An Optical-Tracking Calibration Method for MEMS-Based Digital Writing Instrument

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An Optical-Tracking Calibration Method for MEMS-Based Digital Writing Instrument

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***Abstract*—A μIMU which consists of microelectromechanical systems (MEMS) accelerometers, gyroscopes and magnetometers has been developed for real-time estimation of human hand motions. Along with appropriate transformation and filtering algorithms, the μIMU was implemented as a Ubiquitous Digital Writing Instrument (UDWI), which could interface with PCs in real-time via Bluetooth wireless protocol, to record the handwriting on any flat surface. However, because of the MEMS sensors' intrinsic biases and random noise such as circuit thermal noise, an effective calibration system that provides good reference measurement parameters must be developed to compare the output of the μIMU sensors to human hand motions. In this paper, we present our development of a method to calibrate three-dimensional linear accelerations and angular velocities of human writing motions measured from MEMS sensors through optical tracking techniques. In our experiments, English alphabets were written by the UDWI on a horizontal plane. The sensor output from the writing motions were transmitted wirelessly to a PC and the data were stored in the PC. Simultaneously, we recorded the pen-tip motion during the writing of each alphabet with a high-speed camera, which allowed us to exact the acceleration, velocity, and position of the UDWI's tip through appropriate optical-tracking algorithms. Then, the information is compared with the motion information obtained from the MEMS sensors in the UDWI. The motion data obtained from the high-speed camera are much more accurate, and hence could be used as reference motion data to analyze the performance of the UDWI, and eventually allows improvement of the UDWI performance.**

***Index Terms*—μIMU, accelerometer, block matching, digital writing system, microelectromechanical systems (MEMS), optical tracking.**

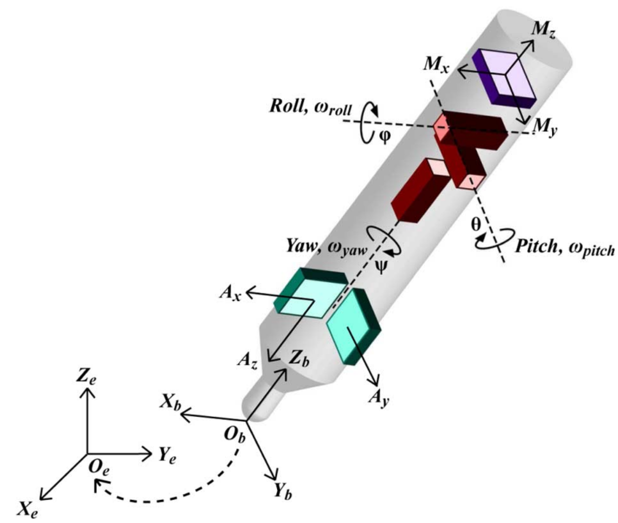

Fig. 1. Coordinate frames of the UDWI.

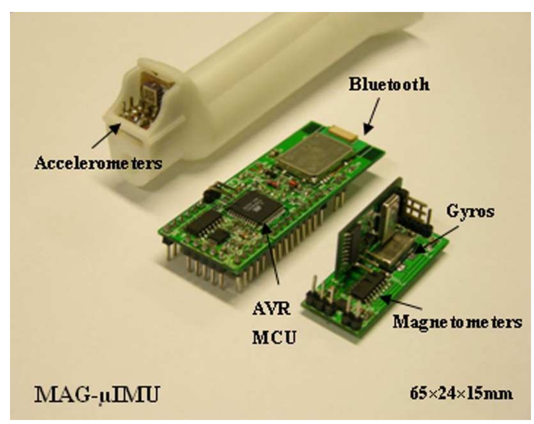

Fig. 2. Major components of the UDWI: μIMU with Bluetooth Module.

I. Introduction

An Ubiquitous Digital Writing Instrument (UDWI) has been developed by our group to capture and record human handwriting or drawing motions in real-time based on a MEMS Inertial Measurement Unit (μIMU) (see Figs. 1 and 2) [1]. Fig. 3 illustrates the system block diagram of the μIMU with a real-time position tracking software that is hosted on a PC. The μIMU is integrated with a Bluetooth wireless subsystem to transmit the MEMS motion sensors output in real-time to a PC host, i.e., the integrated system could be used as a wireless digital writing instrument and to record human handwritings in real-time. The μIMU consists of 3D accelerometers and 3D gyroscopes with strap-down 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 $[\omega_{\mathrm{roll}}, \omega_{\mathrm{pitch}}, \omega_{\mathrm{yaw}}]$, are the body frame accelerations in three-axes and the angular rates, roll, pitch, yaw, respectively. These output signals are collected with an

