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Development of an inertial measurement unit-based pen for handwriting assessment

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Handwriting assessment is important in identifying where a person struggles with handwriting. Unfortunately, the classical method of handwriting assessment is conducted manually by occupational therapists, which is considered qualitative and time consuming. Moreover, technical methods such as the IMU-based pens were only used in conducting tests with regards to handwriting recognition, and no existing literature indicates that an IMU was used for handwriting assessment. This study aims to prove that it is possible to gather raw data from the assembled IMU-based pen made by the group, and transform them into the parameters needed by the clinicians in assessing handwriting. This study does not intend to replace clinicians, but it intends to help them in conducting an assessment from a qualitative to a quantitative standpoint.

Keywords: inertial measurement unit, quaternion algorithm, handwriting assessment

Introduction

Recently, several researchers have focused on developing technologies that will compensate for human lapses. A number of research have been made including handwriting recognition [1], gesture recognition [2], handwriting recognition and gesture recognition combined with its special algorithms such as an accelerometer-based pen with trajectory reconstruction algorithm [3] and an inertial pen with dynamic time warping (DTW)-based recognition algorithm [4]. The stated algorithms were established to further increase the accuracy of handwriting digit and gesture recognition systems. Digitalized handwriting was also a hit back then, for example the AirPen

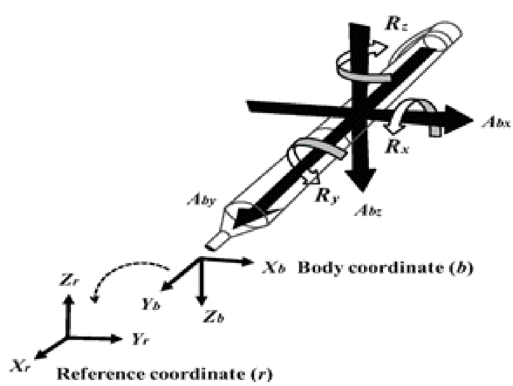

Figure 1. Raw components of the IMU [1]

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(PENTEL CO.) [5], Livescribe (Livescribe Inc) [6], AnotoPen (Anoto AB) [7], MVPen (MVPen Technologies Ltd.) [8], DigiMemo (ACE CAD Enterprise Co., Ltd.) [9], and the digital pen that addresses both handwritten recognition and writing gesture recognition issues using sensor fusion between inertial measurement unit (IMU) and strain gauges embedded on a pen device [10]. These studies showed that inertial-sensing-based pen-based input devices for recognizing handwritten characters and hand gestures can be operated without ambit limitations such as writing ranges, directions, or dimensions [11] which makes an IMU-based pen more suitable and versatile for a number of applications compared to an electromagnetic and pressure type pens where the writing space is limited [12] and a user needs to be in a controlled environment for more accurate results [13].

Recent studies have shown the effectiveness of an IMU-based pen as a handwriting recognition tool but there are no studies that analyze normal handwriting. As the society evolves, handwriting became a basic fundamental skill that people should acquire at their early age. However, 10–27% of students have difficulties in handwriting [13]. Handwriting as a form of communication not only in casual conversation but also between organizations and legal mandates aside from digital documents makes it an essential part of our society.

This research aims to gather raw data from the IMU-based pen and transform the data to the parameters needed by the clinicians in handwriting assessment. Occupational therapists use the classical method as the gold standard. To compensate for the complications and disadvantages of the classical method, an inertial pen is proposed by the researchers to assess and quantify significant data such as the user's handwriting speed with its correlated angles [14]. In practice there is a school-based occupational therapy practitioner that performs a comprehensive evaluation of the quality of students' handwriting skills before recommendations and intervention plans which takes a large amount of time [15, 16]. Normally, occupational therapy practitioners evaluate first the underlying skills such as motor skills, stability of supporting joints, pencil grasp, hand strength, etc. These practitioners emphasize four measuring performance which includes the domains, legibility components, writing speed, and ergonomic factors, however this study focuses much more on domains and legibility components to further analyze, assess, and quantify each stroke for a better data analysis. Under the domains and legibility components are the turning points of this study which provides the elements of the database that are assessed through the user's handwriting performance. The legibility components centralize on the letter formation, alignment, spacing, size, and slant. The letter formation involves the improper letter forms, poor leading in and out of letters, inadequate rounding, incomplete closure, and ascenders and descenders [17].

