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A Novel Real-Time Error Compensation Methodology for µIMU-based Digital Writing Instrument

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Abstract **– A Micro Inertial Measurement unit (µIMU) which is based on Micro-Electro-Mechanical Systems (MEMS) accelerometers and gyroscope sensors is developed for real-time recognition of human hand motion. By using appropriate filtering, transformation and sensor fusion algorithms, a ubiquitous digital writing instrument is produced for recording handwriting on any surface.**

In this paper, we propose a method for deriving an error feedback to a Kalman filter based on the assumption that writing occurs only in two dimensions i.e. the writing surface is flat. By imposing this constraint, error feedback to the Kalman filter can be derived. Details of the feedback algorithm will be discussed and experimental results of its implementation are compared with the simple Kalman filter without feedback information.

Index Terms **– Error Compensation; µ-IMU; Human Motion Sensing; Kalman Filtering; Digital Writing Instrument.**

I. INTRODUCTION

The “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 alphanumeric human-to-computer input device. A Ubiquitous Digital Writing Instrument has been developed by our group to capture and record human handwriting or drawing motions in real-time based on a MEMS Micro Inertial Measurement Unit (µIMU) [1].

A Micro Inertial Measurement unit (µIMU) which is based on Micro-Electro-Mechanical Systems (MEMS) accelerometers and gyroscope sensors is developed for real-time recognition of human hand motions. By using with appropriate filtering, transformation and sensor fusion algorithms, a 3D ubiquitous digital writing instrument is invented for recording handwriting on any surface [1].

In inertial kinematics theory [2], the position is computed by the double integration of acceleration with respect to time. However, due to electronic and mechanical noises in the MEMS inertial sensors, random noise exists in the system measurement output, thus the measured acceleration errors will be rapidly propagated to the position estimate. Kalman filtering can be used to reduce this effect but depends on the measurement inputs.

This application is similar to inertial navigation systems but global positioning system (GPS) accuracy and the fact that it is likely to be used indoors precludes directly using GPS as the reference. Given that most of the handwriting is on a surface, there is zero displacement in z-axis in earth frame. Since the pen is oblique to the earth frame during writing, the error in three axis accelerometers will contribute in the z-axis in the earth frame. We suggest making use of the information associated with the z-axis in earth frame to act as the feedback measurement input for Kalman filter to perform a real-time error compensation to the acceleration measurement for inertial navigation.

The paper is structured as follows: Section 2 describes the architectural design of the ubiquitous digital writing instrument, including the hardware and software structure. We will describe the error compensation algorithm in Sections 3. Simulation and experiment results will be discussed in Section 4. Finally, we present conclusions and proposed future improvements in the last section.

II. ARCHITECTURE OF WRITING SYSTEM

A. *Hardware Architecture of the Digital Writing System*

Fig. 1 illustrates the block diagram of µIMU with the real-time position tracking system. The system can be divided into two parts. The first part is the hardware for the wireless sensing unit and the second is the software for data access and 3D navigation tracking.

The µIMU is developed for a wireless digital writing instrument and used to record human handwriting. The µIMU integrates the 3D accelerometers and 3D gyroscopes with strapdown installation [1]. The sensor unit is affixed on a commercially available marker to measure the inertial information in the pen’s body frame.

The output signals of the accelerometers [A_x, A_y, A_z] and the gyroscopes [ω_{roll}, ω_{pitch}, ω_{yaw}], are the body frame accelerations in three-axes and the angular rates, roll, pitch, yaw respectively. These are measured directly with an Atmega32L A/D converter microcontroller. The serial Bluetooth transceiver is implemented via a USART connection with the MCU for wireless communications. The digital sample rate of the sensor unit is 200 Hz and the transmit baud rate is 57.6 Kbps, which ensures rapid reaction to human handwriting [3].

