Mirrored Motion: Pervasive Body Motion Capture using Wireless Sensors

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ABSTRACT
There has been a lot of discussion in recent years around the disappearing computer concept and most of the results of that discussion have been realized in the form of mobile devices and applications. What has got lost a little in this discussion is the moves that have seen the miniaturization of sensors that can be wirelessly attached to places and to humans in order to provide a new type of free flowing interaction. In order to investigate what these new sensors could achieve and at what cost, we implemented a configurable, wearable motion-capture system based on wireless sensor nodes, requiring no special environment to operate in. We discuss the system architecture and discuss the implications and opportunities afforded by it for innovative HCI design.

Categories and Subject Descriptors
H.5.1 [**Multimedia Information Systems**]: Artificial, Augmented and Virtual Realities

H.5.2 [**User Interfaces**]: Input Devices and Strategies

General Terms
Algorithms, Performance, Design, Human Factors

Keywords
User Interaction, Orientation, Augmented Reality, Mobile Computing, Context Aware computing, Body Area Networks, Wireless sensor networks.

1. INTRODUCTION
Humans have always had difficulties interacting effortlessly with computers. The difference in language is perhaps too great to ensure natural and graceful communication; therefore it could be supposed that interaction may be improved in some ways by taking away some of the physical barriers between the machine and the user. Today many artificial intelligent technologies like speech and image recognition systems are commercially available to make people feel that the device is reacting to them in a more intuitive way. We took this concept a step further and investigated how a wireless sensor-based system could be implemented to allow the capture of human body movement and gestures in real time.

Motion-capture is not limited to man-machine interfacing only, but also has applications in a diverse set of disciplines, for example in movie and computer game production, sports science, bioengineering and other sciences to which the analysis of human body movement is a major focal point. Motion capture systems have tended to be complex, expensive, purpose-built setups in dedicated and strictly controlled environments that maximize their efficiency. However, in the context of pervasive computing, the design of a system to capture motion at any time and any place, is constrained by several parameters that are not considered in traditional systems. Such constraints are the durability, wearability (and discreetness of the system when worn), independence from specially configured environments, power consumption and management and connectivity with other pervasive systems. We aimed to address these problems in our study, and as such began to think about how to develop a low-cost, real-time motion-capture system.

The approach we took was to use sourceless sensors to establish the orientation of the human anatomical segments, from which posture is then determined. Sourceless sensors do not require artificial sources (e.g. IR illumination) to be excited. Instead, they rely on "natural phenomena", e.g. the earth's magnetic field and/or gravity, to act as stimulus [1]. Such sensors need to report their readings so these can be processed and translated into body movement. To achieve this, we thought it would be appropriate that wireless technology was used to connect the sensors, thus forming a Wireless Body Area network (WBAN). Wireless sensors make the system unobtrusive, increase its wearability and compared to a wired solution, allow for a much wider range of applications.

In this paper we present our investigation into the development of a low-cost, low-power WBAN of sensors, as an enabler for HCI applications. We also present an outline of applications where this has been successfully used and discuss future opportunities for this system.

2. BACKGROUND
Wearable sensor systems have been used in the past with success in several contexts of which particular focus seems to have been placed within the domains of Pervasive Healthcare [2, 3, 4] and Interaction with Mixed or Virtual Reality systems [5, 6], and

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Mobile Systems [7]. Wearable sensors have also been used to investigate Interaction in such domains as Computer Gaming [8] and the acquisition of varying levels of Context Awareness [9, 10]. In such respects, while much progress has been made, this progress only partially fulfills the objective of capturing of full body motion in pervasive computing landscapes. There are only a few systems we are aware of which meets this objective; one is in [11], although this system relies on a set of wired sensors and a heavy backpack to power it, limiting its wearability and configurability, as sensors have to be used as a complete set. Two commercial systems work on a similar principle with [11], using sets of sensors wired to a hub, which transmits aggregated data wirelessly using Bluetooth or 802.15.4 (XSens, EoBodyHF). Wired sensors limit the wearability of these systems

