Towards an Ubiquitous Wireless Digital Writing Instrument Using MEMS Motion Sensing Technology

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***Abstract*— A Micro Inertial Measurement Unit (μIMU) which is based on MEMS accelerometers and gyro sensors is developed for real-time recognition of human hand motions, which when combined with appropriate filtering and transformation algorithms, becomes a Digital Writing System that can be used to record handwriting on any surface. The overall size of our μIMU is less than $25mm \times 70mm \times 20mm$, including the micro sensors, processor, and wireless interface components. We present our progress on using this μIMU based on Kalman filtering algorithm to filter the noise of sensors, which has allowed the system to successfully transform hand motions into recognizable and recordable English characters. Our goal is to implement this system to a digital hand-writing system that will interface with PC and mobile computing devices.**

***Keywords*— MEMS, μIMU, Human Motion Sensing, Kalman Filter, Digital Writing System, Wireless Sensing**

I. INTRODUCTION

"Electronic Whiteboard" and "Digital Pen" are new paradigms in the office automation industry that may someday completely replace the computer keyboard, which is still the preferred human-to-computer input device. These new technological devices aim to capture human hand writing or drawing motions in real-time and store human motion strokes for character recognition or information retrieval at a later time.

Currently, ultrasonic waves, infrared or optical sensing are the technologies commonly used for detecting the position of a pen on an electronic whiteboard. These systems allow users to write on specific surfaces with restricted active areas by the usage of special dry-erase pens. The whole setup is bulky and costly. Luidia has proposed a system that can turn any whiteboards interactive by putting a receiver at the corner of the whiteboard [1]. This receiver uses infrared and ultrasound technologies to translate the pen movement into the computer. Logitech [2] and Nokia [3] have promised the availability of the digital pen technology since the Spring of 2004. This technology uses optical detection techniques, where a specialized pen emmits a lightwave that would be deflected by micro structures built onto specialized digital papers. By detecting the reflected light, the pen can be made to record its position on the paper. Hence, all existing products required special writing surfaces or attachments for the system to function.

Our group is currently developing a generalized Digital Writing Instrument (DWI) based on MEMS motion sensing technology that can be potentially used ubiquitously, i.e., can be used on any surface at any time in any orientation. However, to create this novel DWI system, several engineering challenges must be resolved: 1) integration of several MEMS acceleration and gyro sensors with wireless transmission circuit design; 2) appropriate advanced signal processing techniques, such as Kalman filtering and Hidden Markov Models, must be explored to improve sensor calibration and stroke based recognition, since the accuracy of the overall system will contain many error sources, e.g., noise from MEMS sensors and wireless circuit. Wireless digital writing systems will provide new challenges for researchers in the Information Technology arena. Essentially, it is a new technology striving to improve the efficiency of storing information using human writing-strokes as the computer input interface rather than type-stokes as have been done for decades through a keyboard. It is rapidly gaining popularity in modern offices and teaching classrooms because it has many benefits, e.g., allows users to store hand-written meeting or teaching notes in real-time, and that users may some day be able to draw complex drawings or figures without learning complex software tools.

Our system is based on MEMS motion sensing technology. Owning to the availability of low-cost, small-size MEMS sensors, it is possible to build self-contained inertial sensors with overall system dimension of less than 1 cubic inch, and at the same time, the sensors unit can track the orientation and locomotion in real time. As an example, our group developed the Micro Input Devices System (MIDS) [4] based on MEMS sensors as a novel multi-functional interface input system, which could potentially replace the mouse, the pen and the keyboard as input devices to the computer. The DWI is an extension of the MIDS technology.