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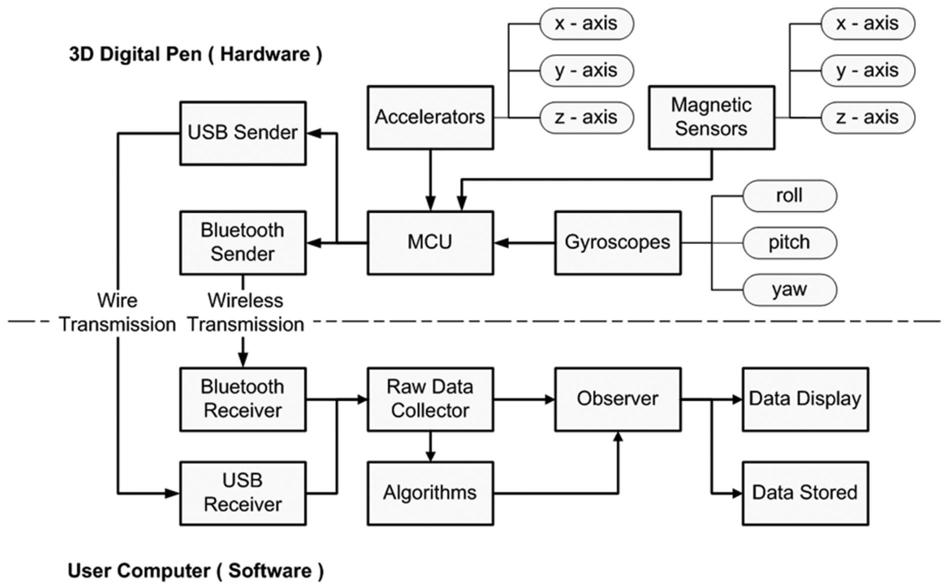


Fig. 3. System architecture of the 3D digital writing system.

Atmega32L A/D converter. 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 Kb/s, which ensures rapid reaction to human handwriting. Our objective is to implement this system into an application for interfacing with PCs and other mobile computing devices. Additionally, we believe this kind of system could be a competitive candidate for other consumer electronics applications, such as an advanced remote controller for digital LCD TVs. Although both the hardware and software of the UDWI have been steadily improved over time [2], [3], noise signal can still exist to affect the UDWI system output. The noise may include the intrinsic drift of the sensors, misalignment of the sensors during PCB integration, and random noise, which are impossible to totally eliminate. Hence, in reality, we have to compensate the sensor drift after a handwriting stroke is completed, which would lead to a delay during real-time handwriting recognition. However, if a real-time error model is available in advance, a more effective compensation algorithm could be developed to overcome the drift.

For conventional navigation inertial measurement units (IMU), the calibration could be done through mechanical motion platforms, i.e., turning the IMU into different precisely controlled orientations and at known rotational velocities [4]–[6]. At each orientation the output of the accelerometers and gyros during the rotations are observed and compared with the precalculated gravity force and rotational velocity, respectively. However, the cost of the mechanical platform can exceed by many times the cost of developing and constructing a MEMS sensor-based inertial measurement unit. Furthermore, the current motorized motion stages do not have enough degrees of freedom to emulate the motion of human handwriting motions in spite of being able to provide high positional accuracy. At last, most of these motion stages can only implement small accelerations while the majority of human handwriting motions are made up of larger accelerations. Although our group had attempted to use conventional X-Y motion stages and Z axis rotational stage to provide translation and rotational input for the MEMS sensors, the experiments failed to produce consistent results due to the limited accelerations producible by the motion and rotational stages. Thus, we have developed an optical-tracking-based system to measure and collect the inertial information of handwriting motions, which could then be used to calibrate the MEMS sensors. We should note here that others have also developed similar techniques to calibrate inertial navigation systems (e.g., see [7]), so the concept discussed in this paper is not entirely new. However, to the best of our knowledge, we have developed the first optical-tracking system for the purpose of calibrating MEMS sensors used for measuring human handwriting motions.

Many matching algorithms and techniques have already been developed for motion estimation with video compression aid, e.g., Three Step Search (TSS) [8], Four Step Search (FSS) [9], and Parallel Full Search (PFS) [10]. Also, there are several kinds of matching criteria, e.g., Correlation Coefficient (CC), Block Distortion Measure (BDM) [11], and Mean Absolute Difference (MAD) [10]. All of these methods are matured and reliable enough to implement the estimation of motion vectors through video sequences. In our experiment, we initially adopted PFS together with CC as the criteria to set up a matching system. This is a widely used method, which is most stable and convenient to realize. The disadvantage of this method is that it needs more computational time. However, longer computational time is not a problem for our experimental goal because we only need to use the optical-tracking system to measure hand motions offline, and need not to perform the computations in real-time.

We have also later improved some functional aspects of the matching system based on the above algorithm, including image smoothing and threshold alternative processing, and free definition of the searching area. Since the displacement between two neighboring points of a picture sequence is very small owing to the high sampling rate we have set, this improvement enhances both the efficiency and accuracy of the matching system.

At last, all the 26 English letters in lower-case were written by the UDWI while a high-speed camera captured all the motions. Through the comparison of the motion information recorded by the accelerometers and the image sequence, the optical tracking system can provide us with a relatively more accurate reference to calibrate the accelerometers in the future application. Additionally, single letter multiple writing experiments were also carried out to test whether the accelerometers could output consistently when we use the UWDI to write the same character.

This paper is organized as follows. In Section II, the optical tracking technique is discussed in detail, followed by a description of the hardware system in Section III. Section IV discusses the experimental results obtained from this optical tracking system, including comparisons between its output and the sensor output from the UDWI for all 26 English alphabets. Finally, a conclusion to summarize this paper and our major findings is presented in Section V.

II. The Optical Tracking Technique

The technique employed in our system mainly consists of two components: (1) the matching algorithm, which is operated in Microsoft Visual C++ environment; (2) the calculation of motion vectors, which runs in MATLAB to convert the position into velocity and acceleration. Thus, combining these two parts makes it possible to obtain optically tracked motion data which were then compared with the UDWI's MEMS sensor output.

