Paper, pen and ink: an innovative system and software framework to assist writing rehabilitation

Leonardo Guardati*, Filippo Casamassima*, Elisabetta Farella†* and Luca Benini‡*
*Department of Electrical Electronic and Information Engineering (DEI), University of Bologna, Italy
†ICT Center - Fondazione Bruno Kessler, Trento, Italy
‡Integrated System Laboratory, Eidgenössische Technische Hochschule Zürich, Switzerland

***Abstract*—Handwriting analysis and rehabilitation is an actively explored area in the diagnosis and treatment of Parkinson's disease, which is usually performed in an ambulatory setting under direct supervision of a clinician. Technology can play an important role to reduce the need of therapist assistance and to enhance diagnostic precision through the computation of non-subjective handwriting quality metrics.**
This paper introduces an innovative handwriting rehabilitation system for PD patients, which ensures a natural writing experience as it is based on pen, ink and paper (as opposed to tablet and stylus). The system is designed for human-in-the loop operation and it can analyze handwriting in real-time and provide vocal feedback to guide the patient during the execution of exercises. We present a detailed comparative characterization of the key components of the system, namely wireless digital pens; in addition, in-field test assessed the system usability regarding its ease of use, calibration precision and vocal feedback effectiveness.

I. Introduction

Handwriting analysis through technology-enhanced devices brought the opportunity to accurately capture and analyze writing features and opened the way to a whole new range of applications to augment the handwriting experience. One of the fields where this trend is being leveraged is the rehabilitation and assessment of illness severity.
An effective solution targeting this application field must satisfy demanding requirements in terms of spatial-resolution, precision of the input device and an appropriate working area. Furthermore, for "human-in-the loop" training and rehabilitation applications, requiring feature analysis for direct feedback provisioning, the system must meet strict real-time constraints. We present a system designed with all the above mentioned requirements. We present an in-depth quantitative characterization of working area, spatial precision and real-time performance. Design constraints were derived from the application domain for fine motor skill rehabilitation and handwriting dysfunctions; a common scenario for Parkinson's Disease patients.
Parkinson's Disease (PD) and Parkinsonism in general are neurological disorders that can impact a person's fine movements abilities [1]. Clinical evidence has shown that a typical PD symptom affecting the gait (Freezing of Gait or FoG [2]) can also affect the distal upper-limb fine motor. Attempts have been made to tackle these problems both in the disease severity assessment [3] and in the rehabilitation therapy fronts. Handwriting is a preferred target domain to find interesting clinical approaches to study and mitigate the disease progression involving the distal upper-limb fine motor skills, as shown by [4], [5].
The setups used in existing solutions, often involve a computing workstation where the patient interacts with an input device like a tablet, a digitizer or some custom device connected to a PC. Those approaches need the clinician to be always present during the exercise sessions to help the patient deal with the interaction. Such systems can be uncomfortable to use, in particular at home, for people not used to technology, even though the patients are highly motivated to avoid the decline or loss of handwriting ability. For example, the use of a tablet and a resistive touch screen as input device can result to be unnatural for a PD patient and can hamper transfer to daily life writing. She/He has to be careful not to lay the hand on the device to avoid glitches on input data, also the perceived effect of sliding the tablet pen on the surface and seeing the computed stroke displayed on the screen is not as natural as a regular pen writing ink on paper.
We have designed a solution to meet the needs of ageing PD patients who are not used to "virtual handwriting" on glassy surfaces. In addition, our handwriting device is fully untethered and does not require a connection to a PC. Furthermore, it has a natural and streamlined user interface which does not require the presence of a clinician during the exercise sessions to guide the patient. The system uses a commercially available digital pen connected to an embedded platform that analyzes the handwriting and gives real-time natural audio feedback to the patient guiding and hinting her/him during the exercise execution. At the same time, the device logs all the data to be then analyzed by the clinician that downloads the exercise sessions data logs into a PC application.
In this scenario the patient can perform the exercises at home, in a comfortable and familiar environment and without the stress induced by a supervisor. Therapists can, in addition, compare the physical handwritten exercise against the data recorded by the device. The system, in fact, enables to extract quantitative information on the writing performance.
The remainder of the paper is organized as follows: in the next section we provide a comparative overview of state-of-the-art approaches adopted in PD handwriting analysis and rehabilitation. Section III describes the system proposed in detail, while in Section IV, we present the algorithms for device calibration and feedback generation. Section V, shows the wireless digital pens characterization to evaluate their suitability for the target application; we also report results of a preliminary test for system usability. The final section draws conclusions on the results obtained and prospects future developments.