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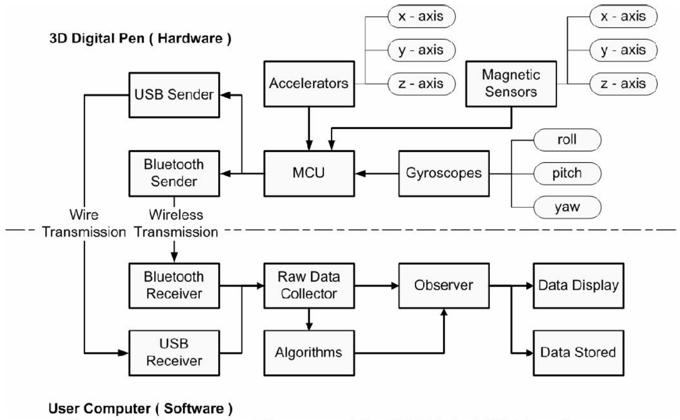

Fig. 1 The System Architecture of the 3D Digital Writing System

Fig. 2 shows the prototype of µIMU with the Bluetooth module for wireless connection. The sensor system utilizes four-layer printed circuit board techniques for noise reduction. The dimensions are within 56×23×15*mm*.

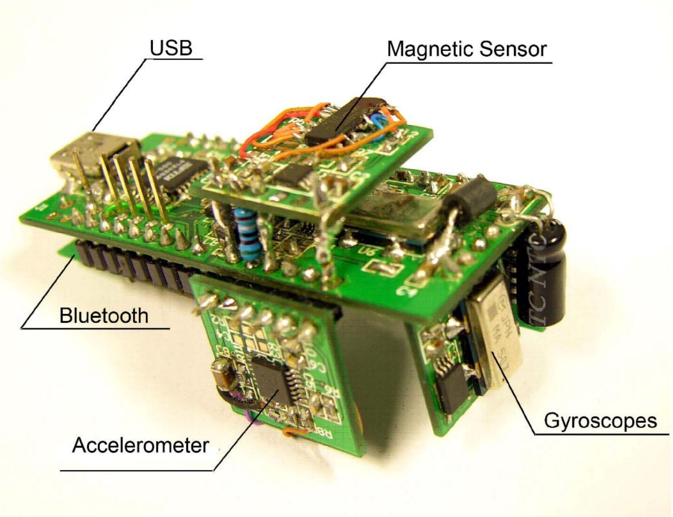

Fig. 2 The Prototype of µIMU with Bluetooth module

B. *Algorithm for Handwriting in the Digital Writing System*

Fig. 3 illustrates the µIMU sensor structure of the digital writing system for position tracking. According to strapdown kinematics theory [2], the body frame accelerations are transformed to the earth frame by a direct cosine matrix (DCM). After compensating for the gravitational and rotational accelerations, the translation accelerations are integrated into 3D trajectories in space. Thus any 2D human handwriting is recorded in real time if the pen touches the white board plane.

$$\vec{A}_b = \vec{A}_{IMU} - \vec{A}_{Rotation}(\omega_{roll}, \omega_{pitchl}, \omega_{yaw}, L) \tag{1}$$

$$\dot{\vec{V}}_e = DCM(\vec{q})_b^e \vec{A}_b - \vec{G} \tag{2}$$

$$\vec{S}_e = \int\int \dot{\vec{V}}_e dt' dt \tag{3}$$

where $\vec{A}_{IMU}$ is the body frame accelerations: [A_x, A_y, A_z],

$\vec{A}_b$ is the translational acceleration in the body frame,

$\vec{V}_e$ is the velocities in the earth frame: [V_x, V_y, V_z],

$\vec{S}_e$ is the positions in the earth frame: [S_x, S_y, S_z],

$\vec{q}$ is the pen attitude in quaternion format,

$\vec{G}$ is the gravity vector: $[0,0,-g]$ and

L is the distance of the gyroscopes from the pen tip.