To create the desired IMU-based pen for the research, necessary calibration techniques for the device (IMU) are done to ensure reliability and accuracy during data gathering. Once this is done, the researchers and study volunteers may now begin the study proper. Initial data are

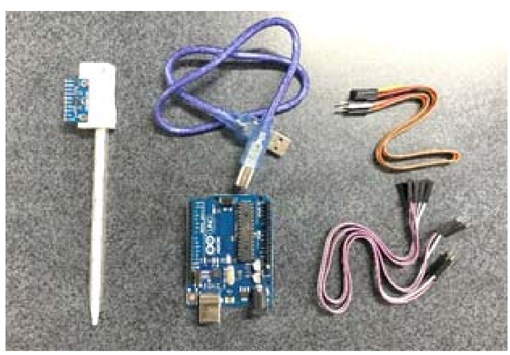

Figure 2. Inertial measurement unit (MPU 9250) attached to a magic pencil with an ArduinoUNO microcontroller

taken from the volunteers and then use it to recreate a new set of filtered data which is done through the use the quaternion algorithm. These gathered data will now be transformed to the needs of the occupational therapists.

For this paper, it is sufficient that the raw data of the IMU, such as the roll, pitch, and yaw angles can be transformed into the parameters needed by the occupational therapists in assessing handwriting that an IMU is capable of.

Experimental

Hardware. The pen was developed using a magic pencil that contains an IMU sensor to quantify the data needed by the occupational therapist. Initially, the IMU will be firmly attached to the upper tip of the pen to gather the roll, pitch, and yaw values while the user is writing using the developed pen.

The hardware used for the IMU is the MPU9250, it is a 9-axis motion tracking device with a power consumption of only 9.3μA. Its gyro noise performance is three times better, and compass full-scale range is over four times better than the previous models. It also has a three-16-bit analog-to-digital converters for gyroscope, accelerometer, and magnetometer for digitizing its output [18]. These sensors help the controller gather the rotational attributes like roll, pitch, and yaw values. This IMU will be inserted in the pen and will be directly connected to the programming language, ArduinoUNO which is connected to the computer.

The MPU9250 was programmed using ArduinoUNO, an open-source platform that consist of a physical programmable circuit board/ microcontroller based on the ATmega3. It has 14 digital input/output pins, six analog inputs, a 16-MHz ceramic resonator, a USB connection, a power jack, an ICSP header, and a reset button [19]. This platform was used to insert the algorithms for the transformation of the output of the MPU9250 which is the raw data: roll, pitch, and yaw to the parameters needed for handwriting analysis such as Acceleration and Euler Angles with the assistance of the programming language MatLab R2018, as well.

Data gathering. Initially, researchers gather raw data that are counterproductive for the actual information needed in the scope of this study. These data are also erroneous due to external factors. To transform these raw data into a useful handwriting parameter and decrease the amount of error, they are filtered and transformed through the quaternion algorithm formulas [20]. Relationships of parameters such as platform orientation, measurement of gravity from accelerometers, and angular rate measurement from gyroscopes are represented in its quaternion form [21]. Through the relationship of these parameters, methods are created and experimented by researchers. Methods such as orientation estimation, and final orientation angles are adapted from this algorithm [20].

Quaternion-based process is used rather than direction cosines because the quaternion representation does not have a problem with singularities and handles normalization better. This algorithm also processes these data fast and it also applies to other reference field sensors for feedback, such as accelerometers or star trackers [21].

