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Handwriting Tracking based on Coupled μIMU/Electromagnetic Resonance Motion Detection

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***Abstract* – We have recently developed a ubiquitous digital writing instrument system based on a micro inertial measurement unit (μIMU), which consists of MEMS (micro-electro-mechanical system), accelerometers and gyroscopes, to compute the position of a marker through double integration of the acceleration measured, so as to real-time record and recognize human handwriting motion in a large writing area, i.e., a large whiteboard or screen.**

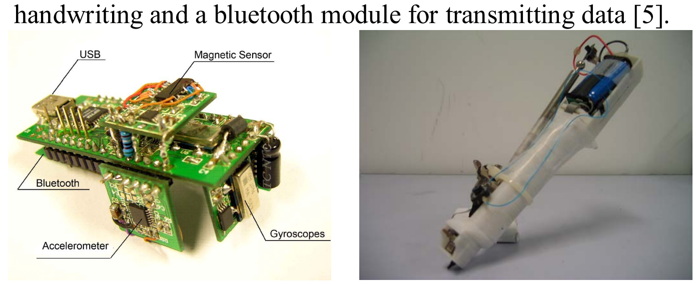
Owing to the random errors that exist in the MEMS sensors, the accuracy of the position estimate degrades with time. Although Kalman filtering algorithm provides a good navigation tracking solution, its accuracy depends on the amount of position information given about the target. In vehicles, the global positioning system (GPS) can be used to augment an IMU with absolute position information and improve its tracking accuracy. However, due to indoor-usage and a higher accuracy requirement, the GPS is not suitable for updating a μIMU used for hand-motion tracking with absolute position information.

In this paper, we propose a novel position estimation method which makes use of an electromagnetic resonance (EMR) motion detection board for position information to improve the tracking accuracy of a μIMU-based digital writing instrument. The EMR board cannot provide high resolution (only 3 cm per grid in our case) position information for a large writing area because of high construction cost and poor tracking performance. However, the combined scheme of using the μIMU and the EMR board can compensate their respective weaknesses. The EMR board can bound the μIMU position estimate error and the μIMU can provide detailed information of the handwriting trajectory for the rough locus obtained from the EMR board. Details of the estimation algorithm will be discussed and experimental results of its implementation are compared with the conventional Kalman filtering without the extra position feedback information.

***Index Terms* – Error Compensation; MEMS μIMU; Human Motion Sensing; Kalman Filtering; Digital Writing Instrument.**

I. INTRODUCTION

In this office automation era, many handwritten documents are digitalized for ease of backup and transmission. The demand for digital writing instruments is thus expected to grow rapidly in coming years. There are many different types of systems already available on the market, e.g. eBeam [1], mimio® [2], Logitech© io™2 [3] and Nokia SU-1B [4]. Recently, we have developed a prototype of MEMS (Micro-Electro-Mechanical Systems) based 3D digital writing instrument as shown in Fig. 1 which makes use of a micro inertial measurement unit (μIMU) constructed from MEMS accelerometers and gyroscopes for real-time capturing of handwriting and a bluetooth module for transmitting data [5].



(a) The μIMU with Bluetooth (b) The 3D Digital Writing Instrument
Fig. 1 The Ubiquitous Digital Writing System

However, the random noises associated in the MEMS accelerometers and gyroscopes, such as thermo-mechanical noises and etc., will propagate to the position estimate through integration process. Although there are many noise reduction methodologies proposed by researchers to improve the position tracking performance, for instance Kalman filtering [6], zero velocity compensation [7] and etc., the performance of position estimation is not robust and position drift exists for the methods proposed. This is because they have not bounded the position estimate.

In vehicles, position drift is also a problem, but a global positioning system (GPS) is used to assist the navigation. GPS receives radio frequency signal from three or more GPS satellites in space. By measuring time delay between transmission and reception of the signal in the receiver, the receiver can compute the altitude and position of the target object [8].

The short-term positional errors from the inertial navigation systems (INS) are relatively small, but the accuracy in position calculation degrades without bound over time. In contrast, the GPS cannot provide high frequency updates of position, but the position from GPS will not drift away with time. Therefore, besides the use of an inertial measurement

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unit, many navigation systems use GPS to provide absolute position information to act as the second measurement input for a Kalman filter to improve the system performance by taking the respective advantages in INS and GPS [9].

