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Testing and Evaluation of an Inertial/Magnetic Sensor-Based Pen Input Device

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Abstract — **Testing and evaluation of a novel pen input device are presented in this paper. The pen input device could be used to write on any type of surface including desktops, blackboards, or in the air. It is constructed by attaching an inertial/magnetic sensor module to a writing instrument such as a pencil, a marker, or a piece of chalk. The inertial/magnetic sensor module has three accelerometers, three angular rate sensors, and three magnetometers. A tracking algorithm and a calibration algorithm are described. The tracking algorithm is for estimating the pen tip trajectories based on the sensor measurements, and the calibration algorithm is for estimating the relative position of the sensor module on the writing instrument. Experimental results for writing alphanumeric characters are presented. The relationship between tracking accuracy and writing speed is also discussed.**

I. INTRODUCTION

THE advent of low-cost, lightweight, low-power sensors and microcontrollers has enabled the integration of these technologies into an ever increasing array of commercial and military applications [1] [2]. MEMS devices, such as accelerometers and angular rate sensors, have been used successfully in areas such as consumer communications, video games, and the automobile safety.

The MEMS sensors have also been integrated with magnetometers to create miniature inertial/magnetic sensor modules. The miniature inertial/magnetic sensor modules are commercially available and suitable for use in applications that include navigation and attitude determination. We have used one of these modules to develop a capability of tracking one's hand-written motions [3]. The MARG (Magnetic, Angular Rate, and Gravity) Pen Tracker is comprised of three essential parts: the miniature inertial/magnetic sensor module, a writing instrument of the user's choosing, and the tracking algorithm. The intent of this project was to make it possible to attach a miniature inertial/magnetic sensor module to any writing instrument available, such as a pencil, a marker, a piece of chalk, or the user's favorite pen. Following a simple calibration, the writing instrument of the user's choice possesses the capability to track writing motions for recording or transmission.

The MARG Pen Tracker has many potential applications. One possible application is in the area of distance learning. A teacher could use a MARG Pen Tracker, which has been attached to a piece of chalk, to teach a class by writing or drawing on a blackboard in the usual manner. Distance learning supported by the MARG Pen Tracker would use very low bandwidth in comparison with a distance learning setup that was based on the use of video cameras. With a camera-based system, high video resolution is required to make written images legible, thus consuming a larger transmission bandwidth. In addition to reduced bandwidth requirements, if the teaching session was to be recorded, the MARG Pen Tracker would have the added benefit of requiring less data storage, if the teaching session was to be recorded. Moreover, there would be no need to zoom, pan, or tilt the camera as the instructor moved from one section of the blackboard to another. Also, any occlusions that may occur with the video camera would not be a concern with the MARG Pen Tracker.

Writings and drawings typically take place in a 2-D plane (or surface), whether it is vertical, horizontal, or any other inclined plane. Even if writings are not exactly in a 2-D plane, as when writing in the air, the MARG Pen Tracker could be configured to project writings to the most appropriate 2-D surface.

In applications where 3-D drawings are desirable, the user may simply draw a 3-D object in the air. A 3-D rendering of the object could then be displayed on a computer screen. It would be useful for teaching science and engineering concepts where 3-D drawings and illustrations of objects and geometry are needed.

II. BACKGROUND

A. Optical Pen Tracking

There are various smart pens or digital pens available on the market, which are designed for recording hand written notes and drawings. Livescribe offers a product called the Pulse Smartpen that captures one's hand-written notes on specially-designed paper imprinted with a fine array of dots [4]. It also records audio. The device uses a high-speed infrared camera to locate the position of the pen tip based on the dot array. Logitech's IO2 Digital Pen is a similar product that uses a special dot-imprinted paper. The Digital Scribe from IOGEAR is another product of this type;