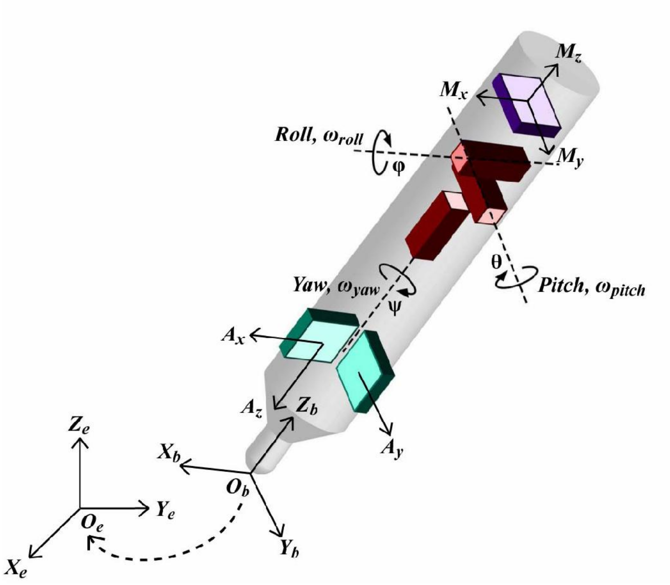

Fig. 3 The coordinate system of the 3D Digital Writing System

III. ERROR COMPENSATION ALGORITHMS

A. *Kalman Filtering Algorithm*

Owing to the random nature of the noise in the accelerometers and gyroscopes, a Kalman filter, which is a stochastic based real-time recursive filter using measurement and noise information, is used to reduce the error of the position estimate.

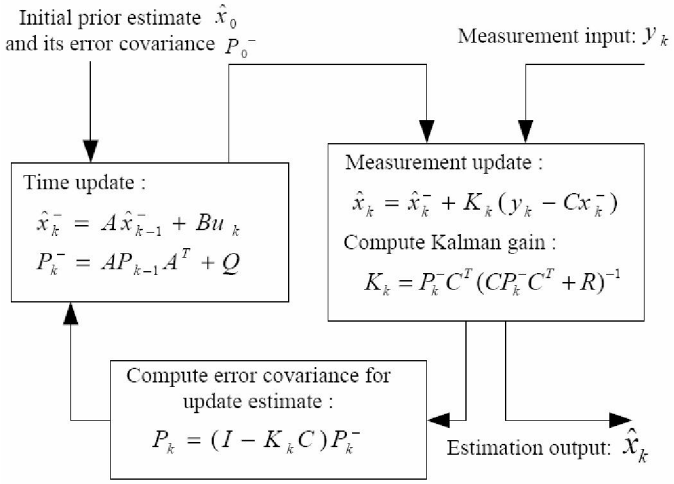

Fig. 4 The Kalman Filter Algorithm

Fig. 4 demonstrates the real-time recursive process of the Kalman filtering algorithm. Pang et al. [4] suggested to use the accelerometer output and the following process noise covariance, Q, and transition matrix, A, to compensate the noise in the accelerometer in each axis i, *where* $i = x, y, z$.

$$x_{k,i} = \begin{bmatrix} s_{k,i\_earth} & v_{k,i\_earth} & a_{k,i\_earth} \end{bmatrix}^T \tag{4}$$

$$y_{k,i} = [a_{k,i\_earth}]^T \tag{5}$$

$$A = \begin{bmatrix} 1 & \Delta t & \frac{1}{2}\Delta t^2 \\ 0 & 1 & \Delta t \\ 0 & 0 & 1 \end{bmatrix} \tag{6}$$

$$Q = \begin{bmatrix} \frac{W}{20}\Delta t^5 & \frac{W}{8}\Delta t^4 & \frac{W}{6}\Delta t^3 \\ \frac{W}{8}\Delta t^4 & \frac{W}{3}\Delta t^3 & \frac{W}{2}\Delta t^2 \\ \frac{W}{6}\Delta t^3 & \frac{W}{2}\Delta t^2 & W\Delta t \end{bmatrix} \tag{7}$$

B. *Feedback from the Pen-tip*

Since Kalman filtering algorithm is one of the solutions of the least square problem, the increase of the measurement input information will improve noise removal in the accelerometer output and also the position estimation of the pen.