Orientation estimation. Using integral operations, filtered signals from the IMU during the preprocessing phase are manipulated to estimate an accurate value for the IMUPEN’s orientation and position [20]. Orientation in all three axes are also estimated, given a small amount of linear acceleration. Through the process of quaternion, accelerometers are used as a corrective measure by taking into account the gravitational force to curb the error of the orientation estimate. Gyroscopes also provide orientation estimate using a quaternion differential equation. Due to integration and sensor errors, there is a drift in this orientation estimate [21].

The quaternion representation of rigid body rotations leads to convenient expressions. A quaternion is four-dimensional complex numbers that has an orientation motion of a vector from the reference frame to the destination frame. The rotation is performed through quaternion multiplication [22].

Final orientation angle. Initial orientation angles contain unwanted errors due to drift errors and user's unconscious trembles. These initial angles are manipulated as well to obtain the final orientation angles using equations 1–7 [20].

$$\varphi(\kappa) = \tan\text{-}1\ (Aby(\kappa)Abz(\kappa)) \qquad \text{[Eq. 1]}$$

$$\theta(\kappa) = \tan\text{-}1\ (Abx(\kappa)A2by(\kappa) + A2bz(\kappa)) \qquad \text{[Eq. 2]}$$

$$\psi(\kappa) = \tan\text{-}1\ (2q1q2 + 2q0q42q02 + 2q12 - 1) \qquad \text{[Eq. 3]}$$

$$q0 = \cos(\alpha)\cos(\beta)\cos(\gamma) + \sin(\alpha)\sin(\beta)\sin(\gamma) \qquad \text{[Eq. 4]}$$

$$q1 = \cos(\alpha)\cos(\beta)\sin(\gamma) + \sin(\alpha)\sin(\beta)\cos(\gamma) \qquad \text{[Eq. 5]}$$

$$q0 = \cos(\alpha)\sin(\beta)\cos(\gamma) + \sin(\alpha)\cos(\beta)\sin(\gamma) \qquad \text{[Eq. 6]}$$

$$q0 = \sin(\alpha)\cos(\beta)\cos(\gamma) - \cos(\alpha)\sin(\beta)\sin(\gamma) \qquad \text{[Eq. 7]}$$

Quaternion representations are used since the physical quantities related to rotation, such as angular displacement, velocity, acceleration, and momentum, are shown to be vector quaternions, and their expressions in quaternion space are derived [20]. From this representation, the compensated acceleration can now be generated and then used to obtain the velocities and position of the IMUPEN in a motion using single integral and double integral respectively.

Results and Discussion

Initially, once the IMU is calibrated, the participants can now perform all the tests needed. To start with, the IMU was tested in a way that it could record consistent outputs on different trials. This was done by letting the participants write a whole complete alphabet and numerals from 0 to 9, three different times.

The first test was for the participants to write the numerals and as seen from Fig. 3 to Fig. 5 and Table 1, the IMU can capture consistent data on different trials. Although the noticeable inconsistence seen is on the hand's speed when writing. Relatively, the speed does not count on

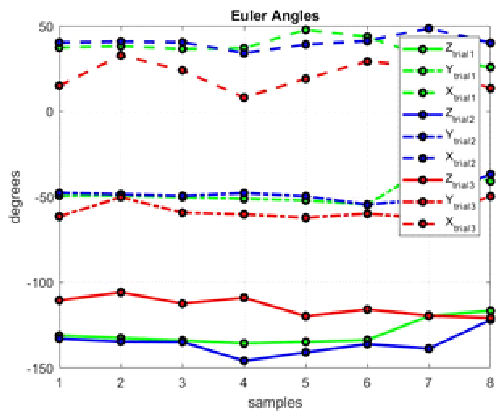

Figure 3. Trials 1, 2, and 3 for the graphical representation of the IMU's Euler angle during the test for numeral '1'

