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<td>Author(s)</td>
<td>Low, Kay-Soon; Lee, Guo Xiong; Taher, Tawfiq</td>
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A Wearable Wireless Sensor Network for Human Limbs Monitoring

K S Low, G. X. Lee, T. Taher
School of Electrical & Electronic Engineering
Nanyang Technological University
Singapore
k.s.low@ieee.org

Abstract – In many applications, it is desired to monitor the human body motion to provide useful information for applications such as rehabilitation, virtual reality, sports science etc. Most existing inertial/magnetic systems used for body motion tracking today come with wiring which restrains the natural movement. In this paper, a wearable wireless sensor network using accelerometers has been developed for monitoring the human motion. The wireless feature of our system allows for unrestrained movements and improves the usability of the system. Moreover, the use of lightweight sensor nodes makes it easy for attachment to the limbs and poses little hindrance to natural movements. The developed system is also portable and low in cost compared to sophisticated visual tracking systems utilizing multiple cameras. The low power consumption of the sensor nodes also makes it suitable for long term monitoring. A prototype has been developed and experimental results show that the system has reasonable performance.

Keywords—Wireless sensor network, wearable system

1. INTRODUCTION

Real time human motion tracking has many applications in fields extending from virtual reality to rehabilitation. The most use technology is the vision-based approach. Vision-based tracking of human motion has been actively research for surveillance monitoring, medical analysis and human–computer interfaces [1]-[3]. Existing visual tracking methods can roughly be divided into two groups, namely the single camera tracking and multiple camera tracking. Single camera tracking costs less and is typically based on shape models. However, it has many constraints and requires prior information of the object’s character such as motion and appearance [4]-[5]. In contrast, multiple camera tracking experiences fewer constraints but is expensive and complicated. Due to the characteristics of visual sensors, both tracking methods have problems such as motion blur and occlusion that hamper performance in real world applications.

Besides vision tracking, several other technologies are also available such as mechanical tracking, electromagnetic tracking, acoustic tracking, and inertial/magnetic tracking. Among these methods, inertial/magnetic tracking technology is attracting more interest as the method is liberated from problems that are present in the other available technologies. An inertial/magnetic tracking system uses a combination of accelerometers, rate gyros, and magnetic sensors [6]-[11]. There is no inherent latency associated with inertial/magnetic sensing. Consequently, all delays are due to data transmission and processing. Another advantage is that it is source-less which is different from electromagnetic, acoustic, and optical devices that require emissions from a source to track the objects.

In this paper, a wireless wearable sensor system based on accelerometers for monitoring patients in their homes is presented. The objective is to allow the patient to be monitored in a natural environment [12]-[15]. Furthermore, it will greatly reduce the needs for the patients undergoing physiotherapy to travel frequently to the hospitals. For monitoring outside the clinical laboratory, a wearable system must not only record data, but also proficiently process data on-board. The proposed approach uses the wireless sensor network concept with all the sensor nodes communicated to the coordinator wirelessly. This will greatly reduce the amount of wires used to connect the sensors. The sensor nodes have small form factor and light weight for easy attachment to the human limbs. Furthermore, it is low cost as compared to the camera system.

The organization of the paper is as follows: Section II describes the configuration of the system. This is followed by a description of the wireless sensor network developed in this study in Section III. The sensor performance is discussed in Section IV. Section V presents the results of the experiments conducted. Finally, we conclude by summarizing our work in Section VI.

II. SYSTEM CONFIGURATION

Fig. 1 shows the configuration of the system. From the figure, it can be observed that the system consists of a number of sensor nodes that will communicate wirelessly with the coordinator based on a star network configuration. The coordinator is in turn connected to a personal computer via RS232 link.

Fig. 2 shows the photographs of a sensor node. Each sensor node has an on board microcontroller (PIC18LF2620) and a capacitive micromachined accelerometer (Freescale MMA7261QT) that can be used to detect the tilt angle of upto 3 axes. The sensor node can be operated using a 6V alkaline battery. Each sensor node measures 40 × 39 × 16 mm and weighs 29g. For the wireless communication, both the sensor node and coordinator use the Microchip 2.4 GHz RF
transceiver MRF24J40 and an onboard PCB trace antenna that has a communication range of 10-50 meters. Fig. 2b shows the photograph of the RF module at the top with the microcontroller module (Fig. 2a) connected at the bottom.

Fig. 3 shows the photograph of the prototype coordinator consists of a PIC18LF2620 microcontroller and a RS-232 port for serial communication to the personal computer.