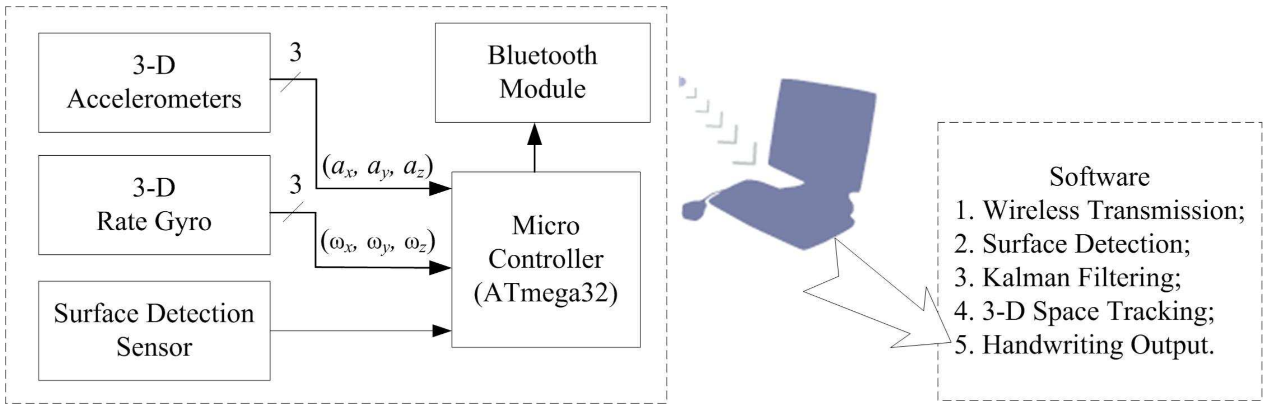


Fig. 1. Wireless Digital Writing Instrument block diagram.

This paper is organized as follows. In Section 2, the architecture of the Wireless Digital Writing Instrument is introduced, including the hardware for the wireless pen and software architecture. We describe the algorithm design of the digital writing system in Section 3, which will also describe the Kalman filtering implementation. Experiments and test results are discussed in Section 4. We draw the conclusion and proposed future improvements in the last section.

II. ARCHITECTURE OF WRITING SYSTEM

Fig. 1 illustrates the block diagram of the Wireless Digital Writing Instrument with a 3-D motion-sensing system. The system can be divided into two parts. The first part is the hardware for the wireless pen with sensors. The other part is the software structure for data access, spatial tracking and handwriting recording.

A. Hardware for wireless pen

We use a microcontroller (ATMEL ATmega32) in the design. The microcontroller has 32Kbyte flash, 2Kbyte of SRAM, 8 channels 10-bit ADC, and an USART (Universal Synchronous and Asynchronous serial Receiver and Transmitter) port [5]. The Bluetooth module is connected with the microcontroller by UART at a baud rate of 56.2 KHz.

For our experiments, we use ADXL203 and ADXRS300 as accelerometers [6] and angular rate gyros [7], respectively. These sensors are produced by Analog Devices, which are low cost and high performance sensors with analog signal output.

To detect the pen touching a writing surface, a focused Infrared Photo Detector - QRB1114 is used [8]. It is very useful for non-contact surface sensing. This sensor has a narrow range of detection making it more sensitive to use as the surface detection sensor in our design.

The output signals of the accelerometers (a_x, a_y, a_z), the rate gyros (ω_x, ω_y, ω_z) and the surface detection sensor are measured directly with an A/D converter inside the microcontroller. The digital sample rate of the microcontroller is 200 Hz, which ensures rapid reaction to human handwriting.

The accelerometers and the gyros act as the micro inertial measurement unit (μIMU) of the wireless pen. These μIMU sensors and the surface detection sensor are housed in the pen tip architecture, as shown in Fig. 2. A button could be used for users to initialize the writing system.

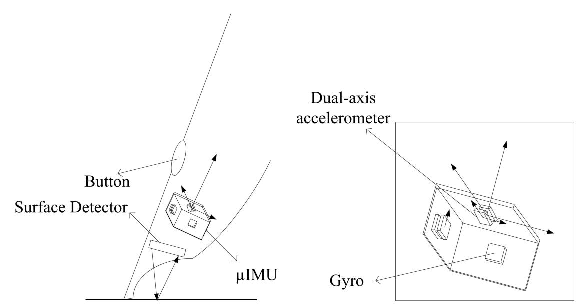


Fig. 2. Pen tip architecture with sensors.

