

Internal Model Control to Characterize Human Handwriting Motion

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Abstract: The main purpose of this paper is to consider the human handwriting process as an Internal Model Control structure (IMC). The proposed approach allows characterizing the biological process from two muscles activities of the forearm, named ElectroMyoGraphy signals (EMG). For this, an experimental approach was used to record the coordinates of a pen-tip moving on (x,y) plane and EMG signals during the handwriting act. In this sense direct and inverse handwriting models are proposed to establish the relationship between the muscles activities of the forearm and the velocity of the pen-tip. Recursive Least Squares algorithm (RLS) is used to estimate the parameters of both models (direct and inverse). Simulations show good agreement between the proposed approach results and the recorded data.

Keywords: Human handwriting process; Internal Model Control structure (IMC); the muscular activities; direct and inverse handwriting models; velocity of the pen-tip; Recursive Least Squares algorithm.

Received January 6, 2015; accepted September 22, 2015

1. Introduction

Handwriting is an individual activity, as well as the language. It is also classified as a means of communication and expression of thought. Therefore, writing becomes not only advantageous but actually indispensable in daily life.

The characterization of the handwriting process has been the subject of several investigations. Considering the handwriting motion as a mass moving in a viscous environment, Mc-Donald proposed in [9], an electronic version of a mathematical model proposed by Van Der Gon, [17]. Yasuhara proposed non-linear differential equations to describe the studied process, [18]. The velocity measurements of the handwriting act have attracted the attention of other researches who considered it as a means of distinguishing between the different kinds of the graphic traces. Plamondon is the first to confirm that the velocity profiles of this process are approximately bell shaped, [12]. Alimi characterize in [1] the on-line velocity profile of some letters by the use of beta-elliptical model. Other handwriting models based on the velocity profile were presented in [7] and [3]. Considering the different complexities involved in the handwriting motion, this paper considers Internal Model Control (IMC) technique to model the human handwriting process.

Based on an experimental approach, the corresponding structure contains direct and inverse handwriting models that are based on the relationship between the pen-tip velocity and two muscles activities of the forearm. Indeed, the proposed IMC structure shows that electromyography signals of the forearm muscles contain useful information reflecting the movement of

the hand during the writing motion.

Recursive Least Squares algorithm (RLS) allowing is used to estimate parameters of both models.

The remainder of this paper is organized as follows: In Section 2, an experimental approach allowing to record Arabic letters, some geometric shapes and EMG signals, is presented. Section 3 emphasizes on presentation of the relationship between the handwriting shapes (letters and geometric forms) and the velocity profile of the pen-tip moving on (x,y) plane. In this section an internal model control structure is proposed to mimic the global generalized handwriting model. Simulation results are showed on Section 4. Section 5 presents concluding perspectives.

2. Experimental handwriting approach

The study of handwriting movement according to (x,y) plane shows that this last one is mainly based on two electromyography signals EMG1 and EMG2, of the most active forearm muscles during the handwriting motion, namely the "Abductor Pollicis Longus" and "Extensor Capri Ulnaris", [15] and [4]. The first muscle is responsible of the vertical displacement and the second is responsible of the horizontal motions, as shown in Figure 1.



a) Abductor Pollicis Longus. b) Extensor Capri Ulnaris.

Figure 1. Forearm muscles used on the experimental approach.

It is important to note that, generally, when a writer had to produce lines or shapes in a non-preferred writing direction, the performance is less precise and more instable. The handwriting velocity increases in the less curved form and decreases in the most curved. Indeed, all individuals have preferred movement's directions. These preferences influence the production of the graphic form. Meulenbroek proved that there is a preference to produce vertical traces, from up to down, and horizontal traces to the right, for the Latin script, and to the left, for the Arabic script. He also showed that vertical lines are faster and more accurate than horizontal lines, [10].

Using these analysis and in order to construct an experimental basis to characterize handwriting process, students from Hiroshima City University wrote a variety of shapes (horizontal, vertical, complexes, rapid and slow movements, Arabic cursive letters) several times. Table 1 presents the different considered shapes. It's important to note that these students are not used to write cursive Arabic letters, this makes the characterization of this biological process more difficult.