II. Related works

Handwriting has been used in the last decades in clinical studies with PD patients to assess the impairment severity

978-3-9815370-4-8/DATE15/©2015 EDAA

and as a rehabilitation approach to delay and mitigate illness progression. In [6] a digitizing tablet (a Wacom device) and a research software tool (MovAlyzeR) were used for diagnostic purposes. Their tests focused on stroke analysis of 1, 2 and 4 cm baseline row height handwriting; assessing the peak velocity, a velocity scaling index and a normalized jerk index. The results show how Parkinsonism affected patients resulted in lower peak velocity and velocity scaling, and a higher jerk. A very interesting work [7] reviews strategies for handwriting analysis, highlighting the use of cueing and its efficacy to initiate and keep a continue handwriting in PD patients [8]. An even more interesting result is the observed benefit of feedback given to the patient during the exercise; the knowledge about her/his own performance helps to improve and motivate the user to do better [9]. Those feedbacks can be given right after the exercise execution or in real-time. Selecting the right frequency and quantity is crucial to avoid any overload that could negatively impact the results. A number of devices have been designed and used for different handwriting applications and their characterisation is useful to understand the physiological limit of the handwriting dynamics and figures; for example in [10], Bashir and Kempf designed a custom pen device called BiSP, consisting of a sensor enhanced Wacom commercial digitizer device, used to analyse and classify biometric features of individuals' handwriting. In [11] a custom tablet device assist the analysis of the 3D force and 2D torque vectors to infer the pen-tip position, velocity and acceleration.

All these works use complex laboratory setups requiring supervision and preventing the opportunity to be autonomously used by the patients at home.

Regarding the use of tablets, an interesting user-study [12] compared writing and sketching using pen and paper versus digital stylus and digitizer on tablets, and concluded that the analog experience cannot be reached using digital tablets because they suffered of the unintended touch problems that in turn lead to unnatural grips. The delay between the writing act and the visual feedback and the friction perceived while writing on the screen glass, led to slower and bigger writing. Another study conducted on children at school [13], concluded that pen and paper resulted in faster and more legible handwriting than writing on touchscreen phones; especially with numerical characters. Considering that our target users, i.e. PD patients, are often aged people and that suffer from fine motor impairments, we believe that touch screens and tablets cannot be as adequate and familiar as paper, pen and ink can be.

Our work introduces a novel approach w.r.t. the solutions described in this section. First, it targets unsupervised exercises i.e. at home on paper. Second, the augmented digital pen is independent from other external devices to log data or extract writing performance features. In fact, data are stored directly on board for further analysis off-line. Third, we target real-time processing and feature extraction for feedback provisioning.

III. System architecture

To pursue our purpose to implement a handwriting tool providing a familiar and natural feeling, we decided to augment a commercial digital pen. Digital pens are input devices able to capture and convert analog writing information created using pen and paper into digital data. Typically this data are used by other applications such as digital notebook, or artistic drawing applications. They can be based on different technologies such as inertial sensing, cameras, infrared or ultrasounds emitters and receivers. Unfortunately, the majority of those digital pens are not open to developers and when an SDK is provided, it is limited to few functionalities. Therefore it is not possible at the moment to develop our algorithm directly on the commercial device. Thus, we identify a couple of them, compliants with application requirements (see Section V), with which it was possible and sufficiently easy to capture spatial and temporal coordinates and developed a prototype add-on board where real-time performance feature extraction and audio-feedback was implemented. We also designed a set of pre-printed sheets reflecting the exercises typically given by therapists. We also use pre-printed elements for calibration and exercise selection at the beginning of a training session.

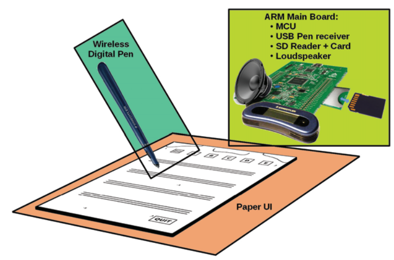

Fig. 1: Hardware Setup.