A. Matching Algorithm

When a writing motion is captured and output as a picture sequence, every pixel in each image can be distinguished from its gray value ranged from 0 to 255. In the program, a template was defined in a rectangular area including the pen-tip according to its position. The upper-left corner's position was recorded as the position of the template. Then the calculation of the sum of gray values is as follows:

$$\sigma_T = \sum_{n=v}^{T_H+v-1} \sum_{m=u}^{T_W+u-1} (Xt(m,n))^2 \tag{1}$$

where u and v are the coordinates of the upper-left corner; m and n are the coordinates of each pixel enclosed by the template in horizontal and vertical directions, respectively; Xt is the gray value and T_H and T_W are the height and width of the template, respectively. δ_T is the sum of gray values squared of the template.

Thus, the whole picture was searched block by block, i.e.,

$$\sigma_S = \sum_{n=j}^{T_H+j-1} \sum_{m=i}^{T_W+i-1} (Xs(m,n))^2 \tag{2}$$

where m and n are the coordinates of each pixel of a block in horizontal and vertical directions, respectively; j and i are the pixel coordinates of the first point. They vary from 0 to $(P_W - T_W)$ and $(P_H - T_H)$, respectively, where P_W is the width and P_H is the height of the picture. $(P_W - T_W + 1)^*(P_H - T_H + 1)$ of blocks were calculated all over the picture.

The classical theory of finding a correlation coefficient could be presented as the following:

$$\rho_{xy} = \frac{\mathrm{Cov}(X,Y)}{\sqrt{D(X)}\cdot\sqrt{D(Y)}} = \frac{\sum_{i=1}^{n}\left(X_i-\overline{X}\right)\cdot\left(Y_i-\overline{Y}\right)}{\sqrt{\sum_{i=1}^{n}\left(X_i-\overline{X}\right)^2}\cdot\sqrt{\sum_{i=1}^{n}\left(Y_i-\overline{Y}\right)^2}} \tag{3}$$

where X, Y are two group variables, $\mathrm{Cov}(X,Y)$ presents the covariance between X and $Y; D(X)$ and $D(Y)$ are the variances, respectively, of X and Y. In the above equation, ρ_{xy} should be a value within $[0 \quad 1]$. In the algorithm, the two variables are the sum of gray values of the pixels in the template and the searched block

$$\sigma_{ST} = \sum_{n=j}^{T_H+j-1} \sum_{m=i}^{T_W+i-1} Xt(u+m-i, v+n-j)\cdot Xs(m,n) \tag{4}$$

where δ_{ST} is the covariance. So the correlation coefficient can be calculated as follows:

$$\rho = \frac{\sigma_{ST}}{\sqrt{\sigma_S \cdot \sigma_T}} \tag{5}$$

Comparisons were done among these ρ's, and the block which has the greatest ρ was determined. We considered this block as the correct place where the pen-tip moved to and we described the location of the block also with its upper-left corner. Then, the estimation about the motion vector could be implemented. Through experiments, this matching algorithm is proved very helpful in reconstructing correct handwritten characters based on those found blocks. Fig. 4 illustrates a comparison between an a written on top of the transparent table and the reconstructed one, which look very the same.

B. Calculation of Motion Vectors

If we keep the relative position and orientation consistent between the camera and table, and also the focus of the camera, the proportional parameter K between the pixels distance and physical distance will be a constant

$$\begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix} \cong \frac{K}{\Delta t}\begin{bmatrix} u_{n+1}-u_n \\ v_{n+1}-v_n \\ 0 \end{bmatrix} \tag{6}$$

$$\begin{bmatrix} acc_x \\ acc_x \\ acc_z \end{bmatrix} \cong \frac{1}{\Delta t}\begin{bmatrix} V_{xn+1}-V_{xn} \\ V_{yn+1}-V_{yn} \\ g\cdot\Delta t \end{bmatrix} \tag{7}$$

where u_{n+1} and v_{n+1} are the pixel coordinates results in the final found block (see Fig. 5); u_n and v_n represent the position of the source block; Δt depends on the sampling frequency of the camera, i.e., $\Delta t = 1/f$. Equation (7) is guaranteed only if the motion plane is absolutely horizontal. Otherwise, the gravity g will take effects on the results of the 2D calculated accelerations.

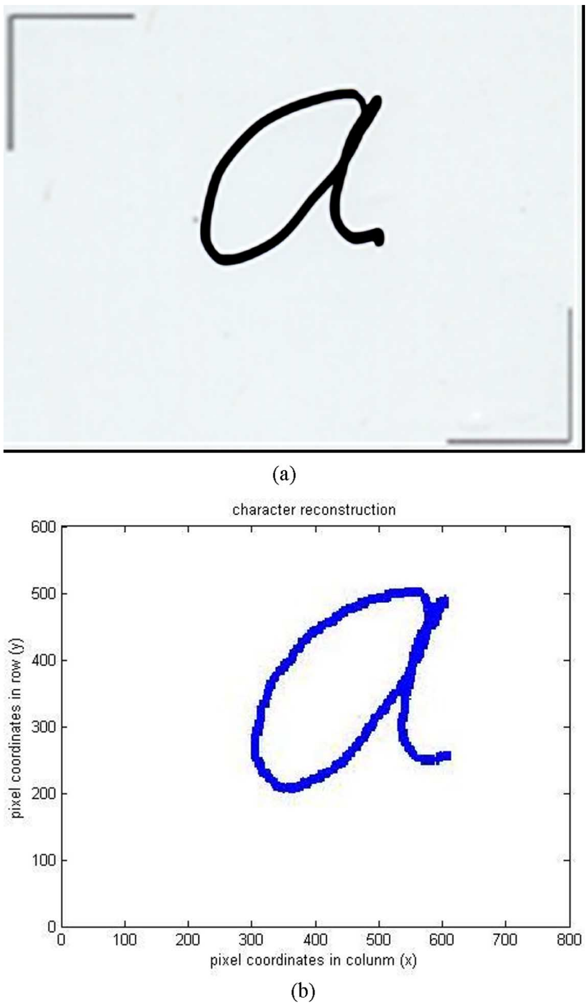


Fig. 4. Character comparison: (a) the written one and (b) the reconstructed one.