We adopt BlueRadios BlueTooth Stamp Module in our system to transfer data to a host system [9]. This Bluetooth module is easy for integration to various host systems. The module is directly connected to the microcontroller by USART port as shown in Fig. 3. The module is very small in size ($20.3 \times 30.8 \times 4mm$ in size) and convenient to communicate with the microcontroller.

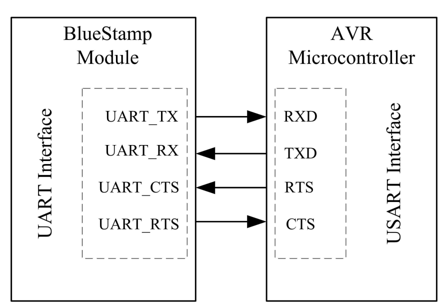


Fig. 3. UART interfaces with Bluetooth module.

The BlueStamp Module contains a complete Bluetooth interface and requires no further hardware to implement full Bluetooth communication. The module has an integrated, high performance antenna together with all RF and baseband circuitry; it interfaces to the host over a straightforward serial port using Hayes AT-style command protocol.

Fig. 4 shows a prototype with μIMU and Bluetooth module. Components are mounted onto a $25 \times 70mm$ two-layer printed circuit board.

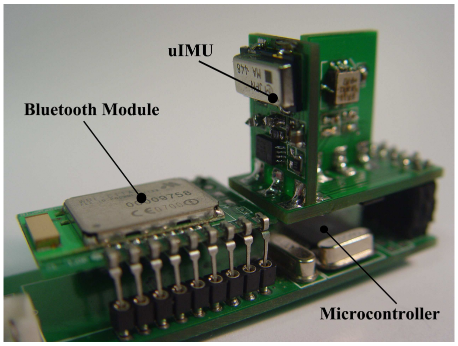


Fig. 4. Prototype with μIMU and Bluetooth module.

B. Software

The software for the microcontroller uses the fixed sampling time to convert the analog signals of the sensors to digital signals through A/D converter, and then they are packaged in the microcontroller in order to decrease the transfer errors, and finally the packaged data are conveyed through the wireless Bluetooth module into a host PC for further processing and reconstruction of handwriting.

The architecture of the software on the host PC for the wireless digital writing system is organized as in Fig. 5. There are four main parts in this software implementation, zero bias compensation, rotation compensation, Kalman filtering and integral operation of accelerations for position results.

In order to improve the precision for the inertial measurement unit, we use zero bias compensation and rotation compensation algorithms in the software architecture.

After pre-processing for the sensors' data, filtering algorithm is used. As the noise associated with accelerometers and gyros is Gaussian white noise and occupies the entire spectrum of frequencies, Kalman filtering is useful to eliminate the noise [10]. Kalman filtering algorithm is a key part in our implementation. After filtering, the handwriting recognition can be achieved by integral operation with accelerations.

III. ALGORITHM DESIGN

A. Zero bias compensation

The output of the accelerometers and angular rate gyros is a constant voltage called zero bias when the inertial unit is stationary. But the zero bias would drift due to the effect of temperature and the white noise of the sensors [11]. The measured accelerations and angular rate gyros output can be compensated by the following method,

$$a_0 = \frac{1}{N}\sum_{k=1}^{N} a_k \tag{1}$$

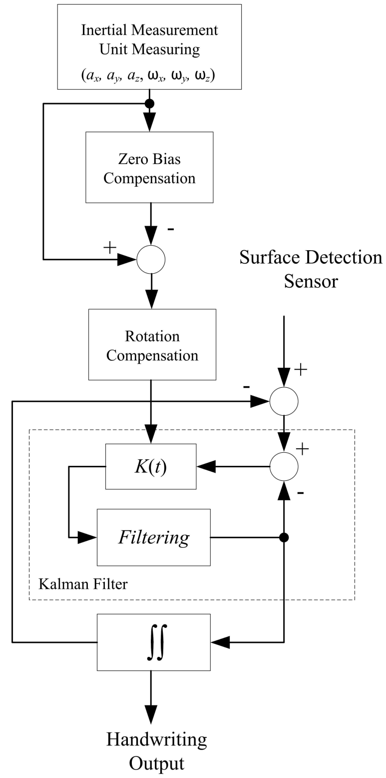


Fig. 5. Software architecture.

$$\omega_0 = \frac{1}{N}\sum_{k=1}^{N} \omega_k \tag{2}$$

where, a_k and ω_k are the acceleration and angular rate, respectively, with sampling data at time k, and N is the number of sampled data.

