Proceedings on Automation in Medical Engineering
Proc AUTOMED, 2026, Vol. 3, No 1, Article ID 2533, 2 Pages

Infinite Science Publishing

A novel validation method for high-precision IMU-based handwriting trace reconstruction

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Abstract: The accurate reconstruction of handwriting gestures is crucial for both clinical and research applications. This study validates a Sensorized Ink Pen (SIP) reconstruction algorithm using an electromagnetic sensor as ground truth. Orientation, acceleration, and velocity signals were compared using RMSE metrics. Analyses were performed for "On-Sheet" and "In-Air" movements exhibiting larger discrepancies for rapid "In-Air" movements. Results show that the SIP reconstruction achieves mean positional errors of 3.5 mm. This validation framework ensures reliability for future handwriting-based assessments and machine-learning applications.

I. Introduction

Handwriting is an extremely complex skill involving several cognitive and motor centers, making it a valuable biomarker for learning disorders and cognitive decline [1], as it offers meaningful insights which may aid screening and monitoring procedures.

Handwriting analysis should yield information regarding both the written process, related to all temporal/frequency domain features of handwriting and product, related to the spatial features and quality of the written text. Several theoretical approaches have been proposed for the analysis of these two domains including the use of digitizing tablets, which, however, attenuate the naturalness of the handwriting act, due to a modified surface. To address this, Nearlab (Politecnico di Milano, DEIB) developed a Sensorized Ink Pen (SIP) which is an ink pen designed to write on paper, equipped with an IMU and a piezoelectric pressure sensor [1]. The SIP has already been employed in a series of studies regarding the extraction of process-related features during handwriting. Despite promising results in the context of dysgraphia and Parkinson's Disease (PD) classification [2] the possibility to reconstruct written product is of crucial importance in the diagnostic process as it allows to highlight disease-specific spatial features, for example "*micrographia*" in the case of PD. Previous work developed a trace reconstruction algorithm to extract written trace directly from the IMU signals [3]. This approach presented some promising results but lacked validation which could assess reconstruction quality, detect sources of error and propose improvements. For these reasons this work proposes a robust validation method to quantitatively characterize reconstruction spatial accuracy, a prerequisite for diagnostic feature extraction.

II. Material and methods

To validate reconstruction quality the NDI Aurora® sensor was employed, which is a small sized (0.3 mm in diameter) Electromagnetic (EM) sensor with 6 DoF. It can only function within an EM field produced by generator in a specific portion of space. This limits its use in ecological or real-world settings, which are useful for studying temporal evolution in pathologies such as Parkinson's disease (PD).When the sensor is in the EM field, an electrical current is induced and its variations allow to determine the sensor's location with an accuracy of 1.12 mm for position and 0.58 mm for orientation. The Aurora sensor was rigidly mounted on the IMU embedded in the SIP.

In terms of raw data, the SIP acquires acceleration and angular velocity (50 Hz) whereas Aurora acquires position and orientation (40 Hz). Firstly, Aurora was oversampled to correspond the SIP's sampling frequency. Subsequently, both signals underwent temporal alignment, measuring units were matched, and a low pass filter was applied at 7 Hz to remove high frequency noise. The IMU-Tip distance, required to reconstruct SIP's trace, was estimated through pivot calibration [4]. Following the algorithm proposed in [3] a Kalman Filter was applied to the SIP to fuse acceleration and angular velocity, in this way orientation was extracted and compared with Aurora's, after conversion into discrete Euler angles. Aurora's position was derived once to extract velocity and twice to extract acceleration. For the SIP, the projection of gravity onto the orientation at each timepoint was removed from global acceleration, thus allowing linear accelerations in the SIP and in Aurora to be compared. Next, SIP acceleration was integrated to obtain velocity. The tip position was reconstructed in Aurora and in the SIP using the estimated IMU-tip and Aurora-tip distances and the approach presented by Bu et al. [5]. The final traces were not directly comparable, due to distinct reference systems. To compare the traces, the Kabsch algorithm [6] was applied to perform alignment as visible in Fig. 1. Disparity was then extracted as the mean distance between the two reconstructed traces and reconstruction signals were compared through RMSE.