However, GPS is not feasible for our digital writing instrument. Firstly, the writing instrument is mainly designed for indoor use, and the GPS signal will be blocked by the buildings. Even if we use the system outdoors, the resolution of GPS system is only to around several meters [8], and cannot provide sufficient accuracy to improve the pen position tracking, which requires accuracy limited to 1 cm or less. Thus GPS is not suitable for writing instrument and an alternative system is needed to obtain position information to improve the Kalman filter. Hence, in this paper, we would like to investigate the feasibility of building a similar position feedback system for a digital pen system to improve the accuracy of the tracked position.

Fortunately, a common human-computer interaction device that can provide position information exists in the form of the graphics tablet. The basic working principle of the graphics tablet is to use the electromagnetic resonance (EMR) to detect the position of a stylus [10].

Although the EMR board can provide position information, its performance is poor for large writing areas, particularly if good resolution is needed. Since the accuracy of the motion detection board depends on the density of the coil, the searching time will increase with the number of channel used and results in the increase of the delay time in finding the position of the pen. Nevertheless, we can still make use of this low resolution of position information from the EMR board to improve the position tracking by the μIMU.

The paper is structured as follows: Section 2 describes the architectural design of the electromagnetic resonance (EMR) motion detection board. We will then describe a coupled μIMU/EMR board system to improve the position tracking accuracy in Sections 3. Experiment results will be discussed in Section 4. Finally, we present conclusions in the last section.

II. ELECTROMAGNETIC RESONANCE (EMR) MOTION DETECTION BOARD

In Fig. 2, a system level diagram of an electromagnetic resonance motion detection system is given. In Fig. 3(a), a grid of wires, which consists of two sets of coils arranged both horizontally and vertically, is used to determine the horizontal and vertical coordinates of the digital pen or eraser. The coil grid acts as antenna to receive the time-varying magnetic field generated by the resonant circuit (RLC circuit) shown in Fig. 2 in the transmitter, which is installed on the pen and eraser as shown in Fig. 3(b). Hence, if the transmitter is within the coil, then that coil will generate a voltage with a magnitude that represents how close the pen is. This voltage is then digitized through an analog-to-digital converter (ADC) in the motion detection circuit as shown in Fig. 3(c) to be transmitted to the host computer through a bluetooth module to locate the position of the pen.

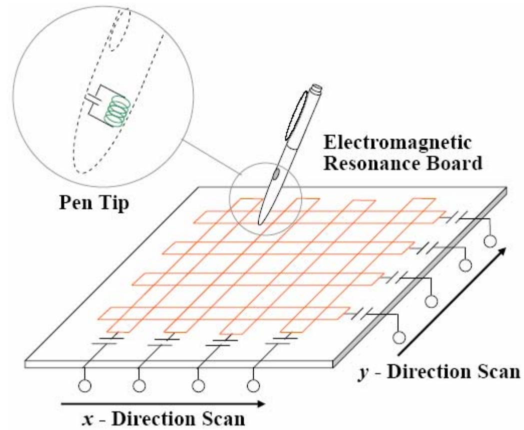
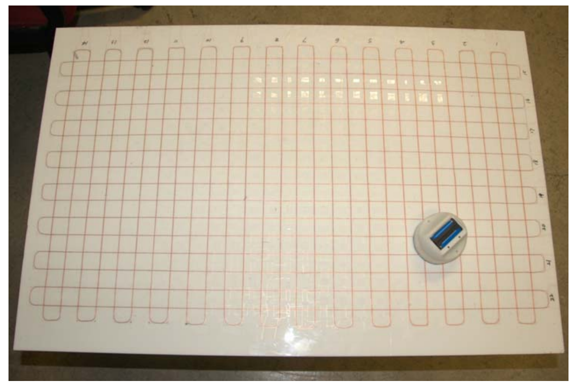
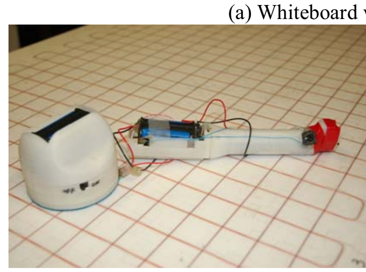