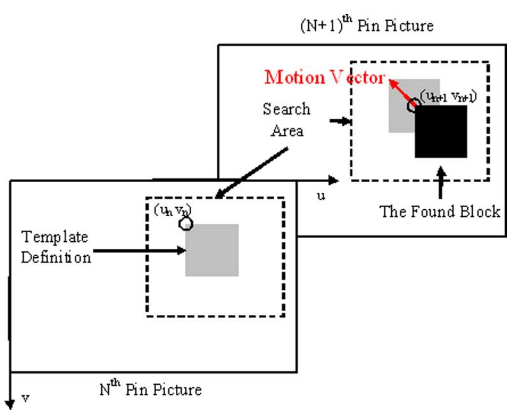


Fig. 5. Estimation of motion vector between two neighboring points.

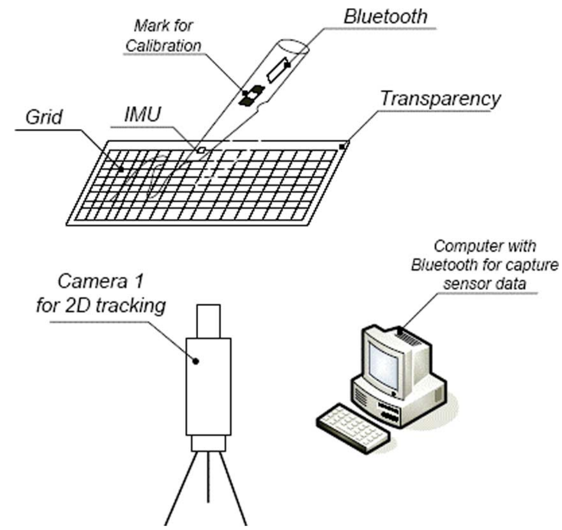


Fig. 6. Schematic of the 2D optical tracking system.

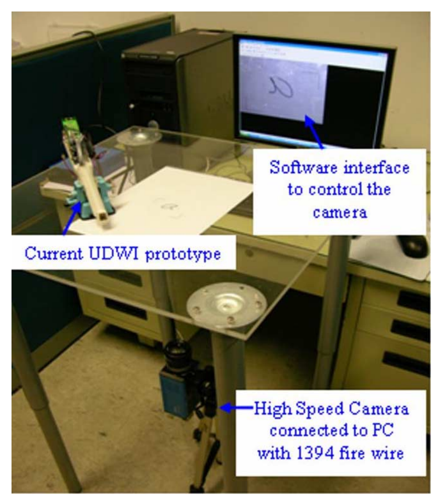


Fig. 7. Experimental setup of the 2D optical tracking system.

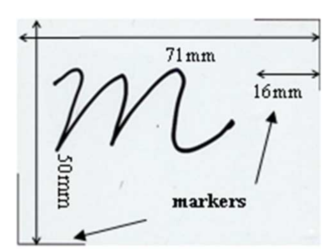


Fig. 8. Transparency with paper as the background for writing.

III. Experimental Setup

A. The Transparent Writing Table

In order to obtain a clear view of the entire motion of a pen-tip while writing characters, a camera is positioned directly below an optically transparent plexiglass. We constructed the plexiglass table on top of height-adjustable legs, which give it a maximum height of 1000 mm. By using these components, a 2D optical tracking system, as shown in Figs. 6 and 7, was constructed. In addition to this table, a transparency with predetermined markers is also necessary to carry out the experiments. The predetermined markers, as shown in Fig. 8, bring two advantages to our experiments. One is that the length of the markers is a constant (i.e., 16 mm), which helps us determine the proportional parameter between pixel and millimeter when we obtain the pixel information of the two pole points of the markers. The other advantage is to help define a writing area which can be observed completely by the camera system, i.e.,

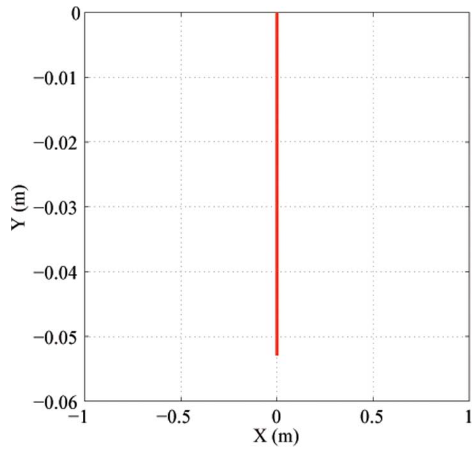
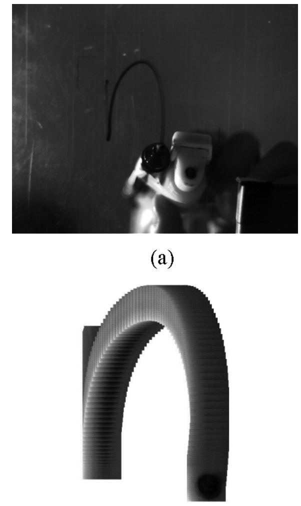


Fig. 9. A reconstructed line using the matching algorithm.



