A USB INTERFACED MOTION CAPTURE SENSOR, USING TRI-AXIS MAGNETIC/INERTIAL SENSORS FOR USE IN KINEMATIC STUDIES.

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Abstract: An unobtrusive tri-axis magnetic and gravitational field transducer for use in kinematic tracking is presented. Outlined is a novel approach for using such a sensor i.e. providing a Universal Serial Bus (USB) interface, allowing the direct utilization of the logical topology of the standard, making scalable deployment possible. Furthermore design considerations; construction and performance of the sensor are analysed and discussed in detail.

Introduction

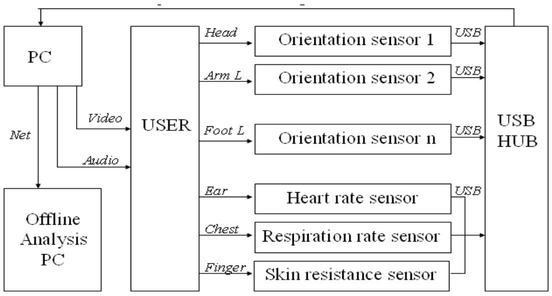

Figure 1: System Block Diagram

In this project we are developing an effective feedback system for a human interface to promote mental and physical relaxation. Therapies such as Yoga and Thai Chi have been shown to have many therapeutic benefits in rehabilitation including enhancing postural awareness and reducing chronic pain and hypertension. We are designing a garment based physiological and kinematic measurement system in order to investigate these therapies a system overview of which can be observed in figure 1 above. This investigation will take a game type format, more accurately the entire garment/suit is to be the human interface to a realtime feedback based video game, for promotion of yoga and thai chi.

In order to achieve this suit, the development of a sensor capable of scalable deployment was essential, multiples of which could be embeded on clothing worn by the subject at key kinematic tracking points on the body.

This sensor has been designed and implemented; it is a Universal Serial Bus (USB) kinematic transducer capable of scalable deployment. Moreover it requires a minimum of instrumentation, is unobtrusive and because of its utilization of SMD technology it has the ability to be made extremely lightweight and be implemented with a considerably small footprint. This paper details the design, implementation and testing of the device.

While a tri-axis magnetic/inertial sensor package, for use in human kinematics studies has been developed previously, the novel aspect of this system is the use of the USB interface.

Kinematic sensor networks reported in some literature have typically utilised 64 channel PCI acquisition boards limiting the number of sensors to 10 or 6 signals per channel. This obviously gives rise to an impractical situation, with excessively cumbersome connections hindering the subjects' movements [1]. USB is clearly a more powerful, modern and scalable technology. The logical topology of the standard allows the host to communicate with all devices as if they were connected to the root hub but always maintains an awareness of the physical topology in order to deal with the addition and removal of external hub devices. This gives the ability to connect up to 127 devices to the host at once [2]; making the hierarchical description of the human body in 3-dimensional space relatively easy to track once an active USB hub is placed on the subject. As a consequence only one lead is required from the USB host to the subject or none if it is placed on the subject himself/herself.

Furthermore, it is worth noting that once the backward compatibility of the forthcoming wireless USB standard is utilised, a wireless human motion capture sensor can be achieved with ease, considering there will be no loss in data rates [3].

Materials and Methods (System Design)

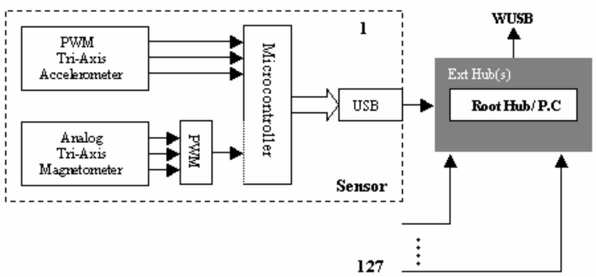

Figure 2: Scalable Kinematic Sensor Block Diagram

A block diagram of the sensor can be observed in Figure 2. The following section details the design of the sensor in question.

The USB interface was achieved by the use of the PIC16C745 from Microchip, an 8-bit microcontroller and some additional circuitry.
This provides transfer rates of up to 12Mb/s when used to provide a USB 1.1 interface [2].

The sensor itself was created using two Analog Devices dual axis pulse width modulated accelerometers ADXL202AE mounted using SMD technology at right angles to each other, yielding tri-axis acelerometer data when recorded via the Pulse Width Modulated (PWM) inputs on the PIC16C745.

Furthermore, the use of the standard Philips design for a digital compass based around the KMZ51 magnetometer was employed[4] i.e. three single axis magnetometers placed at right angles to each other in addition to appropriate circuitry.

At first the three analog outputs of this circuit were interfaced through the A/D analog inputs on the microcontroller. This proved to be extremely inpractical as it resulted in a significant loss of resolution, as the 'PIC' in question only carries an 8-bit ADC. However this loss in resolution was eliminated by the implementation of additional circuitry with the ability to convert these three analog signals in to their Pulse Width Modulated equivalents. This provided the ability to avail of the remaining PWM inputs on the PIC16C745 giving an effective resolution of 10 bits on each channel.