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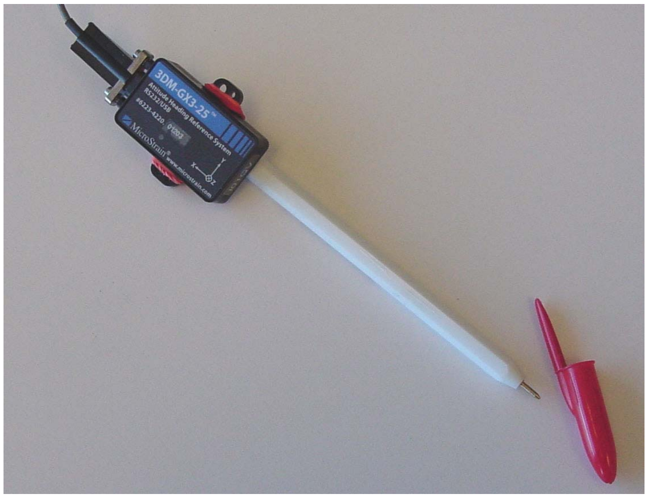
Fig. 1. A MARG Pen Tracker composed of a Microstrain 3DM-GX3-25 IMU sensor and a ball point pen.

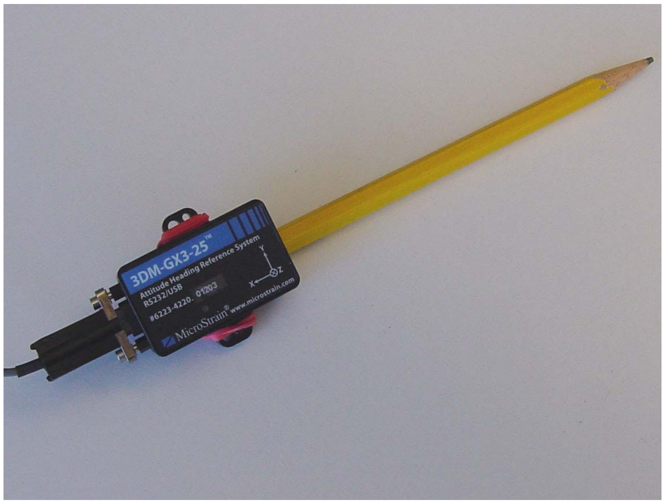
Fig. 2. A MARG Pen Tracker composed of a Microstrain 3DM-GX3-25 IMU sensor and a pencil.

however, it does not require the use of dot-imprinted paper. Instead, an infra-red optical receiver is clipped to the edge of the writing paper, which tracks the pen tip as it moves across the surface of the paper. The Adesso CyberPad records one's hand-written notes, as well. In this device, the user writes on a screen that captures the hand-written information. All of the pen tracking systems described are limited by the fact that they either require the use of special tracking paper or are constrained for use in a specified region of coverage.

B. *MEMS Sensor Applications*

Owing to low cost, small size and weight, and low power, MEMS accelerometers and angular rate sensors (gyros) are found in an ever increasing array of applications. For example, consumer products, such as the Apple iPhone, use the MEMS accelerometer for orientation sensing and display control. The Nintendo Wii-mote uses the MEMS accelerometer for coarse motion sensing, which ultimately drives the game interface [5]. The automotive industry has integrated MEMS accelerometers and gyros into their automobiles for crash detection and vehicle stabilization.

Other applications include the computer mouse from manufacturers, such as Gyration and Logitech. They have incorporated accelerometers and gyros into their designs for orientation sensing and mouse cursor control [6], [7].

The accelerometers and gyros, when integrated with miniature magnetometers, result in small devices suitable for 3-D orientation sensing. The nIMU from MEMSense and the 3DM-GX1 from Microstrain, for example, are commercially available products of this type. The latter device even incorporates a microcontroller with a proprietary algorithm that gives 3-D orientation in the form of a quaternion, or if the user desires, in the form of Euler angles.

C. *Related Work*

Other researchers have realized the potential benefits of using a MEMS IMU in the pen tracking application. Bang et al. developed a pen-shaped input device for wearable computers [8] [9]. The input device is constructed from three accelerometers and three gyros. Zhang et al. also developed a similar device incorporating accelerometers, gyros, but differed in that it incorporated a surface contact sensor to mark the motion intervals [10].

