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Calibration of MEMS Accelerometer Based on Plane Optical Tracking Technique and Measurements

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Abstract— A MAG-µIMU which is based on MEMS accelerometers, gyroscopes and magnetometers has been developed for real-time estimation of human hand motions. Appropriate filtering, transformation and sensor fusion techniques are combined in the Ubiquitous Digital Writing Instrument (UDWI) to record the handwriting on any surface. However, because of the sensors' intrinsic biases and random noise such as circuit thermal noise, a calibration system that provides good reference measurement parameters must be used to compare the output of the MAG-µIMU sensors. In our previous work, a novel idea to calibrate three-dimensional linear accelerations, angular velocities and space attitude through optical tracking techniques had been proposed and proved. In this paper, we will introduce the latest progress in calibrating the accelerometers. In the experiments, the entire English alphabet has been written down by UDWI and these hand-writing motions are recorded by a high speed camera with the same sampling rate as the microcontroller. Then by dividing each image sequence into single frame, the blocking matching algorithm can help us get position information, based on which another group of velocity and acceleration are able to be obtained to compare with the sensor output to calibrate. From the comparison, we can find out how the sensor drifts during the integration. In addition, the consistency property of the sensors is also tested by analyzing a single letter written multiple times. At last, the resolution problem of the calculation of velocity and acceleration by the means of optical tracking measurement is discussed.

Index Terms— Calibration; MEMS; Digital Writing System; MAG-µIMU; Accelerometer; Optical Tracking

I. INTRODUCTION

A 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 Fig.1 and Fig.2) [1]. Although both the hardware and software of the UDWI have been gradually improved over the past year [2] [3], noise signal can still occur and 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 eliminate completely. Hence, in reality, we have to compensate the sensor drift after a hand-writing stroke is completed, which would lead to a delay during real-time hand-writing recognition. However, if a model is available for real-time errors in advance, a more effective compensation algorithm could be developed to overcome the drift.

Many matching algorithms and techniques have already been developed and used in the category of motion estimation with video compression aid. For example, there are Three Step Search (TSS) [5], Four Step Search (FSS) [6], and Parallel Full Search (PFS) [7]. Also, there are several kinds of matching criteria, e.g., Correlation Coefficient (CC), Block Distortion Measure (BDM) [4] and Mean Absolute Difference (MAD) [7]. All of these methods are mature and reliable to implement the estimation of motion vector through video sequences. In the previous experiment, we 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 time to calculate. However, it will not be a problem for our eventual goal because this calibration method needs not to work with a real-time system.
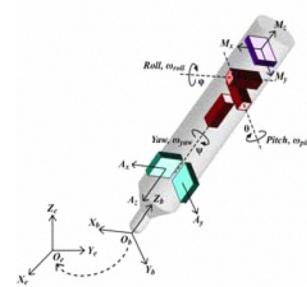

Figure 1. Coordinate frames of the UDWI
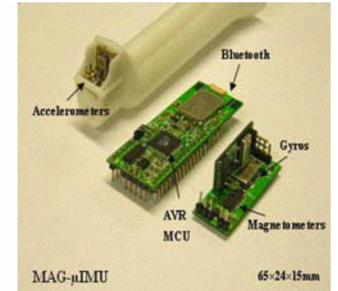
Figure 2. . Major components of the UDWI: MAG- µIMU with Bluetooth Module

By applying the above techniques, a good experimental platform had been developed already [1]. Even though its feasibility was proved, some functional aspects have been further improved based on the previous algorithm, including the image smooth or threshold alternative processing and the free definition of the searching area. In this case, both the accuracy and efficiency can be obviously improved. All the 26 English letters in lower-case were written by the UDWI while a high speed camera captured 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 writing experiments

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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 2, the new improvement of the Matching Algorithm is introduced, which makes the matching system more efficient. Then a test about the tracking reconstruction accuracy of the improved matching algorithm is presented in Section 3. The experimental results will be described in Section 4, where we also introduce the consistent property of the sensor output and present the resolution issue of the velocity and acceleration calculation based on the displacement information from the matching algorithm. Finally, we present conclusions and proposed future improvements in the end.