Fig. 2 Working Principle of EMR Motion Detection Board (modified from reference [11])


(a) Whiteboard with Coils


(b) Digital Pen and Eraser

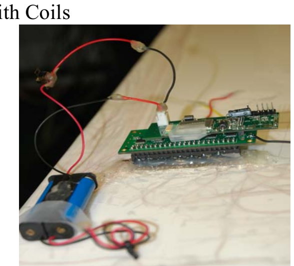
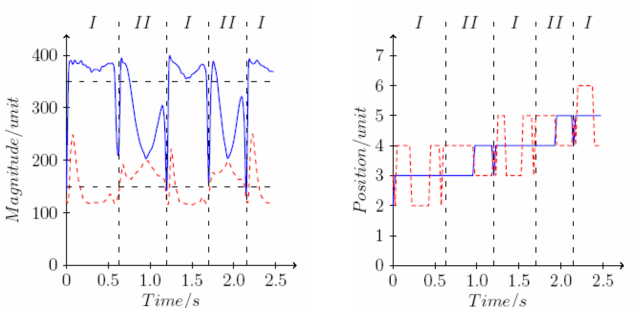

(c) EMR Motion Detection and Data Transmission Circuit

Fig. 3 Electromagnetic Resonance Motion Detection System

Based on the basic working principle described above, the pen moves across the board, the voltage generated in each channel of the coil grid. This voltage will vary with the distance between the transmitter and the centre of the coil. Fig. 4(a) shows the magnetic field strength of two signal channels from the EMR motion detection board, and Fig. 4(b) shows their corresponding coordinates. These two signal channels are picked up from the coils with the largest two voltages, and are the closest two coils to the pen. In Fig. 4, the solid line represents the channel having the largest signal magnitude; whereas the dash line represents the channel having the second largest signal magnitude. If the transmitter is within a coil, defined as region *I*, and the solid line is higher than a threshold as shown in Fig. 4(a). We can obtain the corresponding coordinate as shown in Fig. 4(b). If the transmitter is between two coils, defined as region *II*, we can take an average of the coordinates of the two signal channels to determine the position.



(a) Magnitude vs Time (b) Position vs Time

Fig. 4 Signal from EMR Motion Detection Board

III. A Combined Scheme of µIMU and EMR Motion Detection Board

A. A Combined Scheme

Owing to the existence of the random noises associated in the µIMU, error propagates from accelerometer measurement to the position estimate which is unbounded and drifts with time through double integration process. Many researchers have proposed different error compensation algorithm to solve it. However, up to date, there is no successful real-time solution to solve the problem in handwriting tracking. Hence, we propose a combined scheme of using µIMU and EMR motion detection board, which is similar to the idea of sensor fusion in IMU/GPS coupled systems [9]. A low resolution EMR motion detection board can provide absolute position with bounded error, accuracy being limited by the grid size, and the µIMU can provide the detailed part of the motion. Hence, we combine the benefits of µIMU and EMR through a Kalman filter as shown in Fig. 5 to give more accurate position estimation.

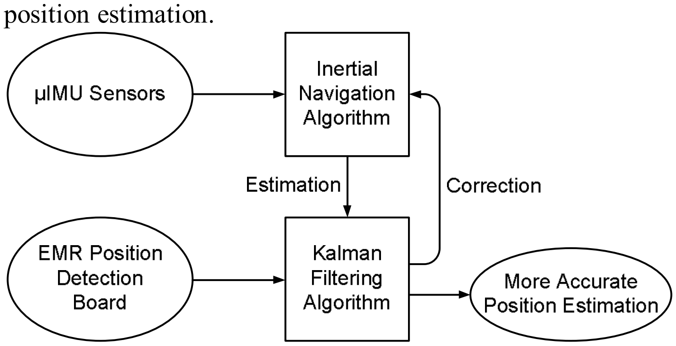


Fig. 5 A Combined Scheme of µIMU and EMR Motion Detection Board

B. Algorithm Implementation

The idea of the combined scheme is based on the architecture of the Kalman filtering algorithm which is shown in the block diagram of Fig. 6.