D. *MARG Pen Tracker*

Our approach to the pen tracker incorporates the use of commercially available miniature IMU's utilizing the MEMS accelerometers, gyros, and magnetometers. The system is envisioned to be such that the user simply attaches one of these IMU's to any particular writing instrument of his/her choice as seen in Figures 1 and 2. In this regard, our proposed solution gives the user flexibility in the selection of the writing instrument (i.e. pen, pencil, chalk) and writing surface (paper, blackboard, or even writing gestures made in the air). After a simple calibration has been accomplished, the user is ready to begin tracking his/her pen motions for recording and/or transmission to another location. A Microstrain 3DM-GX1 was utilized in this work, although other similar devices, such as those from MEMSense or InertiaSense could be easily adapted.

A tracking algorithm was developed that is based in part on the concept of strapdown inertial navigation with zero-velocity updates. The zero-velocity updates provide a means of correcting for errors that tend to accumulate during numerical integration. The next section provides a brief description of our pen tracking algorithm and the calibration procedure.

III. TRACKING ALGORITHM

Figure 3 depicts a MARG Pen Tracker with three coordinate systems. The earth-fixed coordinate system is denoted by $x_e y_e z_e$, and the sensor coordinate system is denoted by $x_s y_s z_s$. A third coordinate system located at the tip of the pen is denoted by $x_t y_t z_t$. Point A is the origin of the sensor coordinate system, and point B is located at the tip of the writing instrument.

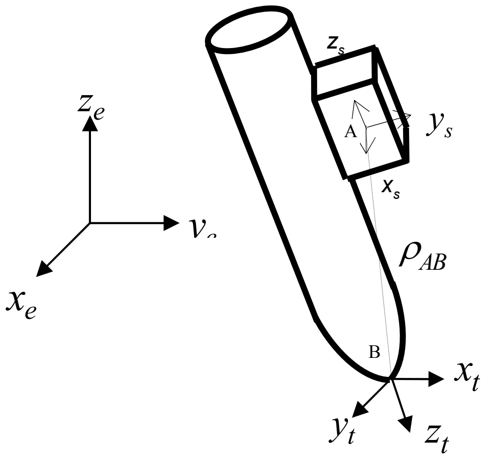

Fig. 3. MARG Pen Tracker coordinate systems

Given the accelerometer, gyro, and magnetometer measurements, respectively, ${}^s a$, ${}^s\omega$, and ${}^s m$ in the sensor coordinate system, the first part of the tracking algorithm is to estimate the position of the pen tip in the earth coordinate system. This is accomplished in six steps:

1) Estimate the sensor orientation using the sensor measurements, ${}^s a$, ${}^s\omega$, and ${}^s m$. Since the sensor is assumed to be rigidly attached to the writing instrument, the sensor orientation is the same as that of the pen. It is noted that in this particular work, the sensor we used provided an orientation estimate, q, which is represented in the form of a quaternion. If the IMU sensor does not readily provide the orientation quaternion estimate, algorithms are available from the literature [11].

2) Convert the accelerometer measurement, ${}^s a$, provided by the sensor in the sensor coordinate frame into accelerations in the earth coordinate frame using the orientation estimate, q, from step 1:

$$ {}^e a = q \cdot {}^s a \cdot q^* \tag{1.1}$$

where q^* is the conjugate of the quaternion q and ${}^e a$ is the acceleration in the earth coordinate system.

3) Integrate the earth-referenced acceleration to obtain a velocity of point A that is also represented in the earth coordinate system:

$$ {}^e v_A = \int {}^e a \cdot dt \tag{1.2}$$

4) Compute the velocity of point B based on that of point A and the angular velocity:

$$ {}^e v_B = {}^e v_A + q({}^s\omega \times {}^s\rho_{AB})q^* \tag{1.3}$$

where ${}^s\rho_{AB}$ is the constant vector from point A to point B.