To better understand the architecture of the system, the description of a typical exercise session is given. The patient conducts the exercises writing with the digital pen on a pre-printed paper corresponding to a specific writing exercise assigned by the therapist and, depending on the level of difficulty, she/he will be supported by visual cues such as pre-printed rows. The Digital Pen provides the handwriting digitized data corresponding to the tip position that are processed by the main board to extract from raw data writing performance features (e.g. speed or size). Depending on the specific exercise, the main board renders an auditive feedback such as a pre-recorded audio message (e.g. "you're slowing down your speed", "please augment the size", "you're doing fine", etc.). At the same time raw data are logged in a SD memory card for off-line further analysis. Therefore, the system considers the user in the loop. In fact, the writing performance extracted by the user interaction with the system generates a feedback that stimulates the user to correct her/his writing, which is again the input to feature extraction from which the feedback is generated accordingly. The user, writing with a normal pen on paper at home, without medical supervision, is relaxed and performs the rehabilitation exercises without stress, giving the best context for performance assessment to the clinical analysis.

The prototype device designed is composed of three main hardware/physical components (Fig. 1): *a*) the Paper UI; *b*) the digital pen; *c*) the main board. The software architecture is composed of the following parts (Fig. 2): *a*) the NuttX RTOS;

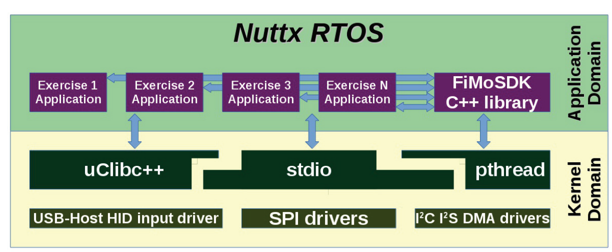

Fig. 2: Software Architecture.

b) the FiMoSDK library; *c*) the exercises applications.
The digital Pen receiver is connected to the main board using the USB interface and the USB 2.0 FS[1] controller unsing the HID[2] class protocol extension.
The Speaker is directly connected and driven by the output pins of the audio codec chip [14], the chip uses two interfaces with the MCU: an I2C interface for control and an I2S interface for audio samples transfers. Finally the SD Card reader is connected to the MCU using an SPI interface.

A. *Digital Pens*

In our work, we focused on two different commercially available digital pens; the Staedtler DigitalPen 990 [15], and the Wacom Inkling [16]. Both devices work using infrared and ultrasound technology. The pen is paired with a receiver (merged in the main board to form a single box) fixed on the paper. The pen simultaneously transmits infrared encoded beacons and ultrasound bursts. The receiver triangulates the pen tip position counting the time interval between the IR reception and the ultrasound reception by two different ultrasounds receivers. Both devices have been tested and characterised to assess their fitness for the application (see Section V.A).

B. *Paper UI*

The digital pen selected enables writing on regular (blank) paper without pre-printed patterns. However, to implement the training protocol designed by therapists for at home rehabilitation, we needed to design a Paper User Interface to enable the selection of daily exercises and to implement the specific assignments. At the same time, to capture the writing exercise correctly, the paper enables an initial calibration. The Paper UI therefore provides a framework where the user can interact with the training program by means of input commands and audio guidance. Fig. 3 shows the layout of an example page where the various elements are highlighted:

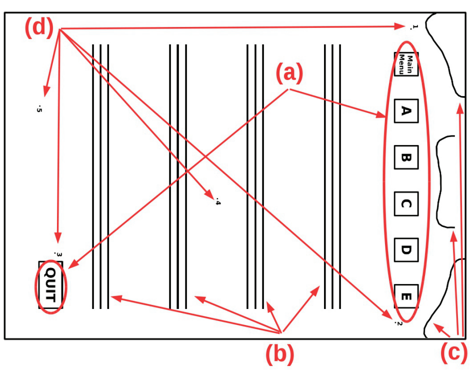

Fig. 3: Paper User Interface elements layout. a) Menu Buttons; b) Exercise rows; c) Pen Receiver suggested positions; d) Calibration points.

a) Menu Buttons: The user, following the audio voice indications, writes a cross inside a box to select a specific command or to activate an exercise.

b) Exercise Rows: These are examples of visual cues customized on the specific exercise. Depending on the configuration parameters the rows can be present or not, partially present and thay can be set to different heights and the paper must be printed accordingly.

c) Pen Receiver suggested positions: The receiver can be placed anywhere around the paper, the top positions are only suggestions.

d) Calibration Points: The prototype system works with 5 calibration points. Their coordinates in the "default" reference system are stored in the application configuration file. They can be changed and/or increased in the printed layout and in the configuration file.