Then the actual output of accelerometers and angular rate gyros can be given by

$$a = a_k - a_0 \tag{3}$$

$$\omega = \omega_k - \omega_0 \tag{4}$$

B. Kalman Filtering

The noise of the sensor output has the characteristics of white Gaussian, which contributes equally at all frequencies and is described in terms of $\mu g/\sqrt{Hz}$(i.e., the noise is proportional to the square root of the accelerometer's bandwidth). Kalman filters are very useful linear filters for tackling such noise characteristics.

The sensor can be described by a linear system as the following equations,

(1) State equation:

$$x_{k+1} = Ax_k + Bu_k + w_k \tag{5}$$

(2) Output equation:

$$y_k = Cx_k + z_k \tag{6}$$

where, x_k is the state of the linear system, k is the time index, u is a known input to the system, y_k is the measured output, and w and z are the random variables represent the process and measurement noise respectively. The matrix C is the measurement matrix. As the sensor system has no any input, the matrix B is zero [12].

A is the state transition matrix as follows,

$$A = \begin{bmatrix} 1 & T & T^2/2 \\ 0 & 1 & T \\ 0 & 0 & 1 \end{bmatrix}$$

where, T is the sample time.

The Kalman filter estimates the process state at some time and then obtains feedback in the form of measurements. So there are two steps in the filter: time update and measurement update.

Time update equations are,

$$\widehat{x}_k^- = A\widehat{x}_{k-1}^- + Bu_k \tag{7}$$

$$P_k^- = AP_{k-1}A^T + Q \tag{8}$$

where, $\widehat{x}_{k-1}$ is the initial estimate of the process state, $\widehat{x}_k^-$ is the priori process state and Q is the covariance of the process noise [13].

The measurement update equations are,

$$K_k = \frac{P_k^- C^T}{CP_k^- C^T + R} \tag{9}$$

$$\widehat{x}_k = \widehat{x}_k^- + K_k(z_k - Cx_k^-) \tag{10}$$

$$P_k = (I - K_k C)P_k^- \tag{11}$$

where, K_k is Kalman gain, C is the measurement matrix, and $\widehat{x}_k$ is the updated estimate of the process state and P_k is the updated error covariance.

The Kalman filter algorithm is shown in Fig. 6 [14].

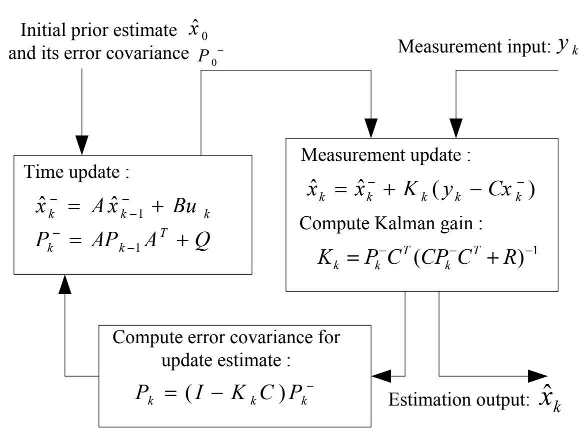


Fig. 6. Kalman Filtering algorithm.

C. Attitude rotation conversion

As the inertial unit will be tracked in the 3-D space, we use a fixed inertial frame with an orthonormal basis to describe the position in the space. The initial coordinate system is called the inertial frame. And the motion coordinate system is called the moving frame associated with the inertial unit, as shown in Fig. 7.