5) Detect the pauses in writing and apply the zero velocity correction. We employed the method described in [8].

6) Finally, the position of the pen tip can be computed by

$$ {}^e p_B = \int {}^e v_B \cdot dt \tag{1.4}$$

IV. CALIBRATION ALGORITHM

A requirement of our MARG Pen Tracker was that one could use the sensor on any type of writing instrument by simply attaching the sensor unit to any typical writing utensil. However, for each application, the particular ${}^s\rho_{AB}$ for that writing instrument had to be derived. Thus, a calibration procedure was developed, which was accomplished after the sensor had been attached to a particular writing instrument. The procedure was based on (1.3) expressed in the sensor coordinate system:

$$ {}^s v_B = {}^s v_A + {}^s\omega \times {}^s\rho_{AB}\,. \tag{1.5}$$

The calibration procedure required the user to move the writing instrument with the attached sensor such that ${}^s v_B = 0$ in (1.5). This was accomplished by holding the tip, point B, of the utensil fixed in one location while the free end was rotated in an arbitrary motion. Now (1.5) becomes

$$ 0 = {}^s v_A + S_\omega\, {}^s\rho_{AB} \tag{1.6}$$

where S_ω is the skew-symmetric matrix associated with the angular rate measurements and defined as

$$ S_\omega = \begin{bmatrix} 0 & -\omega_z & \omega_y \\ \omega_z & 0 & -\omega_x \\ -\omega_y & \omega_x & 0 \end{bmatrix}. \tag{1.7}$$

The rank of S_ω is at most two, and thus it is not invertible. Therefore, the vector ${}^s\rho_{AB}$ can not be solved from (1.6) in its present form. Geometrically, given ω and ${}^s\rho_{AB}$, ${}^s v_A$ is the resulting cross product of the former two vectors. However, ${}^s\rho_{AB}$ can not be uniquely determined because the cross product of ω with any arbitrary vector (of appropriate length) in the plane perpendicular to ${}^s v_A$ may yield ${}^s v_A$. If there are two sets of independent measurements of ω and ${}^s v_A$, then ${}^s\rho_{AB}$ is constrained to the intersection of two planes and can be uniquely determined. During the calibration procedure, many data sets are collected and ${}^s\rho_{AB}$ can be determined using the method of least squares. Let $\omega(1), \omega(2), \ldots \omega(n)$ and ${}^s v_A(1), {}^s v_A(2), \ldots {}^s v_A(n)$ be n sets of angular rate measurements and point A velocities that were collected during the calibration procedure. The velocity of point A, ${}^s v_A(i)$ in the sensor coordinate system, is converted from that in the earth coordinate system by

$$ {}^{s}v_A(i) = q^{*}(i)\cdot {}^{e}v_A(i)\cdot q(i)\,. \tag{1.8} $$

The velocity of point A in the earth coordinate system is obtained using (1.2). Let $s_{\omega}(i)$ be the skew-symmetric matrix corresponding to $\omega(i)$. Now let ${}^{s}V_A$ be the $3n\times 1$ vector constructed by stacking point A velocities, and S be the $3n\times 3$ matrix constructed by stacking n skew-symmetric matrices, such that,

$$ {}^{s}V_A = \begin{bmatrix} {}^{s}v_A(1) \\ \vdots \\ {}^{s}v_A(n) \end{bmatrix}, \qquad S = \begin{bmatrix} s_{\omega}(1) \\ \vdots \\ s_{\omega}(n) \end{bmatrix}. $$

The least-squares solution of ${}^{s}\rho_{AB}$ is then given by

$$ {}^{s}\rho_{AB} = -(S^{T}S)^{-1}S^{T}\,{}^{s}V_A \tag{1.9} $$

As long as there at least two independent sets of measurements obtained from the calibration process, the 3×3 matrix $(S^{T}S)$ is full rank and invertible. Independent measurements are guaranteed by the calibration procedure in which the free end of the writing utensil, point A, is rotated arbitrarily.

