a function of the throughput (bit per second sent by a single node). As the throughput increases the sleep time decreases. The plot can be divided in 3 regions. A leftmost region below

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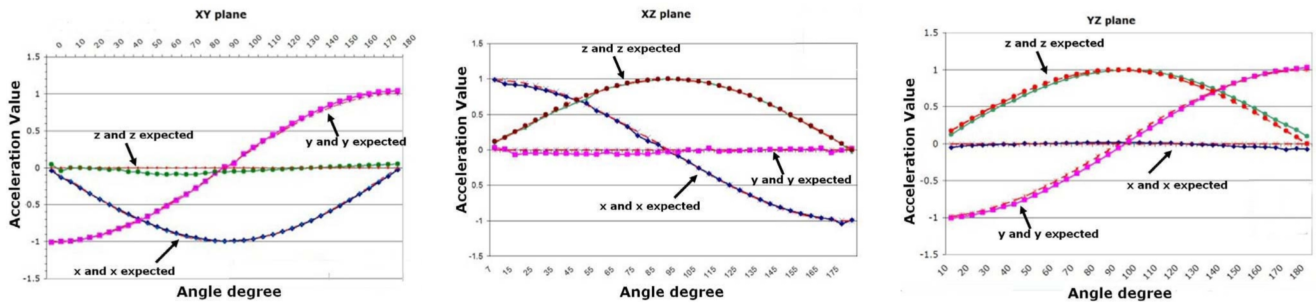

Figure 8. Static plot.

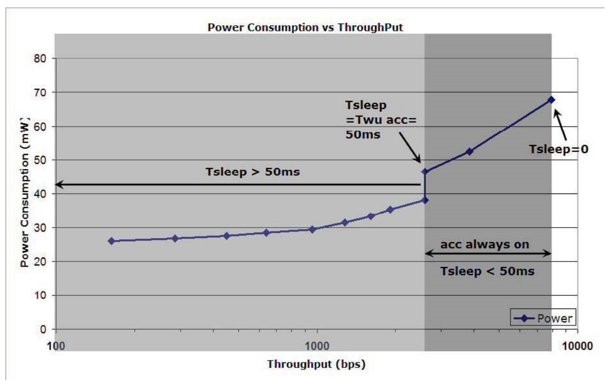

Figure 11. Power Consumption vs Throughput for a single node

2587 bps. In this region the node works as explained in Figure 3.c, where the sleep time is large enough to allow both the accelerometer and the transceiver to be shut-off ($T_{sleep} < T_{wu}$=50ms). In the central region, between 2587 and 7913 bps, the node works as shown in Figure 3.b. Here $T_{sleep} < T_{wu}$. It is worth to observe the step in the power consumption corresponding to transition between these regions, that arises when T_{sleep} is 50ms. The step is a consequence of the power management policy for the accelerometer. Finally, the rightmost region is a single point where T_{sleep} is null. This can be thought as a worst case when no power optimization is possible on the accelerometer because the maximum throughput is reached and data are sent continuously.

7. Conclusion

In this paper we presented the design and implementation of WiMoCA, a wireless sensor node based on tri-axial integrated accelerometers, aimed at detecting human gesture and postures to implement a human computer interface system. We also introduce the concept of wireless body area sensor network and we present its implementation exploiting WiMoCA nodes. The sensor network enables the implementation of a distributed recognition system to detect combined body postures and movements.

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