C. *Main board*

To prepare a preliminary prototype of the main board, we exploited the availability of the STM32F4-Discovery, based on a Cortex-M4 MCU with 1024KB of Flash memory, 192KB of RAM and running at 168MHz. The board includes many useful peripherals, such as USB-OTG FS, USART and SPI interface; it also includes an audio CODEC chip.
The main board therefore extended the Discovery board with an SD card reader using the SPI and a loudspeaker to the audio jack. We used the USB interface and micro connector to connect the digital pen receiver, and the audio CODEC for the audio feedback rendering. The board can be connected to a host PC via USART for console interfacing, for debug and development purposes. All this hardware components form a single entity to be packaged in a box.

D. *NuttX RTOS*

Among the Operating Systems targeting the selected board, the NuttX [17] RTOS has been chosen; it has mature support for the board, is extremely modular and mimic the POSIX standard offering a functional shell and a set of utility to manage the system. It supports C++ language with most of the OOP language features and offer uClibc++, a standard C++ library implementation. NuttX has a binary loader to run applications from a file stored in any local or remote media. It also has POSIX `pthread` facilities to implement a multithread application, like our FiMoSDK library. NuttX is supported by an active developers community and uses a BSD[3] license to distribute the code.
We integrated the USB-HID driver with the missing logic to support the digital pens. For the audio codec device, we integrated the corresponding STM libraries in the NuttX project. The work needed to patch NuttX in order to support the USB pens, has been the implementation of the input driver the RTOS exposes to the applications.

E. *Fine Movements SDK*

The FiMoSDK C++ library is a framework we designed to be used to implement handwriting exercises. `HWInferrer` and `AudioFB` are the entry-point classes for the application code; `HWInferrer` infers handwriting features using all the rest of the framework's classes. `AudioFB` manages the output of audio messages, and can be thought of and used as a `printf()` function that plays the audio file instead of writing messages on the console.
A `RawData` instance is used to receive the samples from the pen and to package them into `Sample` instances for further uses by `HWInferrer` and for logging purposes.
The `Stroke` class is instantiated to store contiguous sets of `Samples` having the `Tip` boolean attribute set. Each `Stroke` is analysed by the `HWInferrer` to compute its features like length, bounding box, speed and direction.
The `rect` class produces support objects to

[1]FS: Full-Speed; a signaling rate of 12Mbit/s introduced by USB 1.1.

[2]HID: Human Interface Device; a standard USB device class extension.

[3]BSD: Berkeley Software Distribution

manage bounding boxes and allows mutual boolean comparisons like intersection or inclusion. `calibrationDesc_t`, `calibrationPoint_t` and `transformationParams_t` are supporting structures used to manage the calibration as explained in the following section.

The `HWInferrer`, `RawData` and `AudioFB` classes are designed to execute their main task using a separate thread of code execution. All the objects that may fail, throws `FiMoExceptions` if they do reach an error condition.

IV. Algorithms

In the following we describe the calibration and the logic governing the audio feedback, both algorithms implemented in the FiMoSDK.

A. Calibration

For the digital pens to work, it is important to place the pen receiver on a fixed position w.r.t. the writing paper. Once started the writing session, the receiver must be integral with the paper to avoid distorted data acquisitions.

Since the system must be used by the patient without supervision at home, it is important to make it robust w.r.t. the receiver placement.

The problem to be tackled each time the system is started, is to find the right parameters for the reference roto-translation with respect to a "default" reference taken once with the receiver placed in a well known position. The solution is to use n calibration points' coordinates (5 points in our case), compare them with the same points taken in the "default" reference system and infer the parameters of the following linear roto-translation transformation:

$$\bar{P_r} = \bar{\bar{A}} \cdot \bar{P_a} + \bar{b} \quad \equiv \quad \begin{bmatrix} P_{r_x} \\ P_{r_y} \end{bmatrix} = \begin{bmatrix} a_{xx} & a_{xy} \\ a_{yx} & a_{yy} \end{bmatrix} \cdot \begin{bmatrix} P_{a_x} \\ P_{a_y} \end{bmatrix} + \begin{bmatrix} b_x \\ b_y \end{bmatrix}$$