1) State Vector: We first define the interested navigation information, which is position, velocity and acceleration of the 3-axis in the navigation frame, in the state vector x.

$$x = [s_{n,x} \quad v_{n,x} \quad a_{n,x} \quad s_{n,y} \quad v_{n,y} \quad a_{n,y} \quad s_{n,z} \quad v_{n,z} \quad a_{n,z}]^T \tag{1}$$

where $s_{n,i}$, $v_{n,i}$, $a_{n,i}$ are position, velocity and acceleration of i-axis in navigation frame, $i=x, y, z$.

2) State Transition Matrix: The state transition matrix A is used to propagate the state vector from time instant $k\text{-}1$ to k.

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

$$A = \begin{bmatrix} A_x & 0_3 & 0_3 \\ 0_3 & A_y & 0_3 \\ 0_3 & 0_3 & A_z \end{bmatrix} \tag{3}$$

where Δt is the sampling period of the accelerometer and 0_3 is the 3×3 zero matrix.

3) Process Noise Covariance Matrix: The process noise covariance matrix Q is used to let the Kalman filter estimate the effect of the noise propagated through integration process.

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

$$Q = \begin{bmatrix} Q_x & 0 & 0 \\ 0 & Q_y & 0 \\ 0 & 0 & Q_z \end{bmatrix} \tag{5}$$

where q_c is the process noise covariance in continuous time.

4) Observation Matrix: The observation matrix H is used to map the state vector with the measurement input vector to update the estimation in the measurement update stage. H_{IMU} is the observation matrix for µIMU which maps the accelerometer measurements with the x,y,z-axis acceleration in the state vector; meanwhile H_{EMR} is the observation matrix for EMR motion detection board which maps the position measurements with the x,y-axis position in the state vector.

$$H_{IMU} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{6}$$

$$H_{EMR} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{7}$$

5) Measurement Noise Covariance Matrix: The measurement noise covariance matrix R is used to tell the Kalman filter what the noise distribution of the measurement input is.

For µIMU measurement noise covariance matrix (R_{IMU}), since the accelerometer in each axis is assumed to be independent with each other, hence R_{IMU} is defined to be a diagonal matrix that $R_{IMU,i}$ is accelerometer noise covariance in each axis i which can be measured through experiment.

$$R_{IMU} = \begin{bmatrix} R_{IMU,x} & 0 & 0 \\ 0 & R_{IMU,y} & 0 \\ 0 & 0 & R_{IMU,z} \end{bmatrix} \quad (8)$$

For EMR motion detection board measurement noise covariance (R_{EMR}), since all the position within the grid is considered as at the centre of the grid by the EMR position detection system and the chance of the pen located is evenly distributed on the whole board, hence the error distribution of the system is the variance of the distance at any point in the grid to the centre of the grid which is a uniform distribution, and the measurement noise covariance in each axis, $R_{MPS,\,i}$ can be computed as follows:

$$R_{EMR,i} = \int_{-b}^{b} s^2 ds = \frac{2b^3}{3} \quad (9)$$

Since the position measurement in each axis is independent with each other, therefore the EMR motion detection board measurement noise covariance (R_{EMR}) is defined as follows:

$$R_{EMR} = \begin{bmatrix} R_{EMR,x} & 0 \\ 0 & R_{EMR,y} \end{bmatrix} \quad (10)$$

6) Initialization: After defining all the parameters required in the Kalman filtering algorithm, we initialize the state estimate vector $\hat{x}_0$ and error covariance matrix filter P_0.

$$\hat{x}_0 = [0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]^T \quad (11)$$

$$P_0 = I_9 \quad (12)$$

where I_9 is the 9×9 identity matrix.

7) Time Update: The time update process is used to propagate the state estimate and error covariance based on the estimation at the previous time instant *k-1*.

$$\hat{x}_k^- = A\hat{x}_{k-1} \quad (13)$$

$$P_k^- = AP_{k-1}A^T + Q \quad (14)$$

where the minus sign (-) superscript represents the a priori estimation; meanwhile the estimation without the minus sign superscript represents the a posteriori estimate, and the subscript k represents the estimation is at time instant k.