(a)

(b)

Fig. 10. Letter "n" from experiment: (a) the written one and (b) the reconstructed one consisting of each found block.

the size of the written characters should be contained in a border of 71 mm $\times$ 50 mm in our system.

B. Usage of High-Speed Camera

The multiple functions of the image sensors in the PCO camera system [12] have proved very convenient as we could capture images both in black-&-white and color formats easily. However, the most important aspect of the camera system is its sampling rate. Since the μIMU is set at a rate of 200 Hz to capture MEMS sensor data, the optical tracking system should capture picture sequences at the same rate in order to synchronize with the MEMS sensor data. Fortunately, the PCO camera has a maximum sampling frequency of 1000 Hz (we have set the system's exposure time to 0.005 second, i.e., 200 Hz, during the experiments).

IV. Results

A. Calculation of Proportional Parameter

An important function of the markers on the transparency, besides defining the writing area, is to calculate the proportional parameter K in (6), which is necessary for the transformation between pixel units and physical length units. Thus, the parameter K could be determined before the calculation of displacement, velocity and acceleration from the optical tracking system in order to unify their units with the MEMS sensors output.

B. Accuracy of Character Track Reconstruction

In order to quantify the accuracy and reliability of the tracking reconstruction based on our matching system, a test was performed on drawing a straight line. In the test, we first drew a straight line with a ruler, which provides a reference length for comparison. Then, the length of this line was obtained from the vision system. Finally, a comparison was made between the actual line length and the length read by the optical tracking system. Note here that using the method described in Section II, the proportional parameter K is determined to be $\sim 1.16e-4$ meter per pixel, which allows us to use our matching algorithm to reconstruct this line and determine its length. Fig. 9 shows the reconstructed line through the improved matching algorithm. The unit here was transformed into meters owing to K. In addition, we had set the beginning point as the origin so the initial point was at (0 0) and the end point was at $(0 - 0.05294)$. Consequently, the length of this image-reconstructed line was 52.94 mm. Compared with the length measured by the ruler (53 mm), the difference was 0.06 mm, i.e., about 0.11%.

C. Alphabet Writing Experiments

As discussed earlier, in order to analyze the drifts of the MEMS inertial sensors, writing experiments were carried out on top of the optical tracking system. All 26 letters of the English alphabet were written in lower-case with the UDWI. During the motion of writing each letter, the attitude of the pen was kept consistent as much as possible and every letter was finished in a single stroke. Hence, two independent groups of motion data were collected in each test, i.e., MEMS sensors output (from the UDWI) and the optical tracking output. In view of the limits of word-length for this paper, only one sample of experimental results (letter n) will be discussed in detail in this section. All the curves for velocity and acceleration in the comparisons below consist of discrete points (the number of points depends on the time required to write the letter), and the time interval between two neighboring points is 5 ms. Using the described matching algorithm, we obtained the positions of the pen tip while it moves on the transparency on top of the transparent table during a handwriting motion. According to these position coordinates obtained after matching, we first reconstructed the written character and compared it with the original character wrote on the transparency. As shown in Fig. 10, it is clear that the two characters are similar enough to prove the position information would be reliable to carry out the calculation of velocity and acceleration. The reconstructed letter n was made up of 215 blocks, which means the duration of the writing motion was about 1.075 s.

Owing to the MEMS sensors' intrinsic drift when measuring acceleration, the calculated data for velocity and position (after appropriate integrations) have large errors from their true

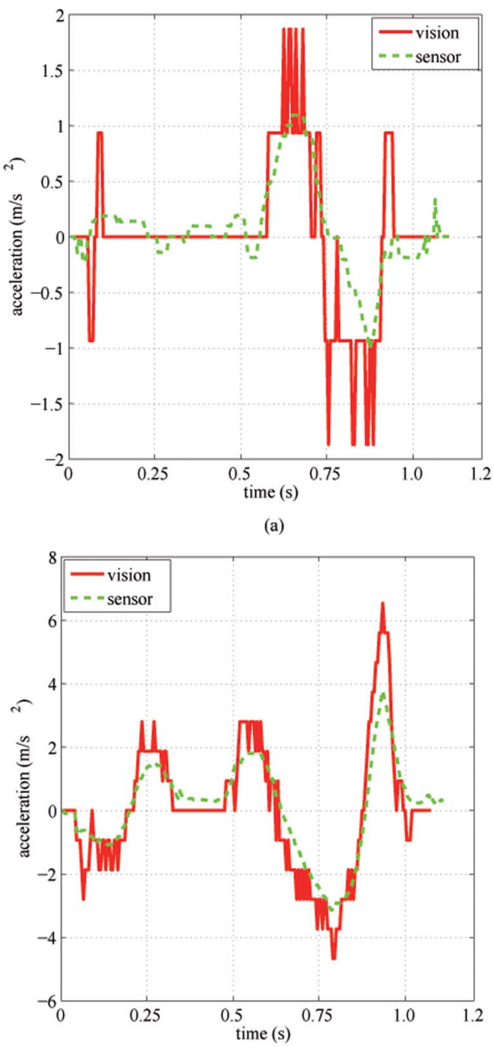


Fig. 11. Comparison of accelerations in writing the letter "n": (a) in x axis and (b) in y axis.