Traditionally, aircraft navigation systems make use of Global Positioning Systems (GPS) to act as the second input of the measurement input of the Kalman filter as it provides an absolute position estimation. However, GPS is not suitable for writing instruments.

Fortunately, most handwriting is done on a two dimensional surface; hence we can make use of the constraint that the z-axis in the earth frame is always zero when the pen-tip touches the writing surface. This is used as the second measurement input of the Kalman filter to allow an error to be derived and feedback to be used. We also note that the pen is oblique to the earth frame during writing so a 3-axis accelerometer is not orthogonal to the earth frame z-axis and hence will project the errors onto the earth frame z-axis.

With this idea, we propose to modify the Kalman filtering algorithm as shown:

$$x_k = \begin{bmatrix} x_{k,x} & x_{k,y} & x_{k,z} & a_{k\_body} \end{bmatrix}^T \tag{8}$$

$$y_k = [a_{k\_body} \quad s_{k,z\_earth} \quad v_{k,z\_earth}]^T \tag{9}$$

$$A_{sub} = \begin{bmatrix} 1 & \Delta t & \frac{1}{2}\Delta t^2 \\ 0 & 1 & \Delta t \\ 0 & 0 & 0 \end{bmatrix}$$

$$DCM_1 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \cos\theta\cos\psi & \begin{pmatrix} -\cos\phi\sin\psi + \\ \sin\phi\sin\theta\cos\psi \end{pmatrix} & \begin{pmatrix} \sin\phi\sin\psi + \\ \cos\phi\sin\theta\cos\psi \end{pmatrix} \end{bmatrix}$$

$$DCM_2 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \cos\theta\sin\psi & \begin{pmatrix} \cos\phi\cos\psi + \\ \sin\phi\sin\theta\sin\psi \end{pmatrix} & \begin{pmatrix} -\sin\phi\cos\psi + \\ \cos\phi\sin\theta\sin\psi \end{pmatrix} \end{bmatrix}$$

$$DCM_3 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ -\sin\theta & \sin\phi\cos\theta & \cos\phi\cos\theta \end{bmatrix}$$

$$A_{feedback} = \begin{bmatrix} A_{sub} & 0 & 0 & DCM_1 \\ 0 & A_{sub} & 0 & DCM_2 \\ 0 & 0 & A_{sub} & DCM_3 \\ 0 & 0 & 0 & I_3 \end{bmatrix} \tag{10}$$

$$Q_{feedback} = \begin{bmatrix} Q & 0 & 0 & 0 \\ 0 & Q & 0 & 0 \\ 0 & 0 & Q & 0 \\ 0 & 0 & 0 & Wdt \cdot I_3 \end{bmatrix} \tag{11}$$

IV. EXPERIMENTAL RESULTS

In order to test the accuracy of the algorithm, we simulated stationary accelerometers and rotated the pen to cause the accelerometers to fluctuate. We assume Gaussian distributed noise in the accelerometers with covariance (σ^2) of 10 cm^2s^{-4} as shown in Fig. 5. As a comparison, the actual noise level of acceleration sensors is around 7 cm^2s^{-4}.

By comparison, the overall noise level using our feedback error compensation technique shown in Fig. 6 is much lower than that using Pang's algorithm shown in Fig. 7, especially in the steady state.

Also by comparing Fig. 8 and Fig. 9, which shown our algorithm with larger noise covariance and smaller noise covariance respectively, the measurement noise covariance (R) controls the error compensation performance. If R is smaller, a longer time is required to reach a steady state. In contrast, if R is larger, a shorter transient is required.