8) μIMU Measurement Update: With the presence of the μIMU measurement, we can correct the state and error covariance estimation with its current acceleration measurement input $y_{IMU,k}$ through Kalman gain for μIMU measurement ($K_{IMU,k}$).

$$y_{IMU,k} = [a_x \quad a_y \quad a_z]^T \quad (15)$$

$$K_{IMU,k} = \frac{P_k^- H_{IMU}^T}{H_{IMU} P_k^- H_{IMU}^T + R_{IMU}} \quad (16)$$

$$\hat{x}_k = \hat{x}_k^- + K_{IMU,k}\left(y_{IMU,k} - H_{IMU}\hat{x}_k^-\right) \quad (17)$$

$$P_k = \left(I_9 - K_{IMU,k}H_{IMU}\right)P_k^- \quad (18)$$

9) EMR Motion Detection Board Measurement Update: With the presence of the EMR motion detection board measurement, we can correct the state and error covariance estimation with its current position measurement input $y_{EMR,k}$ through Kalman gain for EMR motion detection board measurement ($K_{EMR,k}$).

$$y_{EMR,k} = [s_x \quad s_y]^T \quad (19)$$

$$K_{EMR,k} = \frac{P_k^- H_{EMR}^T}{H_{EMR} P_k^- H_{EMR}^T + R_{EMR}} \quad (20)$$

$$\hat{x}_k = \hat{x}_k^- + K_{EMR,k}\left(y_{EMR,k} - H_{EMR}\hat{x}_k^-\right) \quad (21)$$

$$P_k = \left(I_9 - K_{EMR,k}C_{EMR}\right)P_k^- \quad (22)$$

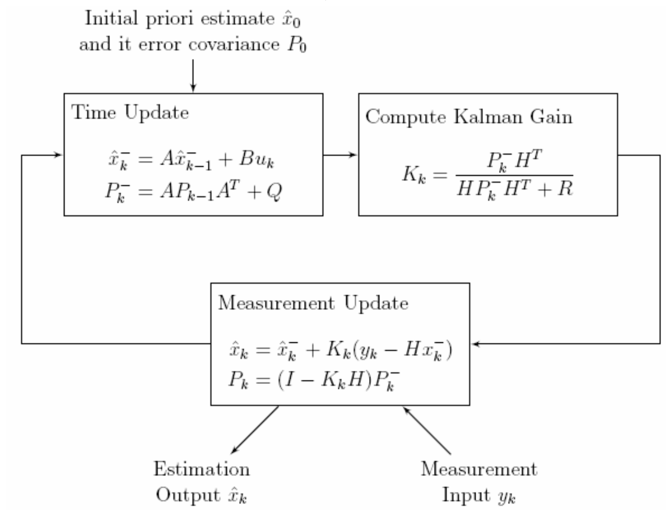


Fig. 6 The Kalman Filtering Algorithm

C. *Synchronization*

Since the measurements from μIMU and EMR motion detection board are separated in the system, a synchronization process should be performed before navigation tracking. We assume that the transmission interval between two sets of data from sensors board are equal, meaning that the transmission intervals in μIMU and the motion detection board are fixed to 200 Hz and 40 Hz receptively. Since we receive the data from sensors board in a block of multiple samples, we use the machine clock of the host computer to record the initial data and final data reception time, and then label data from both μIMU and EMR motion detection board with a timestamp. After that, we sort the two data sequences according to the timestamp and compute the position estimate with ordered data.

IV. Experimental Results and Discussion

In order to investigate the feasibility of the combined scheme, we tested the complete system by writing a letter "A" as shown in Fig. 7 with our new algorithm. In Fig. 9, the dotted line represents the position estimated by the integration from the raw data; meanwhile, the dashed line represents the position information collected by EMR motion detection board, and the solid line represents the position estimated by the combined EMR/μIMU scheme. The EMR motion detection board cannot provide high resolution pen position information as accuracy is limited to a grid separation distance of 3 cm. With the help of the μIMU, improved results are obtained. Compared to the result obtained by the conventional Kalman filtering algorithm, the drift in position has been removed and the position estimate error is bounded in the new algorithm. When we compare the original trajectory with the reproduced one, which is shown in Fig. 8 more clearly, we can prove that the position estimation followed what we have written and did not drift away with time.