In order to measure the transformation from the moving frame to the inertial frame, we use the Rotation Matrix to describe this operation.

$$R(\Theta) = R_{YAW} R_{ROLL} R_{PITCH} \tag{12}$$

where,

$$R_{YAW} = \begin{bmatrix} \cos\varphi & \sin\varphi & 0 \\ -\sin\varphi & \cos\varphi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$R_{ROLL} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{bmatrix}$$

$$R_{PITCH} = \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix}$$

R_{YAW}, R_{ROLL} and R_{PITCH} are transformation matrices based on roll, pitch and yaw directions, respectively, as shown in Fig. 7, and φ, ϕ, θ can be estimated by the gyros.

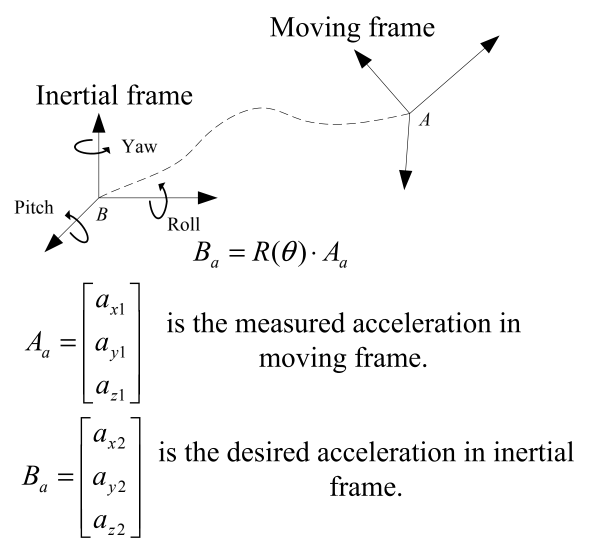


Fig. 7. Attitude rotation conversion.

D. Surface detection

Since our wireless digital writing system does not require any special paper or white board, the wireless pen should detect when the tip touches the surface.

Some tests were performed in order to evaluate the QRB1114 for surface detection. The sensor was tested for surface detection over an $18mm$ range (at $1mm$ increments) on white and black surfaces. These experiments allowed the outputs of the sensor to be compared over the variables of color and distance. The results of the sensor experiments are plotted and compared below in Fig.7.

As shown in Fig. 8, when the output of the QRB1114 is 253, which corresponds to a distance of $7mm$ from a surface, the sensor signal becomes saturated. Hence, by placing a sensor at $7mm$ away from the DWI's writing tip will ensure the QRB1114 distinguishes whether the DWI has touched a writing surface, and the μIMU should initiate the motion detection procedures.

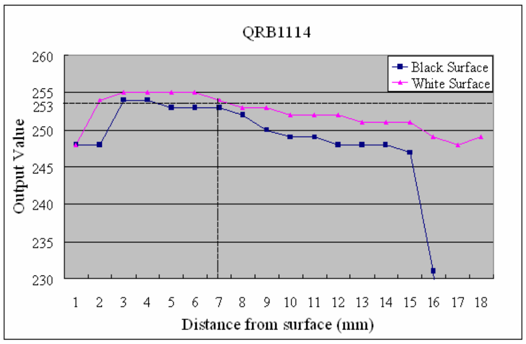
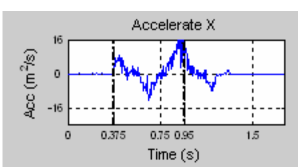


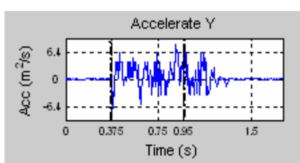
Fig. 8. Output of QRB1114 sensor on white and black surfaces.

IV. EXPERIMENTAL RESULTS

Fig. 9 and Fig.10 show the experimental results with our digital writing system for the character "*N*". Fig. 9(a) and Fig. 9(b) are measured accelerations for x and y axes, respectively. It can be seen that there is much noise in the sensors' output. The Kalman filter algorithm is used to tackle such noise. The filtered results are shown in Fig. 10(a) and Fig. 10(b).