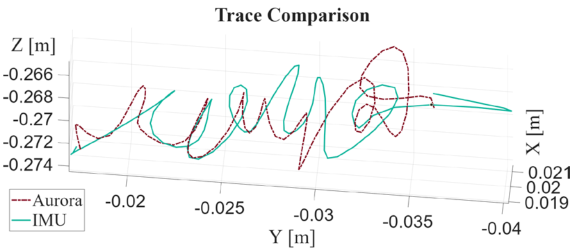

Figure 1: Example of reconstructed and aligned traces from IMU on Sip (blue) and Aurora (red)

Finally, traces were divided into "In-Air" and "On-Sheet" segments and statistical difference was assessed through a Mann-Whitney-U test to understand whether these two movements had different reconstruction profiles.

III. Results and discussion

A total of 52 words and 41 in air movements were analyzed. Four out of five variables exhibited a statistically significant difference between "In-Air" and "On-Sheet" segments. Table 1 reports the comparison of the two traces as absolute and relative magnitude of the disparity vector.

Table 1: Mean and relative disparity with Standard Deviation (SD) for tip position comparison between Aurora and SIP.

Mean Disparity $[m]$	0.0035 ± 0.0019
Relative Disparity [%]	14.6 ± 0.032

Considering that acquired handwriting stroke widths ranged between 3–7 mm, the observed mean error (3.5 mm) remains within the same order of magnitude, suggesting acceptable geometric fidelity (under 30% of maximal stroke expansion). Table 2 reports the results of the comparison on signals which lead to the tip position reconstruction. The adopted RMSE and spatial disparity metrics quantify global reconstruction fidelity. While they do not directly assess preservation of specific diagnostic features, they represent a necessary first step to ensure that reconstructed traces remain within millimeter-scale deviations. Preliminary results reveal measurable errors, especially during the reconstruction of In-Air movements, highlighting the intrinsic challenges associated with accurately capturing fine-grained gestures and suggesting the following considerations: (i) The observed velocity-related discrepancies indicate that standard discrete integration approaches may be suboptimal for this specific application, motivating the exploration of alternative integration strategies; (ii) In-Air movements tend to present greater reconstruction complexity due to their rapid execution and short duration, which may challenge the stationarity assumptions underlying the Kalman Filter. Additionally, orientation estimates during In-Air movements are more susceptible to increased uncertainty when compared to On-Sheet movements as they produce more translation than orientation change. This final observation coupled with the statistical analysis suggests that a separate reconstruction for the two movement types could improve accuracy.

Table 2: RMSE and relative SD computed from the two distributions for orientation, acceleration norm (Acc Norm), and velocity (Vel Norm), together with p-values assessing statistical differences between the distributions.

Variable	**RMSE** On-Sheet	**RMSE** In-Air	**p-value**
Roll [°]	0.80 ± 0.23	1.02 ± 0.36	<0.05
Pitch [°]	0.64 ± 0.26	0.83 ± 0.40	<0.05
Yaw [°]	0.49 ± 0.17	0.90 ± 0.67	<0.05
Acc Norm $\left[\frac{m}{s^2}\right]$	0.81 ± 0.17	1.46 ± 0.49	<0.05
Vel Norm $\left[\frac{m}{s}\right]$	0.051 ± 0.019	0.062 ± 0.041	0.99

IV. Conclusions

The primary contribution of this study lies in establishing the foundations of a novel validation approach to enable the analysis of orientation and translation separately, enabling a comprehensive examination of their characteristics differentially for "In-Air" and "On-Sheet" movements. Future works should employ this approach to evaluate orientation and translation reconstruction methods and identify optimal solutions through a comparative lens. The employed dataset was rather limited, and the incorporation of a more substantial cohort of subjects is recommended. Moreover, an analysis regarding the way segment specific characteristics influence trace and which errors are to be considered acceptable should be conducted.

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