V. DISCUSSION

Through simulation with realistic sensor noise levels, the proposed Kalman filtering technique can be demonstrated to significantly reduce the noise in a pen-based inertial measurement unit. Further investigation will be made on finding the suitable parameter and the acceptable noise level for the digital writing system in the near future from building an error model of the accelerometer.

VI. CONCLUSIONS

In this paper, we have demonstrated a novel Kalman filter based algorithm for real time error reduction in a µIMU-based digital writing instrument. This approach can be used to more accurately determine position in motion sensing based digital writing instruments.

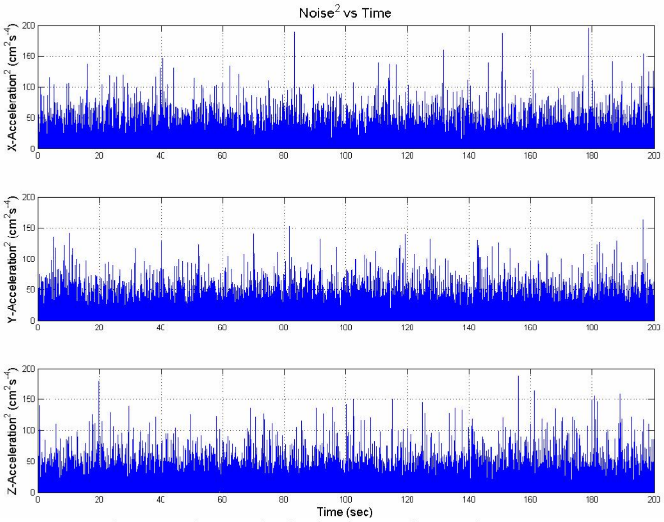

Fig. 5 Random Noise in the three-axis Accelerometers

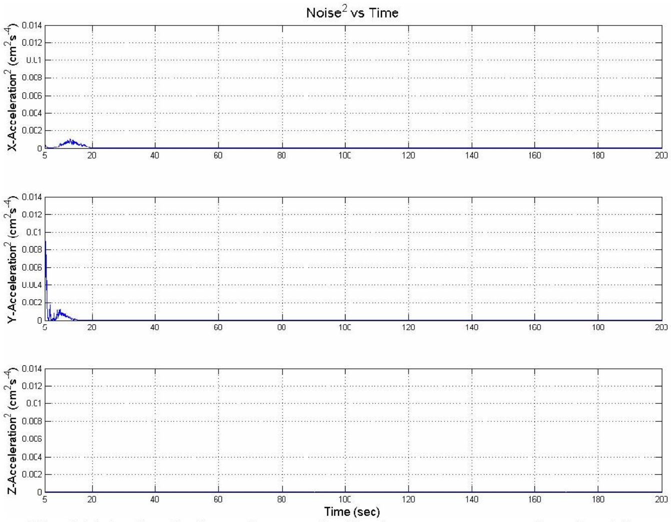

Fig. 6 Noise level after using our feedback error compensation algorithm

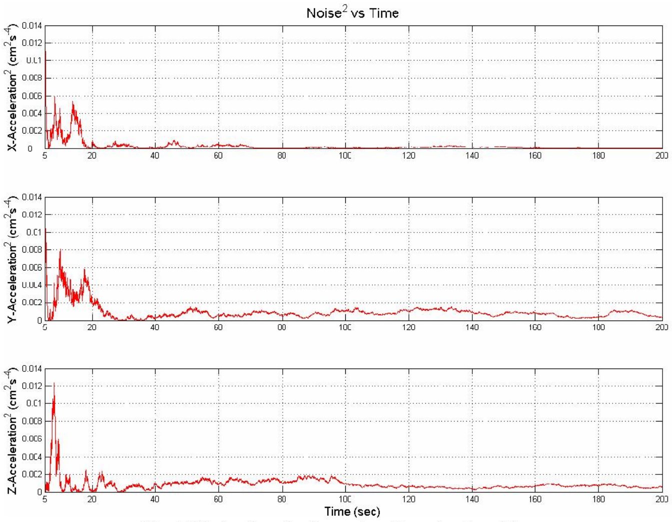

Fig. 7 Noise level after using Pang's algorithm

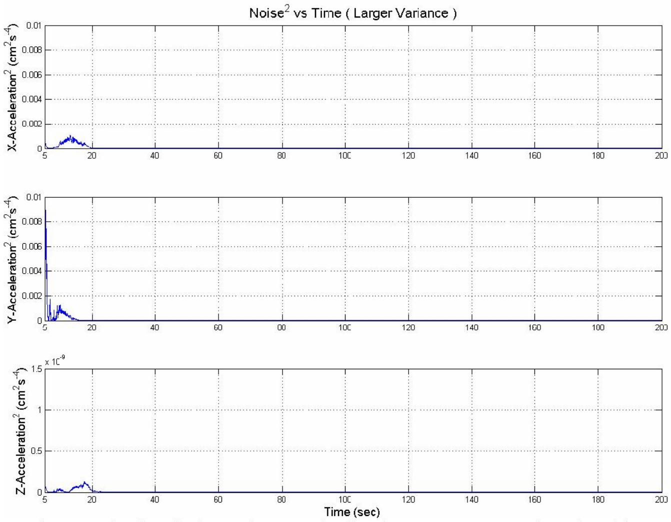

Fig. 8 Noise level after using our feedback error compensation algorithm with larger measurement noise covariance