V. EXPERIMENTAL RESULTS

A. Experimental Setup and Algorithm Implementation

As noted earlier, our MARG Pen Tracker consisted of three components: the miniature IMU, a common writing utensil, and the tracking algorithm. For the IMU, we used the 3DM-GX1 from MicroStrain. It consisted of three orthogonally-mounted accelerometers, gyros, and magnetometers. The accelerometers had a range of +/- 5 G's; the angular rate sensors had a range of +/-300 deg/sec. The magnetometers, having a range of 1.2 Gauss, measured the earth's local magnetic flux density projected onto each of the three sensor body axes. An embedded microcontroller processed the sensor measurements to provide an estimate of the orientation by a proprietary algorithm. The unit provided data at approximately 70 samples per second via an RS-232 interface to a desktop personal computer. Each sample consisted of measurements from the accelerometers, magnetometers, and angular rate sensors, along with a computed quaternion. Additionally, the sensor provided a time increment for each set of sampled data that was subsequently used in the numerical integration of the accelerometer data.

For our experiments, we attached the 3DM-GX1 to a pencil using adhesive tape and rubber bands. After the data had been collected from a given experiment, the logged data was processed using one of the MATLAB scripts developed for this project—either the calibration algorithm or the tracking algorithm.

B. Calibration Procedure

In order to verify the validity of our calibration procedure, the 3GM-GX1 was attached to a wooden dowel at various locations along its length. One end of the wooden dowel was sharpened to a point to simulate the tip of a writing utensil. At each location along the dowel's length where the sensor was attached, a calibration was accomplished and the computed ${}^{s}\rho_{AB}$ was compared with a measured distance. Table I shows the results from this experiment. The data suggest that as the IMU is placed farther from the pivot point, the error in the computed ${}^{s}\rho_{AB}$ tended to increase. This may be attributed to any flexing that might occur in our wooden dowel as it was rotated about the pivot point and magnified as one moved farther away from this point.

TABLE I
RESULTS FOR CALIBRATION PROCEDURE

Measured Distance (cm)	Computed Distance, ${}^{s}\rho_{AB}$ x-coord only (cm)	$\lvert \%error \rvert$
13.3	13.01	0.67
20	21.97	9.85
40	43.97	9.93
60	67.65	12.75
80	87.92	9.9
100	126.97	26.97

Next, the sensor was attached to a pencil approximately 14 cm from the writing tip. The subsequent calibration yielded a ${}^{s}\rho_{AB}$ of [-0.1418, 0.0246, 0.0287], expressed in meters. This vector was then used in (1.3) during the pen tracking procedure discussed in the following section.

C. Pen Tracking Experiments

With the constant vector, ${}^{s}\rho_{AB}$, in hand, a series of pen tracking experiments were accomplished. First, a series of letters and numbers were written on standard paper and taped to a workbench surface. These characters served as a standard reference for comparison with computed tracks and to add a means of reproducing the experiments with similar inputs. Each letter was approximately 20 cm in height.

As the characters were traced with our MARG Pen Tracker, the corresponding measurements were recorded for later processing. Figures 4 and 5 show the computed pen tracks for the various alphanumeric characters used in the experiments.

There are many characters that may be written in one continuous motion of the hand, for example the letter S or the number 3. For this type of character, it was straightforward to locate the interval of motion within the data and carry out the tracking algorithm. To be more specific, the acceleration was compared with a threshold and verified that it exceeded this value for a specified amount of time before the beginning of the motion interval was marked. Once the motion interval was located, the tracking algorithm was applied to the data within that interval.