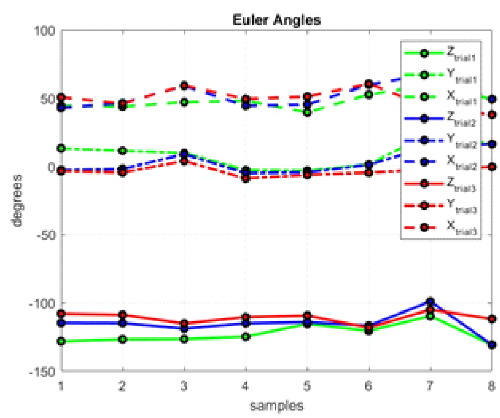

Figure 4. Trials 1, 2, and 3 for the graphical representation of the IMU's Euler angle during the test for numeral '2'

Table 1. Average data on person A with three trials for numeral '1', numeral '2', and numeral '3'

Parameters	Numeral '1'			Numeral '2'			Numeral '3'		
	Trial 1	*Trial 2*	*Trial 3*	*Trial 1*	*Trial 2*	*Trial 3*	*Trial 1*	*Trial 2*	*Trial 3*
$Roll_{ave}$	58.52	60.44125	61.14875	63.6175	49.3175	50.27417	96.56857	97.99125	87.81625
$Pitch_{ave}$	4.45	1.33875	3.565	41.77083	45.52333	42.87417	–32.2714	–28.4875	–28.68
Yaw_{ave}	113.4863	116.3675	99.175	64.20417	89.83917	94.20167	–496.399	–498.84	–504.76
Ax_{ave}	76.90375	–11.84	–62.5625	1114.206	1244.855	1279.313	–496.399	–498.84	–504.76
Ay_{ave}	847.9	923.7025	909.6063	667.7808	632.1858	632.9192	780.1971	788.515	756.47
Az_{ave}	546.7538	434.4475	532.41	663.855	977.635	930.2767	–108.103	–89.4775	24.8425
EulerZ	–129.69	–135.677	–114.109	–93.8772	–99.4972	–100.837	–27.0672	–27.8038	–34.302
EulerY	–47.4537	–48.1199	–58.1205	19.83593	5.474433	8.743975	–31.8344	–33.828	–30.1038
EulerX	37.26505	40.64959	21.00421	34.88898	42.97929	42.88287	–91.9473	–97.5491	–88.2961

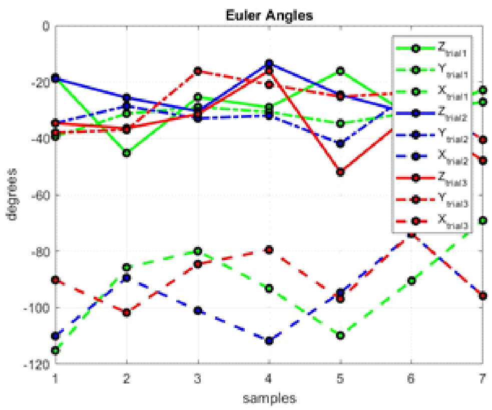

Figure 5. Trials 1, 2, and 3 for the graphical representation of the IMU's Euler angle during the test for numeral '3'

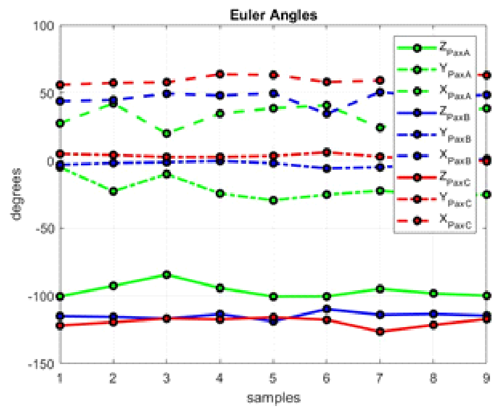

Figure 6. IMU's Euler angle during the test for character 'a'; Participants A, B, and C

achieving a consistent writing pattern if the character is legibly written and read.