Our work's fundamental aim is to investigate the use of a low-cost distributed computing infrastructure with sensors to provide a means of capturing environmental and human activity as part of our research group's current interest areas (pervasive healthcare, mobile spatial interaction and mobile audio-video interaction). For HCI researchers there are exciting opportunities due to the standardization, miniaturization, modularisation and economies of scale presented by the new technologies available for the creation of wireless sensor networks. Of special interest is wireless body area network (WBAN) technology. Using modern silicon Micro-Electro-Mechanical Systems (MEMS) manufacturing techniques, sensors (such as gyros , magnetometers and accelerometers) have become inexpensive, small and can now be worn on the body or integrated into clothing [12]. Such sensors, coupled with low power processors that may integrated the necessary wireless componentry, (such as the 32-bit Freescale MC1322x platform), provide the basic fabric for increasingly powerful wireless sensor networks.

3. SYSTEM DESIGN

From reviewing the existing literature, we identified a set of heuristics against which a pervasive motion capture system must perform well. Our criteria are as follows:

- **Connectivity:** Pervasive systems do not work in isolation. Any sensor-based system must allow its components to communicate with each other and coordinate its behavior. It must, however, also be able to communicate its components' status to external systems in the environment.
- **Power:** A pervasive system must not rely on external sources of power, as these are not omnipresent. It should have its own power source and appropriate power management features that allow it to operate for lengthy periods of time.
- **Performance:** The performance and responsiveness of a pervasive motion capture system must be such that it affords the real-time capture of bodily motion and its transmission to external systems with minimal lag and delay.
- **Wearability:** Systems must be light, easily wearable and discreet. Discretion can be achieved by embedding sensors in everyday objects or garments, or by designing them so that they can be easily concealed.

In designing the Mirrored Motion demonstrator, we considered these heuristics as appropriate to informing our system characteristics.

3.1 Connectivity & Power

Our system is comprised of sensor "nodes" that can be attached to key locations on a user's body, monitoring the movement of major body parts (limbs, torso, head). One of the off-body nodes acts as a "coordinator", gathering data from all nodes and relaying to external systems for further processing. To coordinate the communication between the peripheral and the coordinator nodes, the Bluetooth and IEEE 802.15.4 standards were considered suitable candidates. We also considered 802.11x (Wi-Fi) but this was quickly rejected, as its power consumption is too high for continuous use. A shortcoming of Bluetooth is that it is limited to eight nodes per network, which would be insufficient for covering even just the basic major parts of a human body. In contrast, IEEE 802.15.4 can have 65536 nodes in a network (star or mesh topologies) and can work over similar node-to-node distances as Bluetooth. It can operate with a smaller network stack size, reducing the embedded memory footprint. For the flexible and extensible HCI applications to be considered, the larger node count is useful to create networks that integrate on and off-body nodes and have potentially multiple interacting users. IEEE 802.15.4 data rates are in the range of 20 – 250 Kbps, although in actual use the higher rate cannot be attained due to protocol overheads. Although lower than Bluetooth, this data rate has been shown in our experiments to be sufficient for body-motion frame rates. Because of its characteristics in allowing multiple node connectivity and very low power consumption, we elected 802.15.4 as the preferred communication protocol. The wireless module used in the system is a Panasonic PAN4555.

3.2 Wearability & Performance

Sensors used in each node for the first prototype were a 3-axis accelerometer and a magnetometer per node. A magnetometer-accelerometer sensor can produce accurate orientation information when the only force experienced by the sensor is gravity. However, any additional forces will result in the reference vector produced by the accelerometer to be inaccurate. In a revision to our original design, miniature MEMS gyros were added to the sensor pack. Gyros measure angular velocity and this helps to reduce the effects of non-gravity forces.

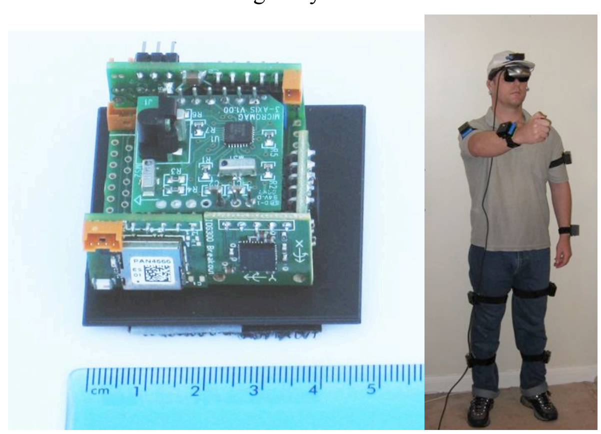

Figure 1. Our custom-designed sensor pack containing 3-axis accelerometer, gyro, magnetometer and 802.15.4 comms (left). On the right, a user demonstrating the small size and wearability of the packs, Velcro-strapped on his body. The cable attaches his VR headset to the host PC.