where: $\bar{P_r}$ is one calibration point from the "default" reference system; $\bar{\bar{A}}$ is the rotation matrix of the linear transformation; $\bar{P_a}$ is the corresponding calibration point in the "actual" reference system; $\bar{b}$ is the translation component of the linear transformation. In this linear system, $\bar{P_r}$ and $\bar{P_a}$ are known; $\bar{P_r}$ coordinates were taken once and are stored among the configuration data of the system. $\bar{P_a}$ are retrieved at run-time during the calibration sequence. The unknown data are $\bar{\bar{A}}$ and $\bar{b}$. Theoretically 3 calibration points would solve the equations; but the noise and the human inaccuracy in tapping on the exact calibration point suggest to include some redundancy. The solution is to create an over-determined linear system using as many points as possible and find the optimal solution that minimize the error from the exact one; the minimization in the least square sense is proved to be an effective technique for linear systems affected with normal noise. The core of the calibration is based on the Least Square fitting algorithm implemented in the GSL project [18]. As a tradeoff between accuracy and usability, we reduced the set point to 5. The system passed as input to the library is $\bar{y} = \bar{\bar{X}} \cdot \bar{c}$; where: $\bar{y}$ is the vector of the observations ($\bar{P_{a_n}}$ in this case); $\bar{\bar{X}}$ is the matrix of the predictors ($\bar{P_{r_n}}$ in this case); $\bar{c}$ is the vector with the unknown parameters to be fitted ($\bar{\bar{A}}$ and $\bar{b}$ in this case).

The numerical method also computes the coefficient of determination R^2 that indicates how well the regression fits the model, ranging from 0 (no meaning) to 1 (perfect fit).

The algorithm implemented in the library uses the R^2 coefficient to filter out potential outliers (for example if the user tap on a wrong point). The code tries to use all 5 calibration points in the LS fitting, but if the R^2 coefficient is under a selected threshold (part of the application configuration data), then 5 iterations follows where the LS method is used with 4 calibration points; each time excluding a single point. If the results show 4 solutions with a good R^2 and only one result with a bad (under-threshold) R^2, then the code can discard the single calibration point that was wrongly acquired and validate the calibration parameters using the remaining 4 valid points.

B. Audio Feedback

An important aspect is the audio feedback generation management. During the exercise session, the user periodically receives audio messages indicating her/his performance; whether she/he is doing good or is writing out of the exercise specifications. The approach used in the prototype demos, uses a set of configuration parameters to fine-tune the output frequency and the threshold over which the messages should be given.

The demo application checks in real-time for stroke features like size and velocity. For each feature a numerical `TargetValue` is stored in the configuration, together with two thresholds; a `ThresholdGood` value and a `ThresholdBad` value. The thresholds are percentages of the distance between the actual value from the `TargetValue`. Using these three parameters, a `Score` value is computed that ranges from $[-1; +1]$ using the relation shown in Fig. 4.

In addition, the application switches between different states

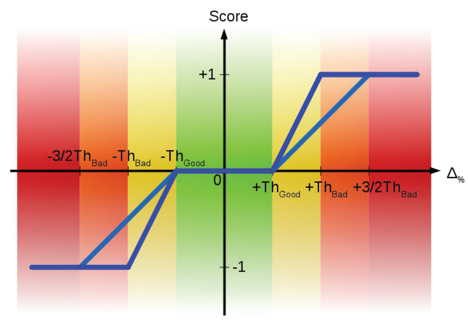

Fig. 4: Score relative to the difference between measured value and TargetValue. Th_{Bad} and $3/2 * Th_{Bad}$ are used depending on the application state.

not to overload with too frequent feedbacks the user prolonging an inadequate performance, "relaxing" the `ThresholdBad`. The application is normally in a `Neutral` state; during the exercise, if the user goes out of `ThresholdBad`, the state gradually switches to a `Relaxed` state, through two intermediate states: `PreRelax1` and `PreRelax2`. The state changes if the distance overflows the relaxed `ThresholdBad` value, as shown in Fig.5.

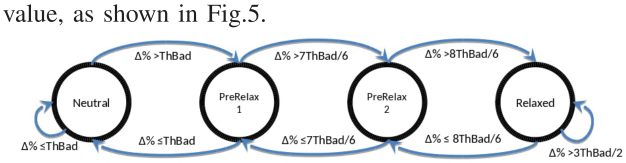

Fig. 5: The state transitions happens with values from ThBad to $1.5{\cdot}$ThBad offering an adaptive behaviour to help and motivate the user.