However, there are many characters that can not be

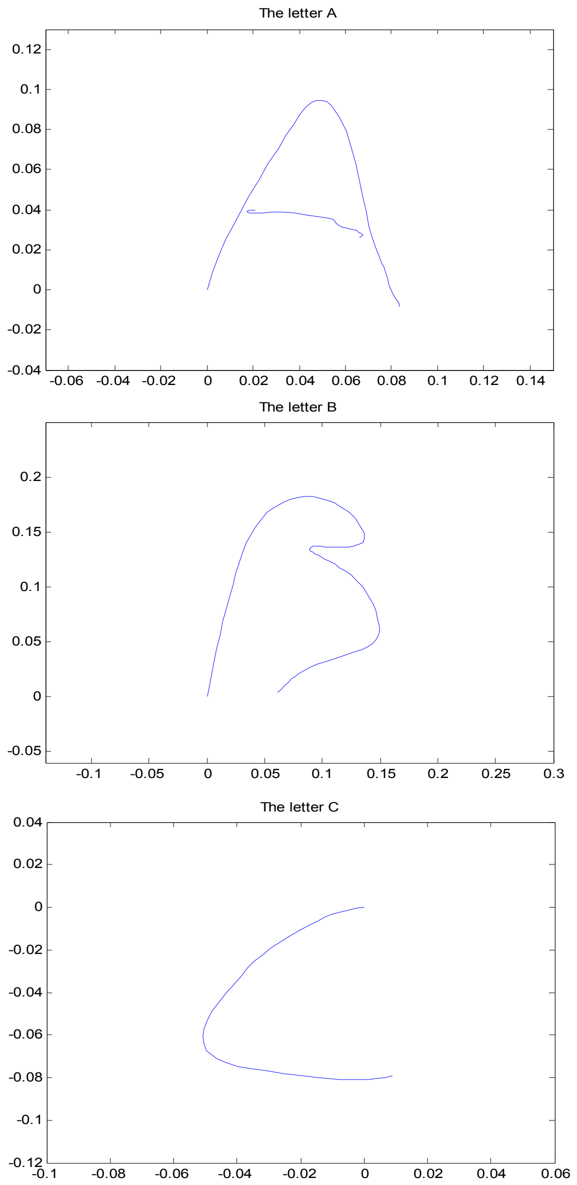

Fig. 4. Pen tracking trajectories for various letters.