These Japanese students was comfortably seated in front of a computer monitor and wrote on the pen tablet (WACON, KT-0405-RN) while looking at the computer monitor that displayed the written traces. Two electromyography signals, EMG1 and EMG2, were simultaneously recorded by the means of bipolar surface electrodes (MEDICOTEST, Blue Sensor N-00-S), placed on two forearm muscles. The recording of the signals is registered into the data recorder (TEAC DR-C2) through the pre-amplifiers (TEAC, AR-C2EMGI). To reduce the influence of noise of EMG signals, they wrap their forearms by bandage. Positions of the pen-tip on (x,y) plane and the pressure exerted by this last one on the digital table are also recorded during the time of writing. The measuring data are synchronized by sending a step signal from the parallel interface port on the computer to the data recorder, as shown in Figure 2 and 3.

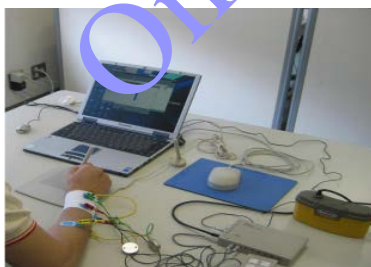


Figure 2. Experimental approach

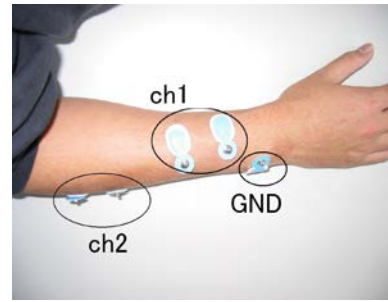


Figure 3. Positions of the surface electrodes ch1 and ch2 to measure EMG1 and EMG2 signals, respectively

Compared with other biological signals, EMG signals are noisy and contain complicated transient phenomena, disruptive signals resulting from various sources, such as electromagnetic phenomenon sector and noise associated with electrodes and uncertainties of measures, electromagnetic induction, motion artifacts, interaction of different tissues, etc. Although, it is difficult to get the useful information from activities of muscles. For this, a variety of signal processing techniques are used to make EMG waveforms easier to interpret. Indeed, the fluctuation of EMG's magnitudes can be filtered to obtain new curves called Integrated EMG (IEMG), as shown in Figure 4.

Table 1. Considered Arabic letters and geometric forms

Description of shape	Shape
Line left to right and then back to starting point	
Line from right to left and back to starting point	
Line from top to bottom then return to the starting point	
Line from bottom to top and back to the starting point	
Circle in a clockwise motion	
Circle in a movement to the left	
Closed triangle in a clockwise motion	
Closed triangle in a movement to the left	
Arabic letter "HA"	
Arabic letter "SIN"	

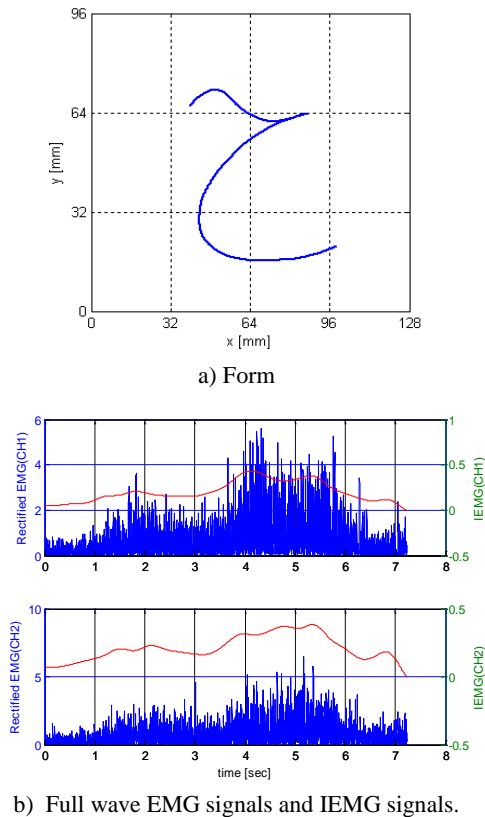
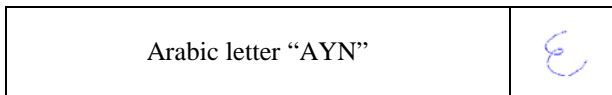