To date the SMD USB interface board, accelerometer, magnetometer circuitry and PWM conversion circuitry have been laid out and constructed as shown in figure 3. In addition a successful USB interface has been achieved between the three magnetic fields, acceleration sensors and PIC16C745, giving rise to a scalable USB based kinematic sensor (Figure 3), which for ease of reference will be refered to as "the sesnor' or 'sensor' hence forth, unless otherwise stipulated.

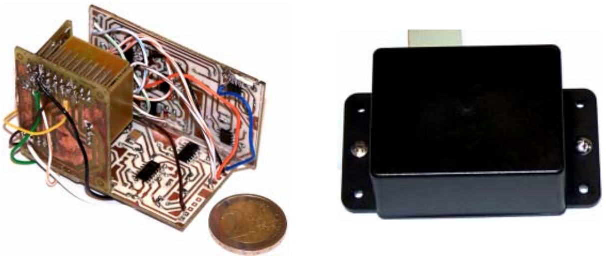

Figure 3: Sensor circuitary Using SMD & enclosed sensor

Materials & Methods (System Theory)

In effect the sensor provides six numbers representing the three gravitational (X_{accel}, Y_{accel}, Z_{accel}) and three magnetic field vectors (X_{mag}, Y_{mag}, Z_{mag}) respectively, these numbers are then normalized on the software side. Note that accelerometers detect all acceleration (gravitational and linear), but for the purpose of this paper the latter is assumed negligible.

It was determined that these six numbers should be used to represent the movement of the sensor in terms of conventional Euler Angles. Hence the movement of the sensor in space, and by association the position of a segment of the subjects' body, is defined by the three angles Yaw (φ), Pitch (Ø) and Roll (ρ) from its previous position. Note, where no previous position is available, a known starting point is used for example (0,0,0). Figure 4 gives an outline of the notation used from here on in for each of these three Angles.

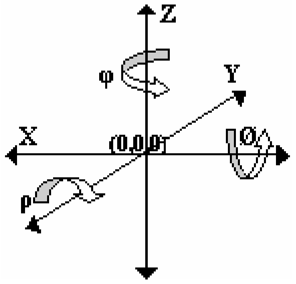

Figure 4: Euler Angles

Pitch and roll are obtained using the formulae outlined in equations 1 and 2. Note that although these angles can be worked out without the use of the Z_{Accel}, it is essential, as it maintains a constant sensitivity across a wider range, in particular those greater than 45 degrees [5].

$$Ø = \arctan\left[\frac{X_{Accel}}{\sqrt{Y_{Accel}^2 + Z_{Accel}^2}}\right] \qquad (1)$$

$$\rho = \arctan\left[\frac{Y_{Accel}}{\sqrt{X_{Accel}^2 + Z_{Accel}^2}}\right] \qquad (2)$$

The azimuth or yaw (φ) is effectively the angle between magnetic north and the heading direction, or simply the rotation around the z-axis (Figure 4). This can be obtained from the use of the magnetic field vectors Y_{Mag} snd X_{Mag} (3). However it is assumed that these vectors are positioned such that they are in the horizontal plane i.e. not under tilt conditions. As the bigger the tilt conditions the greater the error on Yaw.

$$\varphi_{Comp/Mag} = \arctan\left[\frac{Y_{Comp\,/\,Mag}}{X_{Comp\,/\,Mag}}\right] \qquad (3)$$

$$\begin{aligned} X_{Comp} &= X_{Mag}.Cos\phi - Y_{Mag}.Sin\phi.Sin\rho - Z_{Mag}.Sin\phi.Cos\rho \\ Y_{Comp} &= Y_{Mag}.Cos\rho + Z_{Mag}.Sin\rho \end{aligned} \qquad (4)$$

However this is corrected by use of electronic gimbling (4). Where the third magnetic field vector Z_{Mag} is used in combination with pitch and roll, all obtained simultaneously.

This produces X_{comp} and Y_{comp}, which if used instead of X_{Mag} and Y_{Mag} (in equation 3) corrects for tilt [4].

Tests and Results

In order to establish the functionality of the sensor a series of tests were performed, the outline and results of which are as follows:

To avoid overlap only results for one of the Euler Angles obtained by using accelerometers are provided (i.e. Pitch). Also note that the six values produced by the sensor are put through a running average of twenty samples before being normalised and producing the afore mentioned variables X_{Mag},$Y_{Mag,}$,Z_{Mag},$X_{Accel,}$$Y_{Accel}$ and Z_{Accel}.

Initially the sensor was positioned stationary at 175 degrees Yaw and 4 degrees Pitch, which yielded a standard deviation of 1.39 and 0.73 respectively.