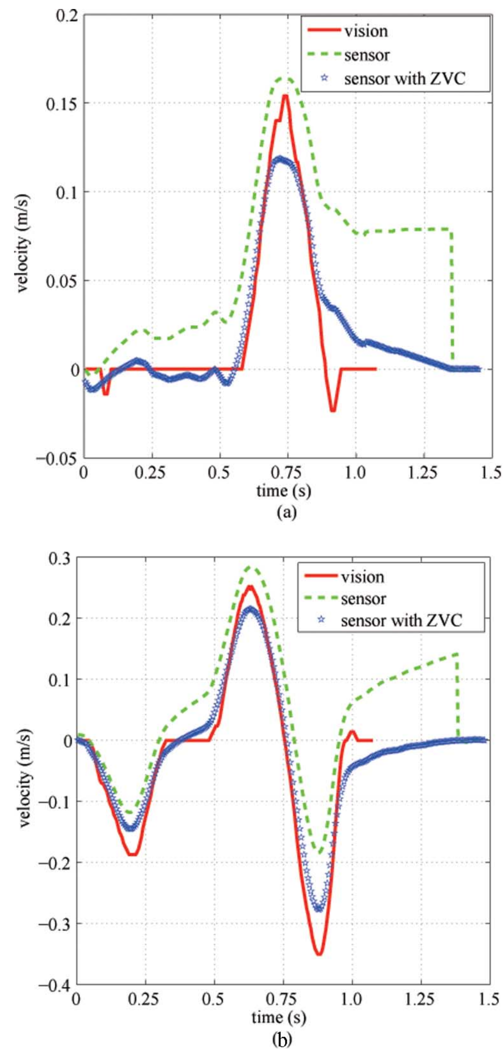


Fig. 12. Comparison of velocities in writing the letter "n": (a) in x axis and (b) in y axis.

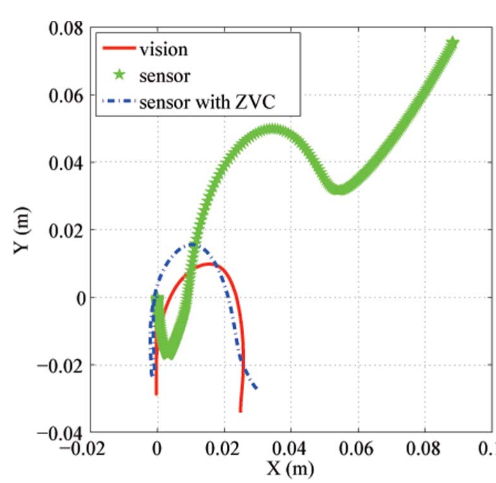


Fig. 13. Comparison of reconstructed letter "n" with optical tracking, MEMS sensors, and MEMS sensors with ZVC correction.

values, and hence, MEMS sensor data could not be used to reconstruct handwritten letters directly. We have implemented the Zero Velocity Compensation (ZVC) algorithm [13] to process the MEMS sensor data, which proves to be effective in achieving better velocity and position tracking of handwriting motions. Fig. 11 illustrates the comparisons of the acceleration between the raw data of the MEMS accelerometers and the calculated data from the optical tracking system. While, in the comparisons shown in Figs. 12 and 13, the processed data using ZVC are also shown. From Fig. 12, the sensor drift clearly existed in the raw data. However, the curve processed with the ZVC algorithm overcame this drawback significantly in both axes. Hence, a much better result could be obtained, which gave more similar velocity information to the results obtained from the optical tracking system. Naturally, as shown in Fig. 13, the letter n after ZVC processing looked much better than the one without it because a more accurate velocity profile is used to obtain position profile through integration. However, we should note here that, from our experiments, not all the letters could be clearly reconstructed based on the MEMS sensor output even with ZVC implementation. This problem will be discussed in Section IV-D.

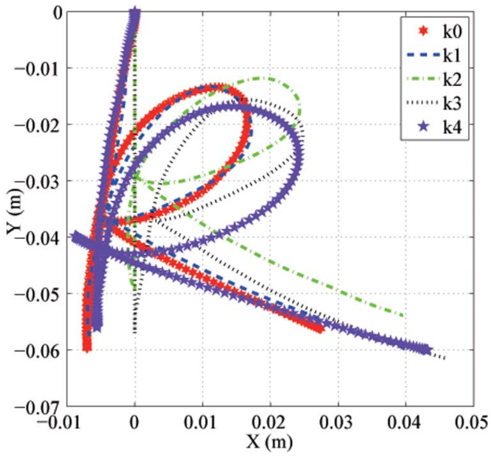


Fig. 14. Letter "k" from optical tracking system and matching algorithm.

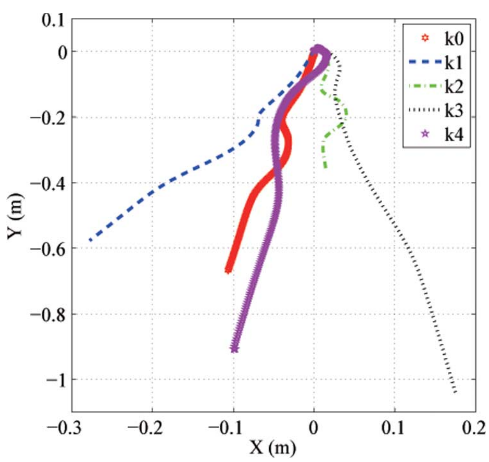


Fig. 15. Tracks of letter "k" from MEMS sensors' raw data.