II. IMPROVEMENT IN MATCHING ALGORITHM

A. Review of Matching Algorithm

The concept is that, in a recorded video, the motion of a pen with μIMU sensors installed is registered while it is writing on a marked paper with a fixed gesture. The video can then be divided into sequential frames, and the frames are analyzed to calculate the position of any particular visible point in the pictures so that the motion track of the pen can be detected from these frames. Since the sampling frequencies of our IMU sensors are set at 200Hz, a high speed camera is needed to synchronize the video data to the sensors' output. The trajectory of the pen on the paper can be recorded on a paper with markers, from which the displacement of the pen-tip can be read out in pixel resolution. With the help of the markers, the length of which is known in advance, it is convenient to calculate the proportionality coefficient between pixel and physical unit. Hence, motion vectors can be estimated for the velocity and acceleration calculation of the pen-tip, which will be used to calibrate the IMU sensor since its motion is the same. In this course, the block matching algorithm [8] is the most important tool for us to deal with the sequential frames and furthermore to guarantee the displacement information of the pen-tip. Additionally, through the Bluetooth wireless technique, the output of the accelerometers installed in the pen-tip could be transmitted and received by a particular PC.

B. Improvement of Block Matching Algorithm

Owing to the drawbacks brought by PFS in our prior work, including the time wasting and the frequent failures in following along the whole sequential frames, some improvement has been added into it. Because of the high sample rate, the movement between two neighboring images is not obvious and significant. So searching the whole area to find the most similar block proves not that effective and takes a lot of extra time. Another few functions have been added into this algorithm, which provide an alternative between proportional model and constant model about the searching

range. In the first model, an area three times larger than the template user defines will be considered as the detected range; while for the constant model, a constant can be input in units of pixel, then the area enlarged by the constant from the template in the orientations of up, down, left and right will be the target. In addition, the image can also be dealt with the smooth function or the threshold function. The smooth function is the default in our current algorithm, which is used to filter some pixels working as a low-pass filter. The gray values of these very bright or dark points will be replaced by the averaged value of the points surrounding it. Hence, both the efficiency and the accuracy are increased through the new improvement, which is very meaningful for the coming quantities of experiments.

III. ACCURACY TEST OF RECONSTRUCTION

In order to ensure the accuracy and reliability of the tracking reconstruction based on our matching system, a test has been completed. 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 vision system. Note here that using the method introduced in the previously, the proportional parameter K is equal to 1.163575e-4 meter per pixel, which allows us to use our matching algorithm to reconstruct this line and determine its length.

Fig. 3 shows the reconstructed line through the improved matching algorithm. The units here were transformed into meters by the parameter 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 52.94mm. Compared with the length measured by the ruler (53mm), the difference was 0.06mm and error is about 0.11%. With such good performance, we think this vision calibration system is qualified to calibrate 2D motions. Although we could not gain the corresponding velocity and acceleration at every 5ms with another means to further examine the algorithm, this good displacement result is still encouraging enough because both of the velocity and acceleration could be derived from the accurate displacement data, as will be shown later in this paper.
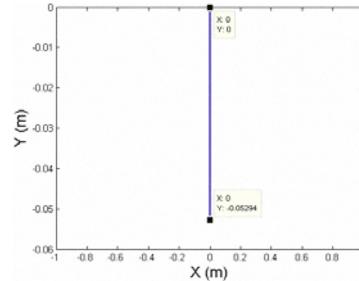