Ax, Ay, and Az, stands for the accelerations of the roll, pitch, and yaw. While EulerX, EulerY, and EulerZ, stands for the Euler angles of the roll, pitch, and yaw, respectively. The noticeable graphs are seen at numerals 2 and 3 based on the Euler angles wherein the waveform tends to spike widely due to the hand's circular movement during writing.

The next conducted tests were writing letters from the alphabet with also three different trials each. The data for the alphabet can be seen in

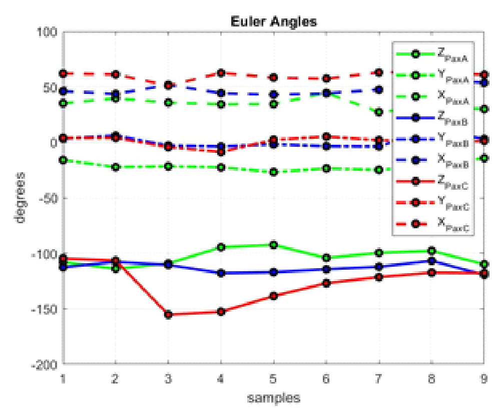

Figure 7. IMU's Euler angle during the test for character 'b'; Participants A, B, and C

Table 2. Average data from three trials on multiple participants for character 'a', character 'b', and character 'c'

Parameters	Character 'a'			Character 'b'			Character 'c'		
	Pax A	*Pax B*	*Pax C*	*Pax A*	*Pax B*	*Pax C*	*Pax A*	*Pax B*	*Pax C*
$Roll_{ave}$	31.72571	23.82469	33.6574	36.53963	24.19444	31.09422	34.66286	26.72542	43.41233
$Pitch_{ave}$	22.80286	39.2625	47.2994	24.17444	42.51444	52.73178	20.62238	38.4925	55.15767
Yaw_{ave}	104.0086	121.3544	118.8954	102.4233	122.6303	122.5556	108.2029	122.3275	147.209
Ax_{ave}	769.3575	1482.447	1601.726	795.9111	1492.669	1574.189	787.5505	1418.199	1597.606
Ay_{ave}	–774.768	659.27	579.2624	835.7415	662.8556	713.1538	776.1767	653.4429	739.8523
Az_{ave}	1293.141	1518.325	1107.655	1283.96	1522.172	899.8611	1239.792	1465.3	795.769
EulerZ	–107.783	–115.394	–117.552	–108.145	–114.089	–113.518	–113.603	–113.982	–119.431
EulerY	–23.4759	–0.45285	5.135938	–27.3308	0.991075	–1.10721	–21.7438	–2.12872	9.21146
EulerX	33.22169	45.61754	56.82113	35.47343	48.69996	62.25394	35.64226	44.89914	65.10846

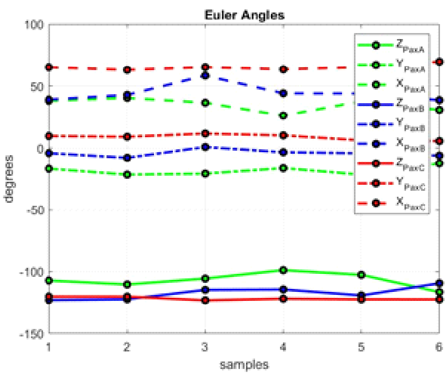

Figure 8. IMU's Euler angle during the test for character 'c'; Participants A, B, and C

Fig. 6 to Fig. 8 and Table 2, in comparing between multiple participants on writing each character. As for each character written, it was also compared to other participants who wrote the same letter. Pax A, Pax B, and Pax C, denotes person A, B, and C, respectively.

As seen from the summary of data, the IMU can be used in comparing different handwriting patterns from different individuals and could be used to compare whether a written character is the same, although it may suffer some inconsistency from time to time due to irregular and involuntary hand movements. These could be used as a standard database for handwriting assessment if enough data is obtained and processed.

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