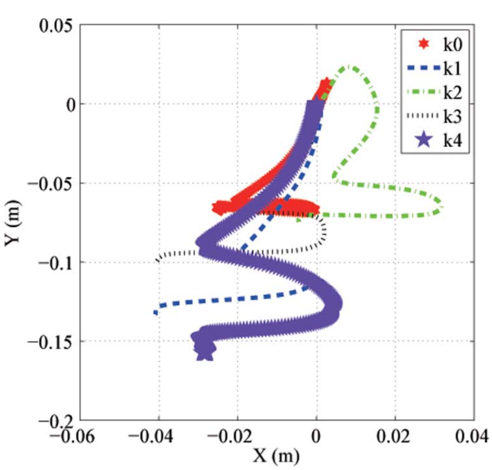


Fig. 16. Tracks of letter "k" from MEMS sensors' raw data processed with ZVC.

D. Multiple Tests of a Single Letter

To test the stability and repeatability of the MEMS sensors, the letter k was written five times. The attitude of the pen was kept as consistent as possible during each stroke. Fig. 14 illustrates all the reconstructed tracks through the optical tracking system. Fig. 15 shows the final results of the MEMS sensor output raw data and Fig. 16 shows those processed with ZVC algorithm. As mentioned earlier, for the letter k, even after ZVC compensation, the MEMS sensors could not give satisfactory position tracking results, i.e., the letter k is unrecognizable in Fig. 16. As a reference, the results from all of the alphabets (except for n and k, which were shown in Figs. 13 and 14 already) are provided in Fig. 17.

From the results of experiments performed on different alphabet letters as described above, we note here the major changes in using MEMS sensors to directly record human handwriting motions. From the Fig. 15, we can conclude that in general MEMS sensors output are not stable enough to reconstruct consistent results even though the input handwriting motions are very similar. Sometimes, even with the implementation of ZVC compensation, the sensor signals would still not be stable enough to represent the alphabet letters clearly. In addition, a fixed (or known) attitude of the writing instrument is necessary to produce accurate tracking results.

E. Resolution of the Optical Tracking Algorithm

Discussed below is the process we have used in estimating the measurement resolution of the optical tracking algorithm. As mentioned earlier, the optical tracking algorithm is used to eventually calculate 2D velocity and acceleration of a pen-tip. The algorithm includes two parts: (1) the matching algorithm which gives the position information of the pen-tip from the image sequence; (2) the other is the calculation of velocities and accelerations based on the previously obtained position information. For (1), the minimum measurement resolution is theoretically one camera pixel length. However, due to the high sampling rate used during our experiments, some pen-tip points between consecutive picture frames may appear to have very small movements. Consequently, the matching algorithm may incorrectly regard these pen-tip points as being stationary over several frames, thereby causing the results of velocity and acceleration calculations to be in accurate, i.e., errors in part (2) of the algorithm. To reduce the tracking errors caused by this problem, a simple filter was added to deal with the position information before velocity calculation. The concept of this filter is to average the image coordinates of five neighboring points and brings the averaged value as the coordinate of the middle point into the latter calculation as shown in the following equation:

$$x(i) = \frac{u(i-2) + u(i-1) + u(i) + u(i+1) + u(i+2)}{5} \tag{8}$$

where x_i is the averaged position coordinate of the ith point and u is the coordinate which can be read from block matching. Hence, the minimum measurement unit is reduced by 4/5 at most, i.e., 0.2 pixel by this filter. Then, the equation below is used for calculating the velocity

$$v_n = \frac{K \cdot (x_{n+1} - x_n)}{\Delta t} \tag{9}$$

where v_n is the magnitude of velocity; Δt is the frame sequence time interval (5 ms). The parameter K is the transformation parameter used to map pixel length to actual distance and was discussed earlier in this paper. It was empirically determined from many experiments and averaged to be $\sim 1.14 \times 10^{-4}$ meter/pixel. Finally, we conclude that the minimum resolution of displacement, velocity and acceleration are equal to