During operation, the accelerometer on each sensor node will measure the 3-axis (XYZ) acceleration. Its analog output values will be processed by the microcontroller via its 10-bits on-chip analog-to-digital converter. These values are then transmitted wirelessly using the RF transceiver to the coordinator. The coordinator will in turn transfer the data serially to the personal computer at a baud rate of 19200 bps.

### III. WIRELESS SENSOR NETWORK

Wireless sensor network is a promising field that integrates sensor technologies, embedded system and wireless communication together to produce small, low cost, low power and reliable system capable of monitoring specific events.

The IEEE standard 802.15.4 is developed targeting specifically for this application domain. It is generally applied in monitoring applications with non-critical data, where longer latency is not a critical issue. Such applications usually do not need high data throughput but emphasize on power saving to maximize battery life. It has been used in a variety of applications including commercial and industrial monitoring, home automation and networking, consumer electronics, personal computer peripherals, home security, personal healthcare, toys and games, automotive sensing, agriculture etc [16]-[17].

Table I lists the data transfer rate and latency requirement of a few applications [18]. From the table, it can be observed that higher data transfer rate is required in entertainment and gaming applications. For personal health care and automation, lower data rate and higher data latency are acceptable.

<table>
<thead>
<tr>
<th>Applications</th>
<th>Maximum data rate required (kb/s)</th>
<th>Maximum acceptable latency (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consumer Electronics</td>
<td>3</td>
<td>16.7</td>
</tr>
<tr>
<td>PC Peripherals</td>
<td>115.2</td>
<td>16.7</td>
</tr>
<tr>
<td>Home Automation</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>Personal Health Care</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>Toys and Games</td>
<td>115.2</td>
<td>16.7 - 100</td>
</tr>
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(a) Network selection

One class of wireless personal area network is the Bluetooth/IEEE Standard 802.15.1 which is also widely used in consumer based wireless motion tracking application. The most notable example is the Nintendo Wii gaming platform which also utilizes the tri-axis accelerometer. A summary of comparison between Bluetooth and 802.15.4 is given in Table II. As can be seen from Table II, the Bluetooth offers higher data rate (3Mbp with Enhanced Data Rate (EDR)) than the 802.15.4 (up to 250kps) at the expense of higher power consumption and form factor. Thus, the choice of a wireless standard in the design is dependent on the application. Though the 802.15.4 offers a lower data rate, it is more than sufficient for the intended rehabilitation application that typically not requires a high throughput. In addition, it offers a lower power consumption solution that is more suited for the proposed wearable system that should be able to monitor the body motion for a long period of time. As such, a wireless sensor network system based on 802.15.4 is used in this design.

In this study, the MiWi networking protocol has been used for the wireless communication due to its simplicity and small stack size. MiWi is a proprietary protocol stack similar to the ZigBee in that both are based on the medium access control (MAC) and physical (PHY) layers of the IEEE 802.15.4 specification. The MiWi aims at smaller applications that have relatively small network sizes, with few hops between nodes.
and offers an alternative for applications that do not need interoperability with other ZigBee devices. It supports a maximum of 1024 nodes on a network and a data rate of up to 250kbps. Each coordinator is only capable of having 127 children or nodes, with a maximum of 8 coordinators in a network. Packets can travel a maximum of 4 hops in the network and 2 hops maximum from the PAN coordinator. For a wearable sensor network comprising of a small number of sensor nodes (in the range of 2~30) in a star or relatively flat hierarchy peer-to-peer topology, the MiWi protocol is more than sufficient for our sensor network.

### TABLE II. COMPARISON BETWEEN BLUETOOTH AND 802.15.4

<table>
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<tr>
<th>Bluetooth/IEEE 802.15.1™</th>
<th>IEEE 802.15.4™</th>
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<tr>
<td>Range</td>
<td>Frequency Band</td>
</tr>
<tr>
<td>~10 m (class 2)</td>
<td>2.4 GHz, 868, 915 and 2.4 GHz</td>
</tr>
<tr>
<td>~100 m (class 3)</td>
<td>≤250kbps</td>
</tr>
<tr>
<td>Data Rate</td>
<td>Operating Power Consumption</td>
</tr>
<tr>
<td>3 Mbps with EDR</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>Ultra Low</td>
</tr>
<tr>
<td></td>
<td>Size</td>
</tr>
<tr>
<td>Small</td>
<td>Very Small</td>
</tr>
<tr>
<td>Cost/Complexity</td>
<td>Complexity</td>
</tr>
<tr>
<td>Low</td>
<td>Very Low</td>
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(b) Software development

The central of the network is the PAN coordinator. The PAN coordinator is the device that starts the network, and selects the channel and the PAN ID of the network. All other devices joining onto the PAN have to obey the instructions of the PAN coordinator. In this system, the PAN coordinator is configured to perform as a relay module by simply acquiring and aggregating the information received from all the sensor nodes and sending the information to the computer for further analysis and manipulation. Fig. 4 shows the program flowchart of the coordinator.