Figure 3. The reconstructed line by the matching algorithm

IV. EXPERIMENTAL RESULTS

A.   Writing Experiments of English Alphabet

In order to analyze the properties of our MEMS inertial sensors, writing experiments were carried out. All 26 letters of the English alphabet were written in lower-case with the UDWI shown in Fig.2. 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., sensors output and the optical tracking output. Consequently, a comparison between the output data could be achieved, which will be helpful for us to overcome the drift better in the future. In view of the limits of word-length for this paper, only one sample of experimental results (letter *u*) will be introduced 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 it takes to write the letter), and the interval between two neighboring points is 5ms. Using the improved matching algorithm, we obtained the positions of the pen tip while it was moving on a transparent table during a hand-writing motion. According to these position coordinates obtained after matching, we first reconstructed written character and compared it with the original character we wrote. As shown in Fig.4, 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.
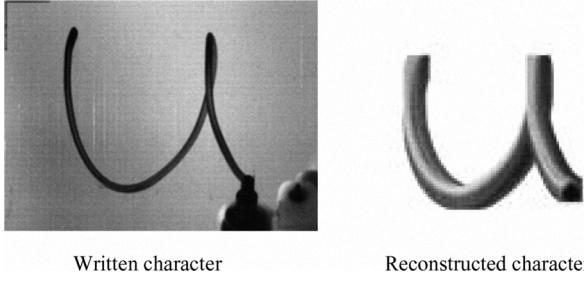
Figure 4. Comparison between original character and the reconstructed one

The reconstructed letter *u* was made up of 215 blocks, which means the duration of the writing motion was about 1.075s. Owing to the sensors' intrinsic drift, which occurred when the accelerometers output underwent an integration into velocity, became even worse after a double integration to get displacement, the Zero Velocity Compensation (ZVC) algorithm [9], was added into the sensor data processing algorithm in order to get better velocity and final results. This compensation algorithm, together with stroke segmentation algorithm [10], is supposed to overcome the drift in some level and useful to get more accurate velocity information. After our algorithm for sensors was improved in this way, new curves about the velocities and the reconstructed tracking could be guaranteed. In these curves, we regarded some peak

point as the reference point in order to synchronize the two group data. Fig.7 illustrates the comparisons of the acceleration between the raw data of the accelerometers and the calculated data from optical tracking system. While, in the following comparisons in Fig.8 and Fig.9, the curves from ZVC are compared.
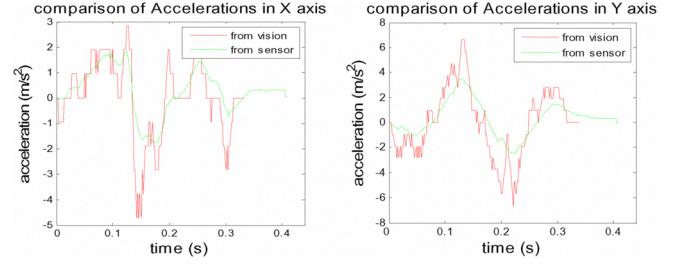

Figure5. Comparisons of accelerations of letter *u*
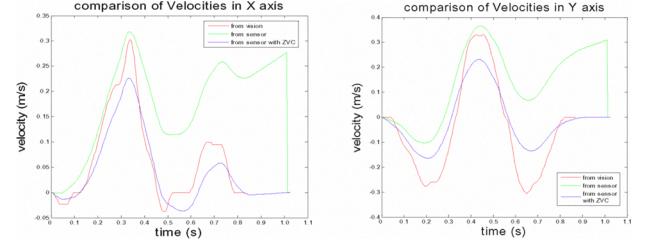
Figure6. Comparisons of velocities of letter *u*
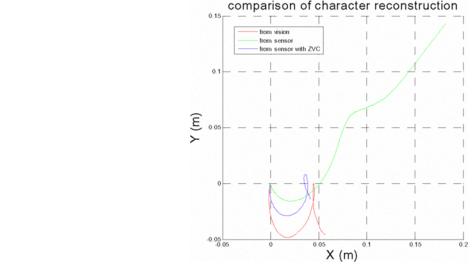
Figure7. Comparison of reconstructed characters of letter *u*

B.   Consistency in Writing a Single Letter

In order to test the stability of the sensors, the letter *s* was written eight times. The attitude of the pen was kept as consistent as possible during each stroke. Fig.8 illustrates all the eight reconstructed tracks through the optical tracking system. For the first two instances, since they were written some time before the other six, there were some differences between them in shape. As to the remaining six examples, we tried to write the letter in the same track which would make it more convenient for us to compare the sensor output. Let's now examine the results from the sensor output to determine whether the sensor output gave similar information when the pen was writing the same letter. Fig.9 shows the final results of the sensor output raw data and Fig.10 presents those with ZVC.