V. Experimental Results

Here after we present the results obtained by the wireless digital pens characterization. Afterwards, a preliminary test on healthy users is described to assess system usability.

A. Digital Pen Characterisation

As previously explained, a system designed to offer real-time handwriting analysis and feedback, must necessarily meet specific requirements. At this regard, the choice of the input device, i.e. the digital pen, is crucial. It acts in fact as the sensing element of the system and therefore needs to be validated in terms of spatial resolution, working-area, sample frequency and accuracy. To the purpose, we tested in particular two digital pens: the Staedler Digital Pen 990 and the WACOM Inking pen. Results are presented in the following.

1) Staedtler Digital Pen 990

The Staedtler DigitalPen is a commercially available USB-FS 1.1 input device. The device adheres to the official HID USB profile using a proprietary protocol extensions to produce the data. The physical device uses infrared and ultrasounds emissions to track the pen tip position. The time difference between light and sound propagation is used to track the pen tip distance and to triangulate its position using two embedded ultrasound receivers. The pen tip reacts to pressure with a switch that, when in Mouse mode, is used as the left mouse button. The pen is also equipped with an additional button located in the pen body. When connected to a host device via the USB cable, the pen can work in two different modes; “Mouse” mode and “Pen” mode.

When the device is in mouse mode, the host recognizes it as a standard HID pointing device. The working area of the physical pen is reduced to a rectangular area variable with the screen resolution of the PC.

When the device is in pen mode, the device changes the HID data descriptor used to send the samples. The working area is determined by the receiver range. When in Mouse mode, the working area is typically reduced to a rectangle, which size varies with the host device screen resolution. For example, testing the pen with a device having a screen resolution of 1280×800 pixels, the working area is 166×125 mm^2. Coordinates (X, Y) are contained within the intervals shown in Tab. I. Comparing the coordinate ranges with the length on paper, the spatial resolution of the device is of $48pt/mm$ (or $0.021mm/pt$). The precision is reduced by the noise present in the data produced. The noise absolute amplitude is of 6 points in each direction (Fig. 6). Thus the resolution locates each sample within a $0.126 \times 0.126mm^2$ box. There is no difference with the spatial accuracy when the device is in Pen mode or in Mouse mode. On the other hand, the timing of the samples produced differs between Pen mode and Mouse mode. When the device is in Mouse mode, it produces a new sample every $15ms$ ($\sigma = 3ms$). When in Pen mode, the samples are presented to the host device in pair every $30.9ms$ ($\sigma = 6.4ms$). The resulting single sample time performance in steady state is equivalent to the one in Mouse mode, but with reduced protocol overhead. The timing results are summarized in Tab. II.

Description	Unit	Value	
		Mouse Mode	Pen Mode
X-Coordinate Range	pt	$\sim [1000; 9000]$	$\sim [-13000; 13000]$
Y-Coordinate Range	pt	$\sim [0; 6000]$	$\sim [0; 16000]$
X length on paper	mm	166	400
Y length on paper	mm	125	300

TABLE I: The Staedtler Digital pen 990. Ranges in “Pen” mode and “Mouse” mode when the host device has a screen resolution of 1280 x 800 pixels.

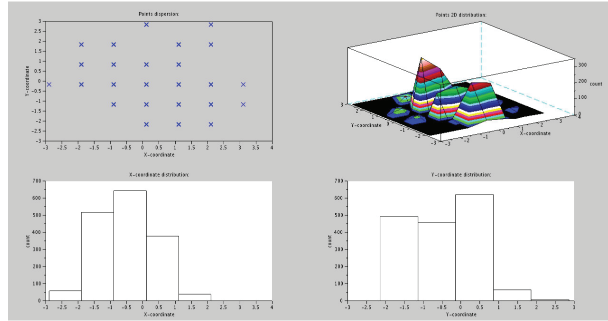

Fig. 6: The Staedtler Digital pen 990 distibution of the coordinates of the pen tip held still caused by noise.