V. Conclusion

In this paper, we have demonstrated a novel position estimation technique which is based on the µIMU/EMR motion detection board coupled system. This approach can improve the position estimation from the µIMU by combining a low resolution absolute position reading from the EMR board with detailed but noisy information from the µIMU. An experimental result is also given to demonstrate the feasibility of the idea.

Acknowledgment

We owe gratitude to the Hong Kong Innovation and Technology Commission (ITF-UIM-151) and DAKA Development Ltd. for sponsoring this project.

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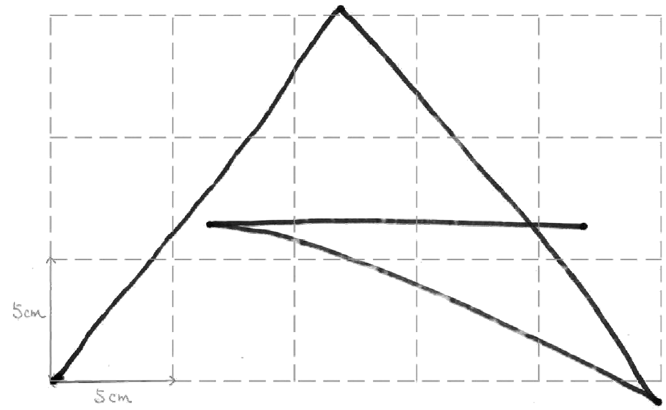

Fig. 7 The actual "A" written in the experiment.

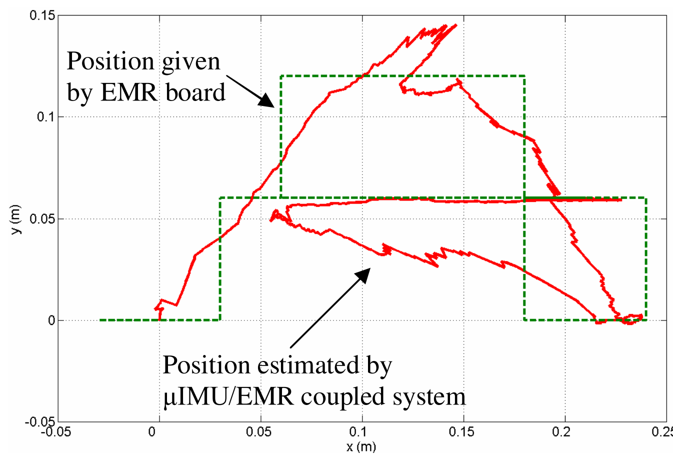

Fig. 8 "A" reproduced by µIMU/EMR motion detection board coupled system

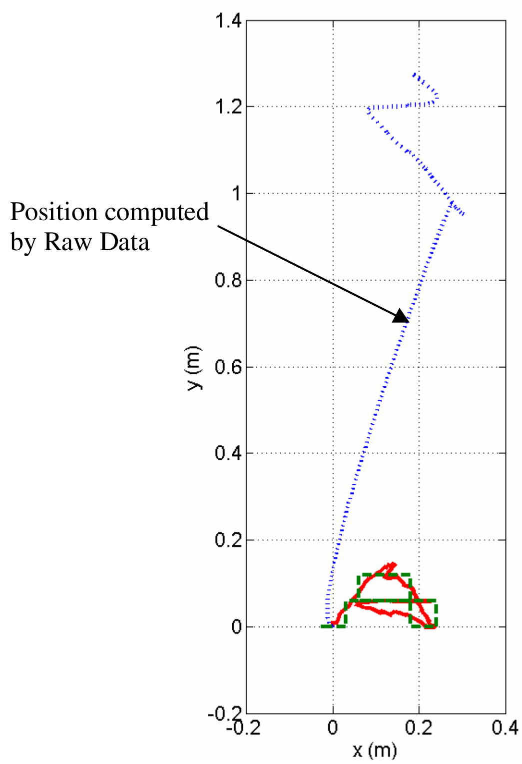

Fig. 9 A Comparison of new algorithm with integration from the raw data