As shown in the figure, the coordinator firstly performs a power channel search to find the channel to communicate with minimum interference and noise. Subsequently, it waits for any node to join its network. After forming a network, it carries out its MiWi protocol predefined tasks that include letting other nodes to join its network, and send back acknowledgement. If any node exists in the network then the PAN coordinator receives the data and sends the data to the computer through its RS-232 module at a baud rate of 19200 kbps.

Fig. 5 shows the program flowchart of the sensor nodes. As shown in the figure, the sensor node starts by initializing its input/output configuration registers, internal pull-up registers, interrupt configuration registers and the RF module after it is powered on. Then it searches for an available network and tries to join that network. If the node is not able to find a suitable network to join or unable to join any found network, it will try to search or rejoin until it finds one.

Upon successful joining a network, the node activates its three A/D channels sequentially and acquires data from the accelerometers. The readings are then converted with a sampling rate of 10 Hz to 8 bit values. The data are then packed as payload for transmission. Once the information is ready to be transmitted, the node sends the data to the PAN coordinator.

**IV. THE ACCELEROMETER SENSOR**

In this design, a 3-axes accelerometer has been used for sensing the arm movement. It uses the Freescale MMA7261QT low-g micromachined capacitive accelerometer with a selectable range of ±2.5g/3.3g/6.7g/10g and corresponding sensitivity of 480mV/g - 120mV/g. In static conditions, the tilt angle, \( \theta \), of the accelerometer can be determined easily by measuring the acceleration due to gravity, \( g \).

As shown in Fig. 6, the acceleration, \( A_y \) in the Y-axis and \( A_z \) in the Z-axis can be determined as:

\[
A_y = g \sin \theta \\
A_z = g \cos \theta
\]

The tilt angle \( \theta \) can be determined as

\[
\theta = \tan^{-1} \frac{A_y}{A_z}
\]

with the quadrant of \( \theta \) determined by the sign of \( A_y \). For dynamic motion, the magnitude of the acceleration due to human arm can generally be neglected with respect to gravity.
To characterize and calibrate the accelerometers, the sensor node is mounted on a rotary stage using a precision piezoelectric motor that has a positioning accuracy of 0.0001° resolution. Calibration is done to determine the offset of the accelerometer at 0g. To investigate the accuracy of the accelerometer, the accelerometer is oscillated from -90° to 90° through various angular speed from 10°/sec to 160°/sec and the measured position determined from the wireless sensor network system using (3) is compared with the actual position captured from the rotary stage encoder. Fig. 7 shows the mean error and standard deviation of the angle of rotation. From the results, it is observed that the mean error is between 0.2° to 1° over the range of angular speed. The standard deviation of the error is slightly larger at higher angular speeds than at lower angular speeds. This is probably due to the effect of neglecting the additional acceleration apart from the acceleration due to gravity in the determination of angle.

Fig. 7. Variance of x-axis accelerometer at various speed

Fig. 8. Accelerometer data of sensor node

V. EXPERIMENTAL RESULTS

Fig. 8 shows the real time accelerometer data of an accelerometer mounted on a human forearm as it undergoes flexion over its full range of motion (about 145°). Fig. 9 shows an actual picture where the sensors were attached on the arm during the data collection process. The data was logged for 10 swings of such motion. The data has been captured at a sampling rate of 10 Hz.
Fig. 9 shows the results after data conversion and display on the computer monitor in real time with the sensors being mounted on the arm. The results show that the system has fairly good correlation between the actual arm movement and re-constructed movement on the computer screen. The system works well even if the person is moving away from the network coordinator at a distant of 20m in the laboratory environment.

VI. CONCLUSIONS

In this paper, a new approach for remote measurement and monitoring of the human motion based on a wearable wireless sensor network has been presented. A prototype has been successfully fabricated and real time experiment conducted. The results have demonstrated the feasibility of the proposed approach. Although the present prototype uses only two sensors for a single arm, it can be extended to multiple sensors attached to other parts of the body for the monitoring of other limb movements. As compared with the existing approaches, this new method allows the monitoring of patients without restraint and rehabilitation can be carried out in home environment instead of specialized laboratory in the hospital.

REFERENCES


Fig. 9. Real time data display showing arm movements