Device Mode	USB Transaction Timings		Single Sample steady state timings	
	Period (ms)	Frequency (Hz)	Period (ms)	Frequency (Hz)
Mouse (one sample)	15	66	15	66
Pen (two samples)	30.9	32	15.45	64.7

TABLE II: The Staedtler Digital pen 990 samples timings in in “Pen” mode and “Mouse” mode

2) Wacom Inkling

The WACOM Inkling pen is a USB 2.0 FS device. It is a composite device embedding a MSC[4] memory device, and an HID input device. The interface can be switched and the two devices cannot be simultaneously active. The device, when connected to a USB Host and used as an HID device, reduces the working area to a box of 200×150 mm^2. The pen HID device provides samples that include the pen tip position, the pen tilt and the tip pressure intensity. The working area for the Wacom pen (X and Y ranges) is detailed in Tab. reftab:WacomRange, achieving a maximum rectangle of 200×150 mm^2. Comparing the coordinate ranges with the actual length on paper, the spatial resolution of the device is not proportional. The X resolution is of $9.6pt/mm$ (or $0.1042mm/pt$). The Y resolution is of $12.8pt/mm$ (or $0.0781mm/pt$). The coordinates received by the host are not affected by noise, this is probably because the receiver pre-filters the raw data before sending it over the USB interface. The samples are produced on average every $\sim 6.6ms(\sigma = 0.7ms)$. The USB transactions are distributed with intervals mostly of $6ms$ or $7ms$.

Description	Unit	Value
X-coordinate range	pt	$[0; 1920]$
Y-coordinate range	pt	$[0; 1920]$
X length on paper	mm	200
Y length on paper	mm	150

TABLE III: The Wacom Inkling ranges and length.

3) Comparison

After the characterisation, some considerations can be done regarding the performance of each device w.r.t application requirements.

Range: Both the devices have similar ranges, and both have a dual mode (“Mouse” mode and “Pen” mode); the big difference is that the Steadtler device has been designed to allow mode switch when connected to the USB Host, while this is not true for the Wacom device[5].

Timings: The Wacom device presents a faster timing profile

[4]MSC: Mass Storage Class. A standard USB device class extension.

[5]The mode switch command is not available for the Wacom pen, although is likely be to present like it is on the Staedtler pen.

for sample transmission that is $\sim 2.5\times$ the Steadlter device. Nevertheless both device resulted sufficiently fast to allow the handwriting analysis needed by the application.
Noise/Precision: Both devices presents a similar precision, due to the fact that both uses the same underlying technology to track the pen tip. The main difference lies in the fact that the Wacom device pre-processes the raw data, smoothing the resulting stroke and filtering out the noise, while the Steadtler device transmits non pre-filtered raw samples.
X-Y aspect ratio: The Staedtler have a square aspect ratio that results in easier software management of the data (calibration, measurements, ecc.); the Wacom, having an anisothropic resolution, leads to a more complex handling of coordinates transformations.
Extended information: The Steadtler device, along with the coordinate position, transmits the binary status of the pen tip; pressed/released. The Wacom device transmits additional information; the pen tip is provided with a 1024-level pressure sensor, furthermore the pen tilt is transmitted in the packet. This data helps to compensate the effect of different handholds on coordinates calculation.
In this first system prototype we privileged the size of the working area and the isotropic aspect ratio, choosing the Steadtler pen w.r.t. the Wacom pen, even thought the latter offers interesting additional features. We therefore compensate the weaknesses of the Steadtler pen, e.g. filtering the noise on coordinates in the main board firmware.

B. Field Tests

A preliminary test, conducted on 5 healthy subjects, was aimed to assess the system usability. The main aspects under test were *a*) calibration; *b*) sound quality; *c*) physical setup.
Users were required to write repetitively the character l without interruptions within given reference rows at a given (parametric) speed, filling the entire row height. Test revealed a minor drift $(1-2mm)$ on coordinates for both pens due to different pen handhold and inclination between the calibration phase and the actual exercise execution. This drift can be mitigated by adding or subtracting the projection of the tilt to the received coordinates (available on Wacom pen only).
The sound quality of the digital samples is lossless PCM encoded audio sampled at 44000Hz with 32bit resolution; the codec outputs, the internally amplified signal and the final audio quality perceived by the users depends on the quality of the loudspeakers. During the development of the prototype, different loudspeakers have been used with different results, ranging from signal intensity of loud/noisy for low quality speakers to loud/clear for good quality ones; in all cases the vocal messages content where always intelligible.
The physical setup was acknowledged as unobtrusive and usable and familiar as pen and paper.