These sensors were originally packaged in a rather large form, roughly the size of an average mobile phone, as pre-configured development kits were used to prove the concept. Once satisfied with the performance of the system, we re-designed the hardware and created custom sensor packs that were optimized for size.

Each pack is relatively small (less than 4 x 3”). They are attached to the user’s body with Velcro straps, making them easy to wear and remove. Because of their size, they are concealable under normal clothing. Because this is an experimental platform we created a modular construction allowing the removal and addition of the sensor and wireless components. The necessary connectors and modules take up extra space. A custom version could be created with a smaller footprint, with all parts integrated onto a single PCB. Sensor nodes are placed on each of the tracked human limbs (upper and lower arm, head, torso, upper and lower leg) to track the orientation of each. The raw data acquired by the sensor WBAN is transmitted wirelessly to an external system (in our experiments, a typical PC). We set a data acquisition target for our system to achieve real-time performance at a sampling rate of 30Hz, as this would, in theory, allow us the re-creation of a user’s skeletal model on an external system with a refresh rate that would yield about 25-30 FPS, which is adequate for real-time video.

The posture of the skeleton is calculated in real-time through forward kinematics. Kinematics simplifies computations by decomposing any geometric calculations into rotation and translation transforms. Orientation is obtained by combining (or fusing) these information sources into a rotation matrix – an algebraic format that can be directly applied to find the posture of the user. The result is a simple skeleton model defined as a coarse representation of the user.

3.3 The sensor Network

The sensor nodes were successfully tested at a 30 Hz sample rate but this appeared to be the upper limit. Our empirical results show that the coordinator could handle up to 360 packets per seconds (i.e. up to ~12 nodes) with latency between 5 and 25 mS for the coordinator (using a simple 8-bit processor) to collect and forward any given frame to the external systems (PC). We would like to point out however that in our current system the packet rates are dependent on the constraints of the simple processing hardware and the application running on it. A lightweight application or better processor will probably handle much higher packet rates.

In order to provide a synthesis of human movement and position within the system, a skeletal model was developed on the PC receiving the motion data. Similar models have been used successfully in the past [13, 14, 15]. Our model uses the lower torso as the root link and tracks the position of each limb as a set of links connected to each other starting at the root. The skeleton model we produced is easily extensible and can be augmented to incorporate many more nodes, such as to track palm, finger or foot movement. Because the receiver (coordinator) node on the PC is connected using a serial USB connection, it is possible to have multiple WBANs on the user’s body, each with up to 12 sensor packs (in order to maintain very low latency levels). Our system is, in this respect, very highly configurable, as not all of the nodes need to be attached to the body or activated in order for the system to work. It is possible to arrange the system in such manner as to detect only arm movement, torso movement, leg movement or any combination of these, simply by strapping on the appropriate sensor packs and indicating to the capture interface which sensors are being work by checking the relevant boxes (see Figure 2).

A calibration procedure has to be enacted at the start of a motion capture session by the user. Posture calibration is performed with the user assuming a predefined reference posture (standing up straight, arms down), as in [15]. The calibration takes approximately 2-3 seconds to complete, which can be considered to be a low overhead for the human actor. The captured data is sent from the coordinator to the PC and is then processed through a configurable low-pass filter before going through the skeletal transformation. At this stage, the PC can then display a stick-figure animation as shown in Figure 2. The calibration interface and sensor placement guide on the human is also shown in Figure 2.