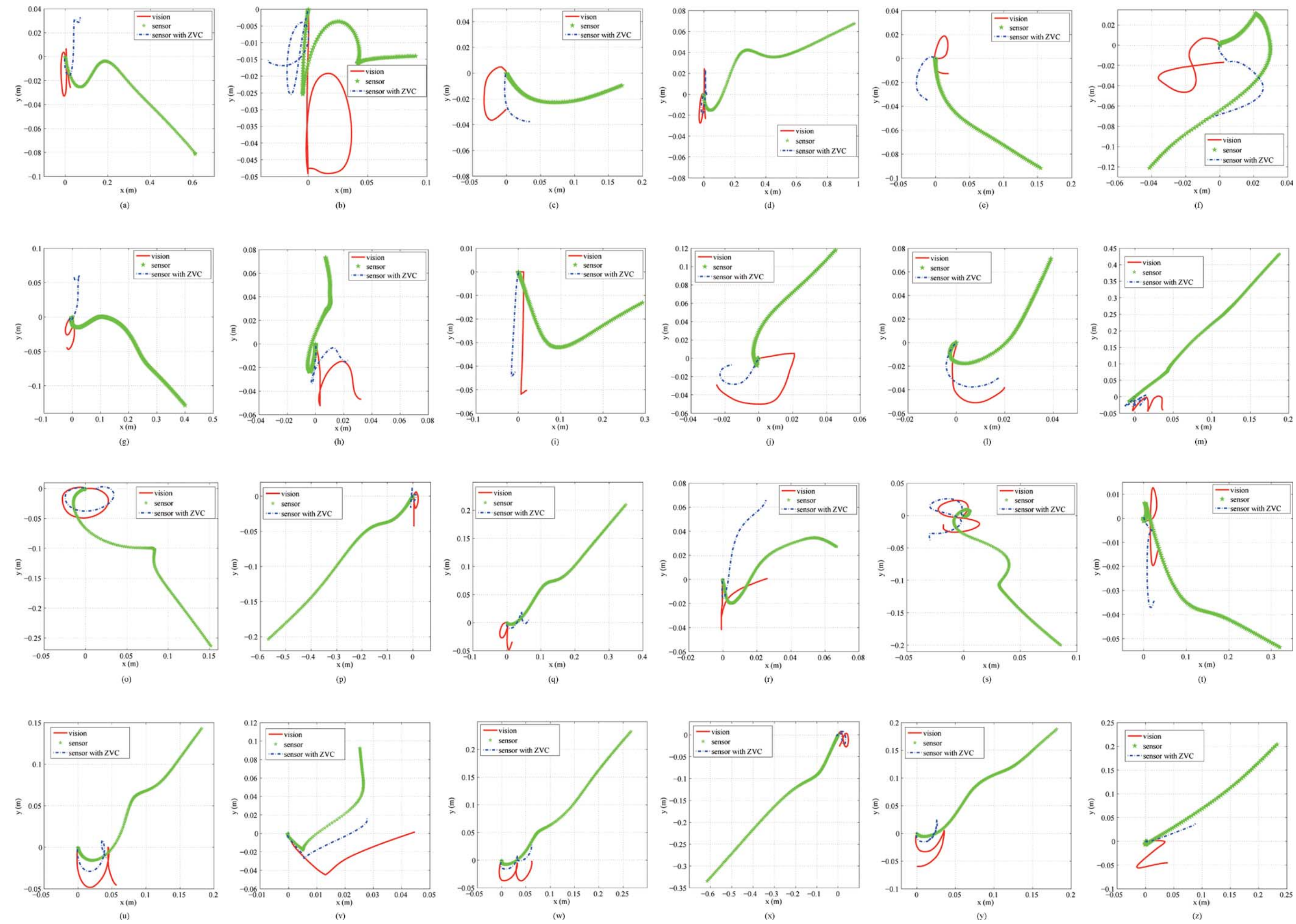


Fig. 17. Reconstructed English alphabets using the optical tracking and MEMS-based sensing system described in this paper (except for "n" and "k," which were shown in Figs. 13–16).

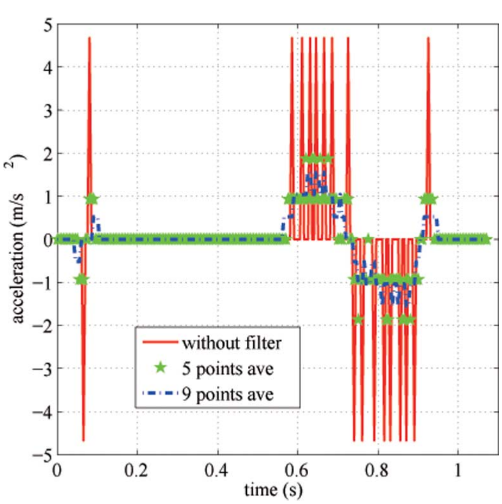


Fig. 18. Curves of accelerations in x direction with different filters.

$2.23\ \times 10^{-5}\ \mathrm{m}$, $4.58\ \times 10^{-3}\ \mathrm{m/s}$ and $9.15\ \times 10^{-5}\ \mathrm{m/s}^2$, respectively.

We note there that the "multiple-point-average" filter described above is very effective in smoothing the curves of calculated velocities and accelerations. Fig. 18 shows an example of comparing calculated acceleration in the x direction of letter n.

V. Conclusion

This paper presents the complete design of an optical tracking system for calibrating the MEMS accelerometers used in an Ubiquitous Digital Writing Instrument (UDWI) that intends to digitally record human handwritings on any flat surface in real-time. An optically transparent table with adjustable height was built to capture and record the pen-tip motions of the UDWI using a high-speed camera positioned underneath the table. Based on the image sequence captured by the camera of the UDWI's tip motion, we developed algorithms to calculate the tip's position, velocity, and acceleration as a function of time. The inertial information was then compared with the acceleration, velocity, and position information captured by the UDWI's MEMS sensors. Hence, the accuracy of the MEMS sensors' output can be directly quantified, as the optical tracking method are known to be much more accurate than the MEMS motion sensor-based tracking method. Through the comparisons between the optical results and MEMS sensors output, it is found that, as expected, the sensor drift is a significant problem when we integrate the MEMS-sensor-measured accelerations to obtain the velocities and displacements. However, we have shown that the ZVC algorithm could be used to improve the MEMS sensor out results, but the results are still significantly worse than the results from the optical tracking technique described in this paper. All 26 English alphabets in lowercase have been written on the transparent table and were analyzed in terms of the position, velocity, and acceleration versus of their writing strokes. From these experiments, we have proved that the most dependable motion information such as displacement, velocity and acceleration, can be obtained through the optical tracking system described in this paper. Hence, we can now use this system to calibrate and compare MEMS accelerometer output from human handwriting motions.

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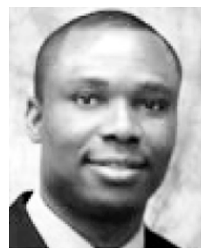

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