VI. Conclusion and Future Works

In this paper, we presented the work of design and implementation of a novel tool to be used in writing rehabilitation. We presented the characterization results and the feedback received by preliminary user tests.
The system targets in particular PD patients that experience difficulties with writing. Our aim is not only to provide a daily life instrument for training at home, but also to enable PD experts to investigate the impact of writing exercise to improve fine motor skills. Furthermore, the configurability of the system will also support the study of which feedback strategy is most user-friendly and effective in the long-term.
Future work therefore includes a complete assessment of the prototype system on PD patient with the help of therapists, which results will support the optimization and fine-tuning of the system.

Acknowledgment

Research funded by the European Union - Seventh Framework Programme (FP7/2007-2013) under grant agreement n.288516 (CuPiD project). Authors would like to thank Prof. Alice Nieuwboer, Evelien Nackaerts, Dr. Elke Heremans and Marc Beirinckx for their contribution.

References

[1] J. Jankovic, "Parkinson's disease: Clinical features and diagnosis," *Journal of Neurology, Neurosurgery and Psychiatry*, vol. 79, no. 4, pp. 368–376, 2008.

[2] J. G. Nutt *et al.*, "Freezing of gait: moving forward on a mysterious clinical phenomenon," *The Lancet Neurology*, vol. 10, no. 8, pp. 734 – 744, 2011.

[3] M. P. Caligiuri *et al.*, "Handwriting movement kinematics for quantifying extrapyramidal side effects in patients treated with atypical antipsychotics," *Psychiatry Research*, vol. 177, no. 12, pp. 77 – 83, 2010.

[4] M. M. Ponsen *et al.*, "Impairment of complex upper limb motor function in de novo parkinson's disease," *Parkinsonism & Related Disorders*, vol. 14, no. 3, pp. 199 – 204, 2008.

[5] H.-L. Teulings *et al.*, "Parkinsonism reduces coordination of fingers, wrist, and arm in fine motor control," *Experimental Neurology*, vol. 146, no. 1, pp. 159 – 170, 1997.

[6] M. P. Caligiuri *et al.*, "Quantitative measurement of handwriting in the assessment of drug-induced parkinsonism," *Human Movement Science*, vol. 25, no. 45, pp. 510 – 522, 2006.

[7] E. Nackaerts *et al.*, "Relearning of writing skills in parkinson's disease: A literature review on influential factors and optimal strategies," *Neuroscience & Biobehavioral Reviews*, vol. 37, no. 3, pp. 349 – 357, 2013.

[8] A. b. Nieuwboer *et al.*, "Cueing training in the home improves gait-related mobility in parkinson's disease: The rescue trial," *Journal of Neurology, Neurosurgery and Psychiatry*, vol. 78, no. 2, pp. 134–140, 2007.

[9] M. A. Guadagnoli *et al.*, "The relationship between knowledge of results and motor learning in parkinsonian patients," *Parkinsonism & Related Disorders*, vol. 9, no. 2, pp. 89 – 95, 2002.

[10] M. Bashir *et al.*, "Advanced biometric pen system for recording and analyzing handwriting," *J. Signal Process. Syst.*, vol. 68, pp. 75–81, jul 2012.

[11] J.-F. Luo *et al.*, "A novel f-pad for handwriting force information acquisition," in *Proceedings of the 8th International Conference on Intelligent Computing Theories and Applications*, ICIC'12, pp. 138–144, 2012.

[12] M. Annett *et al.*, "The pen is mightier: Understanding stylus behaviour while inking on tablets," in *Proceedings of the 2014 Graphics Interface Conference*, GI '14, pp. 193–200, 2014.

[13] V. Bahamóndez *et al.*, "Analysis of children's handwriting on touch-screen phones," in *Proceedings of the 15th International Conference on Human-computer Interaction with Mobile Devices and Services*, MobileHCI '13, pp. 171–174, 2013.

[14] Cirrus Logic Inc., *CS43L22 - Low Power, Stereo DAC w/Headphone & Speaker Amps*, 03 2010.

[15] Staedtler, "Digital pen 990 device." http://www.staedtler.com/.

[16] WACOM, "Inkling device." http://www.wacom.com/.

[17] G. Nutt, "Nuttx: a real-time operating system (rtos) with an emphasis on standards compliance and small footprint." http://nuttx.org, 2007–2014.

[18] B. Gough, *GNU Scientific Library Reference Manual - Third Edition*. Network Theory Ltd., 3rd ed., 2009.