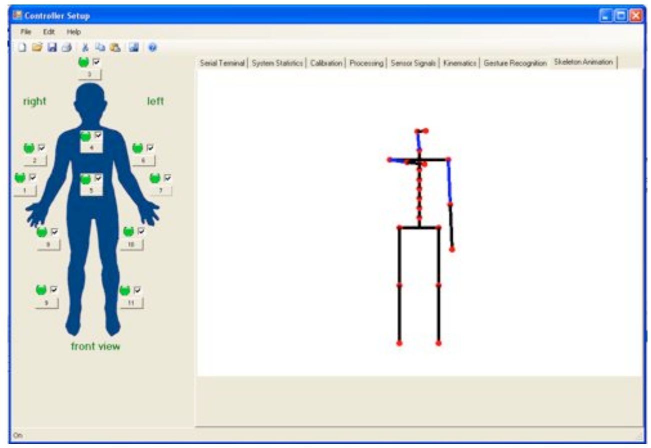

Figure 2. The motion capture interface (PC). A user can indicate which sensor packs are being worn by checking the relevant boxes on the human outline shape. The green status dots turn red when the sensor pack is not transmitting. The skeleton model on the right is constructed in real-time.

3.4 Whole Body HCI

Achieving motion capture solves only one part of the problem in creating novel human-computer interfaces. In one demonstration application, the movement is captured from the user and then the skeleton is covered with a digital skin, using DirectX and integrated into a synthetic 3D environment as shown in Figure 3. In this demonstrator, the user is equipped with a VR headset as well as the motion capture system. The 3D world is the start of the experimentation with interaction. This experiment provides smooth motion tracking from first (with 2/3D head mounted display) and third person perspectives. So when the user holds up their hands in front of them in the real world they see their hands in a 3D virtual world (videos of this can be viewed on our website[1]). In another application, we augmented our nodes with an optical proximity sensor, to allow a sensor node to be mounted within a training shoe to undertake a field investigation of foot motion. We are building a prototype football/soccer game that will enable the user to practice their kicking skills and assess their performance while playing in a virtual football field.

Further to this, we are investigating how our equipment can be used to accurately detect gait and foot clearance for elderly persons, helping solve and investigate issues in fall prevention. This is particularly important as until now, people could only be monitored in specialized labs (with expensive video equipment); now for the first time it is feasible to monitor an elderly person in their own environment and for extended periods of time, at a relatively low-cost. At present (October 2008) a laboratory-based trial is underway to compare an existing video-tracking system with our foot-mounted sensor system. The first results are

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[1] Mobile & Ubiquitous Computing Research Group: http://www.mucom.mobi

extremely promising, with a high degree of correspondence between the two data sets.

Figure 3: Real-time mapping of user body movement to a 3D virtual avatar in an immersive world.

Continuing in the domain of pervasive healthcare, we have also produced a prototype of a Marble Maze game that was used with a wobble board. The user stands on the board and makes small movements in order to guide the marble through the virtual maze, helping improve body balance and posture for rehabilitation patients. We used one sensing node to detect the movement of the wobble board with a high level of success. Finally, we investigated the use of the Mirrored Motion system to create a virtual musical instrument. The sensor data was mapped to musical parameters and gestural interpretation was applied to allow a user to control the instrument.

4. CONCLUSIONS & FURTHER WORK

We described in this paper how we defined a set of criteria for a pervasive body motion capture system and created a system informed by these, which was then used to investigate whole and partial body interaction in a series of demonstrators. Throughout our development we aimed to make use of easily available, low-cost components, keeping the cost per node to approximately £150. Given the many different environments (e.g. healthcare, gaming, music etc) in which we wished people to interact with and benefit from our work we needed to ensure that the system was additionally highly configurable, to allow a wide range of interaction opportunities to be investigated. Overall we were successful in delivering a high-performance, truly pervasive, extensible and highly wearable system that fulfils the criteria for such systems. We believe that our system will prove an extremely useful tool for a range of interaction opportunities; aside from our previous projects we are working on applying our system in several areas. We are particularly interested in its potential in mixed reality situations for gaming, We also wish to investigate issues in human-human interaction through embodied agents, controlled through the motion capture system. We are looking into the control of VR agents, as well as robotic agents for which the metaphor of "transferring one's soul" will be used to investigate response and interaction with other humans. Finally, we are interested in pursuing applications in tangible interfaces and semi-virtual artifacts, as well as gesture-based whole-body interaction with large situated displays. We hope to be able to create new types of human-computer interfaces for manipulating program windows, arranging or opening files using ad-hoc large projected or semi-transparent situated displays.

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