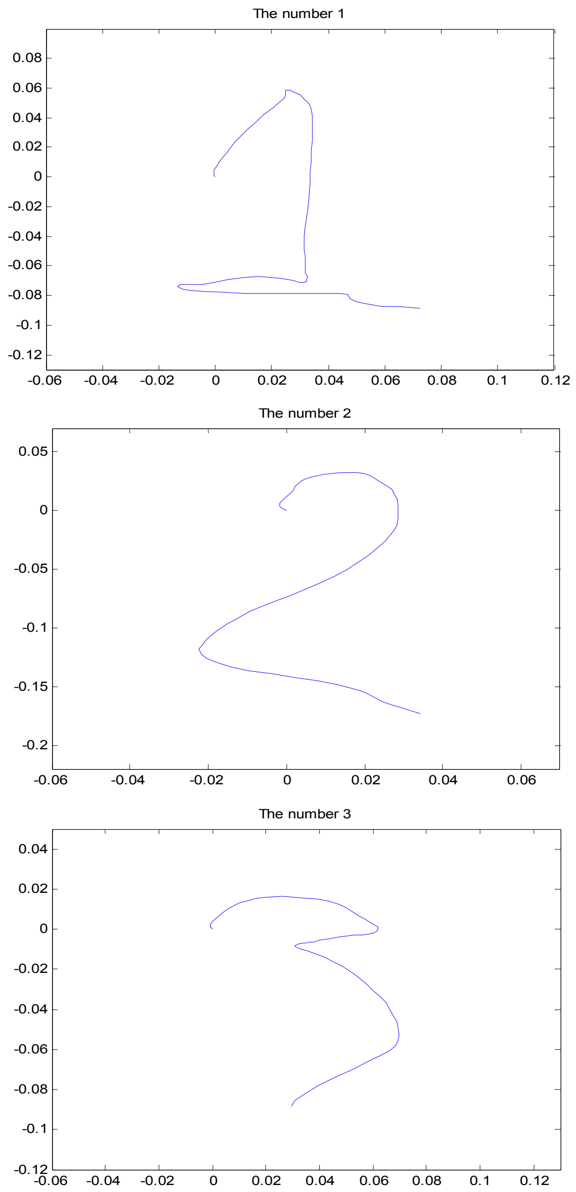

Fig. 5. Pen tracking trajectories for various numbers

written in one continuous motion of the hand. For these characters, one is required to raise the writing instrument from the writing surface and place the tip at another location to complete the character. Consider the letters T and E, for example. For these letters, it was necessary to manually locate the point where the pen was lifted from the surface and set the beginning of the computed track at a suitable location to form the character. While this was not considered to be appropriate for a practical implementation, without some means of detection of pen tip contact, no alternative was readily apparent.

For each of the characters that were reproduced with the MARG Pen Tracker, several trials were conducted, and a typical track was presented here. During our experiments, we observed that the accuracy of the letters and numbers seemed to be related in part to the speed with which one wrote the characters. With this in mind, we devised an experiment to investigate the relation between writing speed and the legibility of the pen tracks.

D. Tracking Accuracy vs. Writing Speed

To investigate this idea, we conducted a simple experiment that moved the sensor through three different speeds. First, the sensor was removed from the writing instrument and placed flat on the workbench surface. Then, the sensor was moved through a horizontal distance of 20 cm at three different speeds (slow, medium, and fast). The horizontal motion was conducted such that it was aligned with one of the sensor axes, i.e. the x-axis, while the y-axis

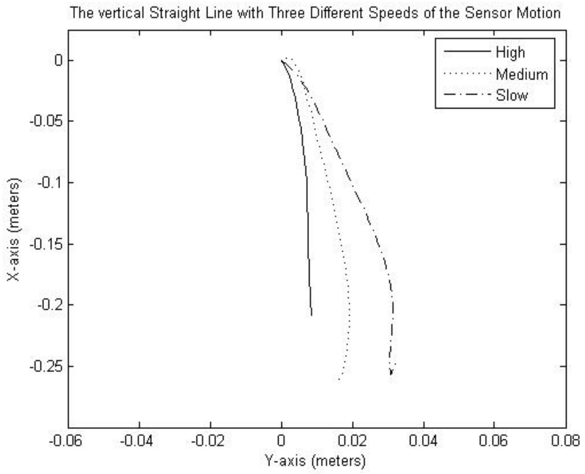

Fig. 6. Sensor moved in a straight line with three different speeds to illustrate dependency of tracking accuracy on writing speed.

was orthogonal to the direction of motion and would exhibit little or no acceleration. The z-axis, being normal to the horizontal plane, also would experience little or no acceleration. Additionally, the orientation of the sensor was maintained constant during the brief interval of motion. This eliminated the use of the quaternion and reduced any portion of the tracking error that would have resulted from errors in the orientation.

Figure 6 shows the x-y track for the three intervals of motion. The high-speed track most approximates the straight line track, while the slow track exhibits the largest amount of error in the y-axis. While this result confirms the dependency of writing speed on tracking accuracy, a more thorough analysis is required to fully quantify this relationship.

VI. CONCLUSION

We have demonstrated an initial capability of tracking one's writing motions using the MARG Pen Tracker. This approach used a commercially available inertial/magnetic sensor module that was attached to a common writing utensil. The use of the tracking algorithm and the calibration algorithm were also demonstrated.

Preliminary experiments indicated the MARG Pen Tracker is a potential tool for use in the area of distance learning and possibly even as an alternative computer interface. However, more work will be required to improve the accuracy and repeatability of the tracked letters and numbers. The motion speed was found to be related to the overall performance, although we only investigated a qualitative relationship.

We learned that it was rather straightforward to track those characters that could be drawn in one continuous motion. On the other hand, those characters that can not be drawn in this fashion required a manual resetting to accurately reproduce the desired character. Further work will be required in this area. Under consideration to address this problem is the integration of a user operated trigger that is set/reset to mark the motion for appropriate processing or the adoption of a unique character set, such as the "Graffiti" used in the Palm Pilot, as in [8].

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