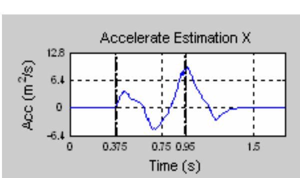


(a) x axis

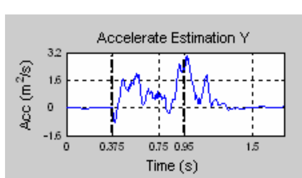


(b) y axis

Fig. 9. Acceleration without Kalman Filtering.



(a) x axis



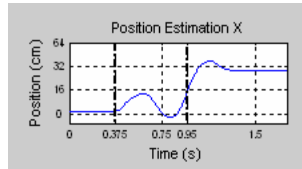
(b) y axis

Fig. 10. Acceleration with Kalman Filtering.

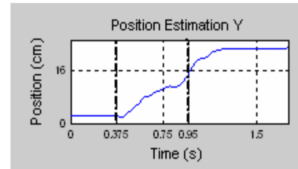
In order to calculate the position, we use the integral operations for the accelerations according to (13):

$$s_k = s_{k-1} + v_{k-1}T + \frac{1}{2}aT^2 \qquad (13)$$

where, s_k and v_k are position and velocity at time k respectively, a is acceleration and T is the sample time. The positions of x and y are shown in Fig. 11(a) and Fig. 11(b).



(a) x axis



(b) y axis

Fig. 11. Integrated position results from estimated accelerations.

Fig. 12 is the data from the surface detection sensor. As seen, the pen tip touches the white board surface from $0.375S$ to $0.95S$ because that the output of the surface detection sensor is greater than the threshold (253 for our experiment) during this time interval. Fig. 13 shows the handwriting of "*N*" character with the Digital Writing Instrument. Fig. 13(a) is unfiltered result and Fig. 13(b) is the result filtered by Kalman filter. The "*N*" character was written on a horizontal white board using our prototype system. Figure 14 shows the characters "*CMNS*" (Centre for Micro and Nano Systems) written with the prototype system. The characters were written separately and then merged into a single $x - y$ frame.

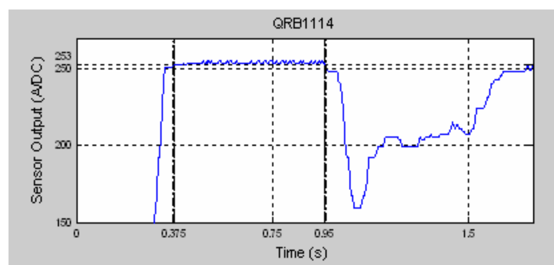
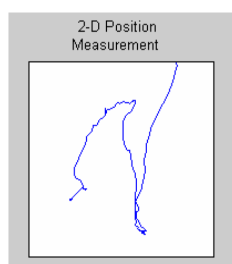
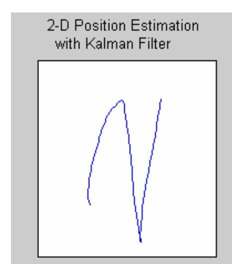


Fig. 12. Data of the surface detection sensor for writing on a board.



(a) unfiltered



(b) filtered

Fig. 13. "*N*" character written with our prototype.

V. CONCLUSION

We are developing a ubiquitous wireless digital writing system using a micro inertial measurement unit (μIMU) with MEMS motion sensors for hand movement tracking. The writing system consists of a μIMU, a surface detection

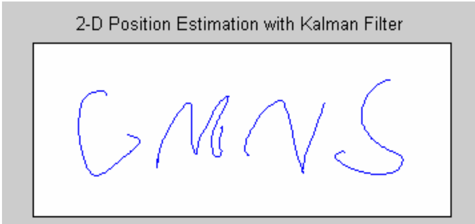


Fig. 14. "*CMNS*" written with the Digital Writing Instrument.

sensor, a computing microprocessor and a Bluetooth wireless module. Thus far, we have shown that Kalman filtering is a very effective technique to reduce noise for the hand motion tracking μIMU. The prototype can now be used to transcribe the hand accelerations into English characters on horizontal surfaces. Our future work is to develop a writing system that works on surfaces of different orientations.

VI. ACKNOWLEDGMENTS

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