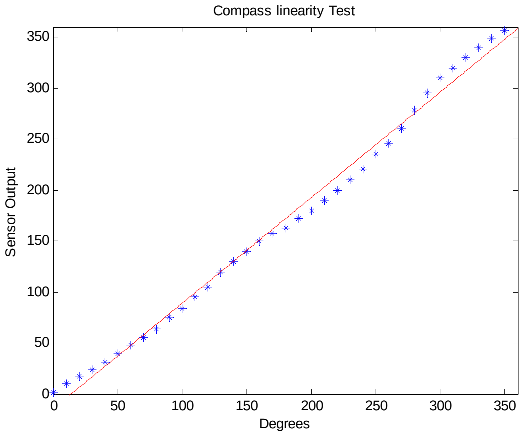

Figure 3: Yaw Linearity Test

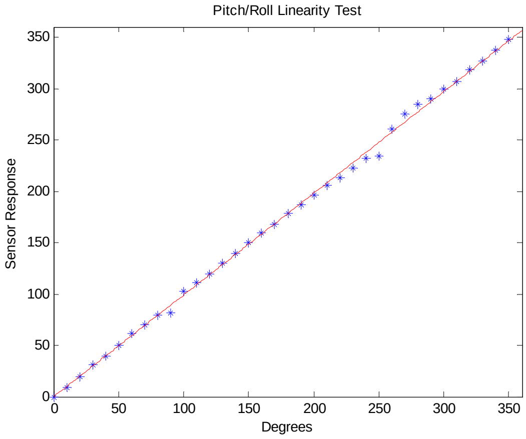

Figure 4: Pitch/Roll Linearity Test

Table 1: Linearity Test Results

	YAW	PITCH
Slope	1.036±0.02	0.99±0.001
Intercept	-14.7±3.10	-0.076±1.25

The sensor was then rotated in steps of ten degrees around the x-axis (pitch), and then around the z-axis (yaw) perpendicular to the earth's magnetic field, meaning no tilt compensation was required and by extension not allowing any error on the part of pitch and or roll readings affect the determination of yaw accuracy.

These results were then plotted (Figures 5-6 below) and an algorithm was used to determine the slope and intercept of each [6], the results of which can be observed in Table 1.

Finally the sensor was found to provide a data rate of 12 samples per secound.

Discussion and Future Work

The slope recorded for both Yaw and Pitch can be seen to give rise to a distinct linear response in both experiments (figures 3-4) however there are discrepancies to this:

Firstly, the eronious values produced as Pitch tends between 85-95 and 175-185 degrees, can be atributed, not to a failing on the part of the sensor but to that of the use of Euler Angles themselves. Although generally considered easy to use and understand, they have an inherent mathematical limitation when use to measure these angles.

A solution to this would be the adoptation of a method outlined by Rong Zhu and Zhaoaying [7]. This is a Kalman Filter based method which avoids Euler Angles singularities and has computational effeciency producing a single rotation rather than three successive ones.

Also the accelerometers are limited inherently as they are sensitive to both linear and gravitational acceleration. This however is not considered a significant problem as the overall goal of the proposed system (figure. 1) is to detect positions obtained in Yoga and Thai Chi, and the vast majority of these are low frequncy measurements.

The non-linearities in the use of the X_{Mag} and Y_{Mag} axes and the realtively large intercept error can be attributed to a magnetic field interference in the immediate environment of the sensor and to a lack of accuaracy in positioning the sensor exactly perpendicular to the earths magnetic field . The latter is compensated for by use of the 3rd magnetic field vector Z_{Mag} in collaberation with simultaneous measurements for ptich and roll (i.e. tilt compensation, eqn.4) and the prior can be corrected by using the sensor in an interference free enviroment or one that is predictable for which there are numerous document solutions [4].

In addition to these there are inherent system design issues that can be addressed, in order to further improve accurracy and sample rate.

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Primarily the addition of three of Analog Devices single-axis ADXRS150EB Gyroscopes, a proven method for providing vastly improved performance and accuracy[7]

Aside from this, as stipulated signal conditioning on the sensors six outputs has been a simple running average solution, the results of which could be improved by the adaption of a more powerfull signal conditioning method such as Kalman Filtering[7].

In terms of the sensors current profile there are some alterations that would be benificial:

An upgrade to Microchips PIC18F2455 with some slight alterations to the USB interface circuitry would produce a USB 2.0 interface and provide data rates forty times faster than the current USB 1.1 standard in use[8]. This would produce a considerable upgrade on the recorded 12 sample per secound.

Also upon construction of a sensor it is considered imperative that each magnetometer/accelerometer be maintained orthogonal to one other, although in order to govern against the possibilty that this does not occur to specifications, current published mathematical methods for correcting this should be employed [9]

Finally the size of the sensor currently 65mm(L), 35mm(H), 35mm(W) (figure 3) can be reduced considerably by use of multiple layer boards and professional track routing software. This will give the ability to seamlessly integrate the sesnor with a garment so as to provide comfort for the user and achieve the end goal of full kinematic measurement.

Conclusion

This paper details how small, lightweight, unobtrusive kinematic sensor systems can harness USB to provide a scalable, robust tracking system for active human motion studies.

Also discussed are methods for improving the sensor further so as to operate with even faster data rates and accuracy.

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