From the figures, we can conclude the sensors output was not stable enough to reconstruct the same moving track after several similar motions were done. Sometimes even with the aid of ZVC, the sensor signal was not good enough to present the letter clearly. Sensor drift causes great difficulty in reconstructing the letters that we had written. Besides this, there were several other factors to affect the accelerometers' performance. Firstly, the different tracks. From Fig.8, it can be seen that the shapes of *s* were not exactly the same which might lead to different motion properties of each stroke. Secondly, the sensor performance also depends on the stroke-- how fast it was written each time and how smooth it was. The sensors responded differently even to the same letter written by different motions. Finally, attitude might change during one stroke. A fixed attitude is necessary to guarantee more accurate results. Hence, we can briefly conclude that the current conditions probably cannot provide us with a consistent result from the sensors when writing a single letter repeatedly. Letters generated by MEMS sensor data could hardly be recognized visually, and even the recognition software has difficulty identifying the different letters. More experiments like this will be carried out in the future to determine whether the sensors can give consistent results for the same letter.

C.   Resolution of current algorithm

The vision algorithm is used to calculate 2D velocity and acceleration, including two parts: one is the matching, which gives the position information of the pen-tip from the image sequence; the other is the calculation of velocities and accelerations based on the previously obtained position information. In the first part, the minimum measurement unit can reach one pixel already, so the main factor the resolution depends on is the calculation. Because of the high sampling rate of the camera, there must be some very small movements, which the matching may incorrectly regard as being stationary. To reduce the effects of these mistakes, a simple filter was added to deal with the position information before calculation. The concept of this filter is to average the image coordinates of five neighboring points and brings this averaged value as the coordinate of the middle point into the latter calculation. It can be briefly presented as the following:

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

Hence, the minimum measurement unit is reduced by four-fifths at most, i.e. 0.2 pixel by this filter. According to the assumed mathematical model, we can get the equation for the calculation of velocity as the following:

$$v_{x\_n} = \frac{K \cdot (x_{n+1} - x_n)}{\Delta t} \quad (2)$$

where, xn is the averaged position in the x axis of the nth point by the filter; vx_n is the magnitude of velocity in the x axis. As to the parameter K, we have obtained it for each character then calculate an average value for it, which is equal to 1.144e-4 meter per pixel. Finally, we get the minimum measurement units of displacement, velocity and acceleration, which are equal to 2.288e-5 meter, 4.576e-3 meter per second and 0.9152 meter per second squared respectively.

Besides the currently used filter of 5-point average, other methods were also tested with different number of averaging points, including the calculation model without a filter. Consequently, the filter is very effective to smooth the curves of velocities, especially for the accelerations. And, the higher quantity of points we averaged, the better resolution and smoother curves could be obtained. Fig.11 illustrates one example of the letter *s0* from the multiple tests of *s*. In addition, we found that almost the same letter figuration was reconstructed in different cases, which means all the velocities and accelerations were derived from reliable position information. However, a filter with high quantity of averaged points may lead to a loss of true motion information, e.g., a fierce sudden movement. Even though a satisfactory reference has been achieved, we will improve the algorithm to be better in accordance with the practical demands in realizing a commercial digital pen product eventually.
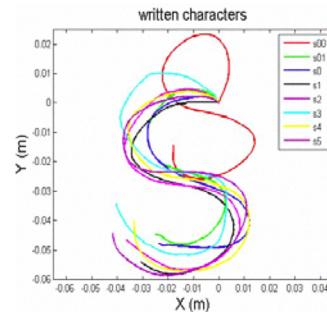