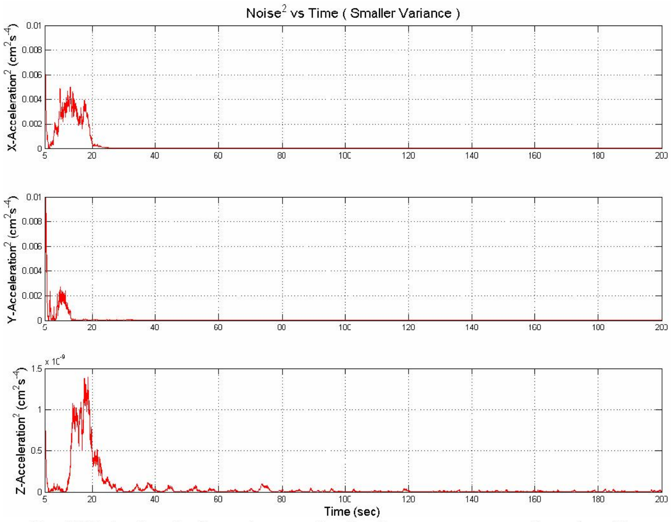

Fig. 9 Noise level after using our feedback error compensation algorithm with smaller measurement noise covariance

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REFERENCES

[1] Guanglie Zhang, Guangyi Shi, Yilun Luo, Heidi Wong, Wen J. Li, Philip H. W. Leong and Ming Yiu Wong, "Towards an Ubiquitous Wireless Digital Writing Instrument Using MEMS Motion Sensing Technology", *Proceedings of IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, 2005 pp.795–800.

[2] D. H. Titterton, J. L. Weston, *Strapdown Inertial Navigation Technology*, 2nd Edition, AIAA, Reston, USA, 2005.

[3] Yilun Luo, Chi Chiu Tsang, Guanglie Zhang, Zhuxin Dong, Guangyi Shi, Sze Yin Kwok, Wen J. Li, Philip H.W. Leong, Ming Yiu Wong, "An Attitude Compensation Technique for a MEMS Motion Sensor Based Digital Writing Instrument", *Proceedings of 2006 IEEE International Conference on Nano/Micro Engineered and Molecular Systems*, 2006.

[4] Grantham Pang, Hugh Liu, "Evaluation of a Low-cost MEMS Accelerometer for Distance Measurement", *Journal of Intelligent and Robotic Systems*, Volume 30, Issue 3, Mar 2001, pp. 249–265.