Figure 8. Letter *s* from optical tracking system and matching algorithm
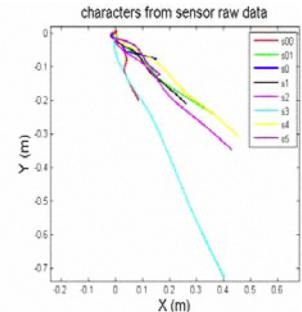
Figure 9. Tracks of letter *s* from sensors' raw data
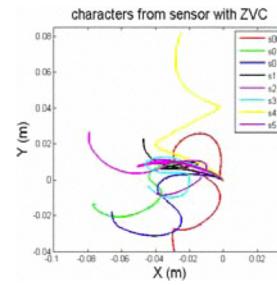
Figure 10. Tracks of letter *s* from sensors' raw data with ZVC
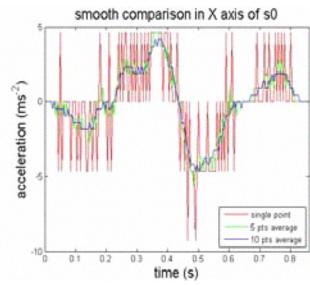
Figure 11. Curves of accelerations with different filters
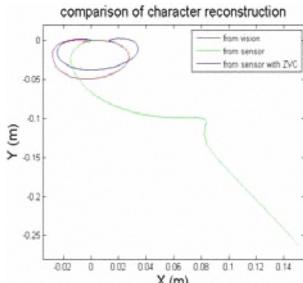
Figure 12. Comparison of data of letter *o*
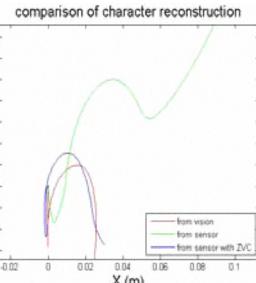
Figure 13. Comparison of data of letter *n*
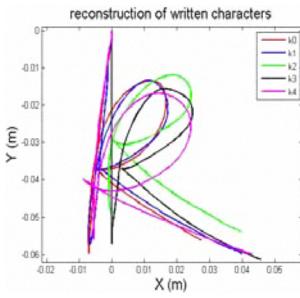
Figure 14. Letter *k* from optical tracking system and matching
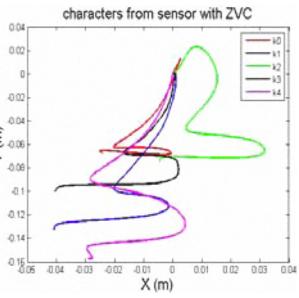
Figure 15. . Tracks of letter *k* from sensors' raw data with ZVC
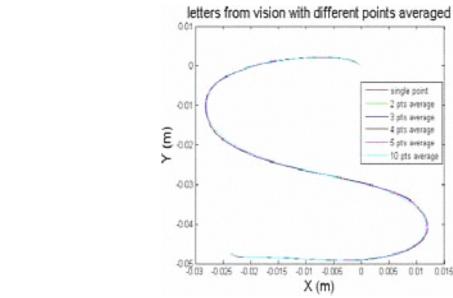

Figure 16. . Letters reconstructed based on the position information calculated from the accelerations and velocities with different filters

V.   CONCLUSION

This paper presents the latest improvement based on our original software algorithm for the calculation of the accelerations by optical tracking, owing to which the accuracy and efficiency of the matching algorithm have been significantly increased. Experiments on the accuracy of tracking reconstruction proved the position data from matching are reliable enough to be applied into the further calculation of motion parameters. Comparisons have been done between the MEMS sensors' output and optical tracking data from the 2D accelerations using hand-written English alphabets. The stability of the MEMS sensors should be

further investigated in order to develop a software for writing recognition. Furthermore, the current resolution of the velocities and accelerations calculated by the optical tracking and matching algorithm is discussed in this paper.

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