Figure 4. Example of the experimental recordings,

3. Proposed handwriting internal model control

During the human handwriting motion, several factors

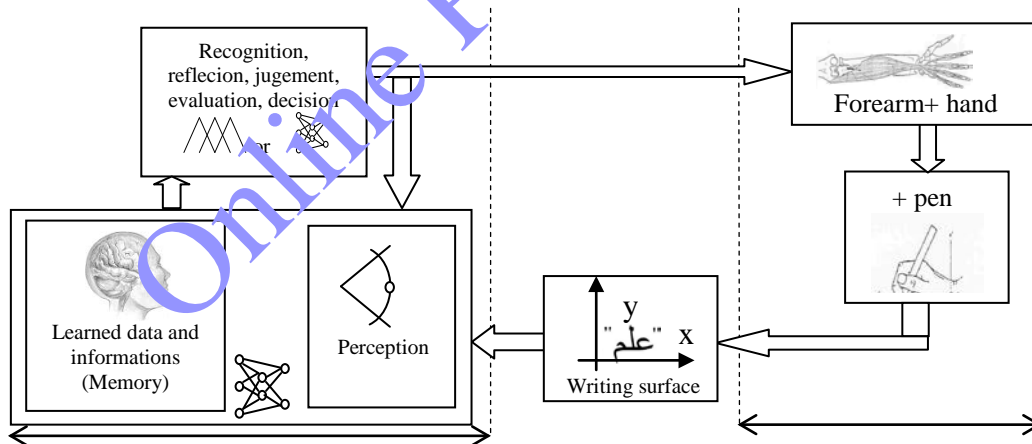
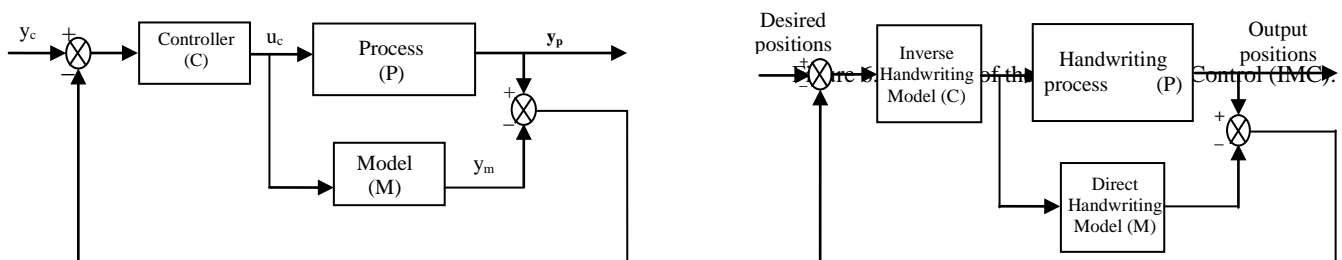


Figure 5. Global generalized handwriting process model.



and elements intervene to generate the graphic traces, such as the system of perception, the brain, the muscles, etc. In this sense, [2] represents a global generalized handwriting model to prove that the pen-tip position is detected by the means of the eyes and transmitted to the brain to be analyzed and compared with the desired position. Finally, forearm muscles activities, named ElectroMyoGraphy signals (EMG), are sent to perform the desired movement on the writing surface. This analysis recalls the principle of the Internal Model Control structure.

The proposed approach resumes the relationship between the pen-tip, perception, brain and hand. In this model, the role of the eyes is modelled by a feedback. This approach is presented by figure 5.

The generalized model of the handwriting motion, given in figure 5, is similar to the IMC structure, shown in figure 6. Indeed, this section focuses on the characterization of the control structure of the studied process using internal model control technique.

The signal command, u_c , generated by the Controller C is applied simultaneously to the Process P and to its Model M placed on parallel, [11], [13] and [14].

Independently of the process P, equation (1), shows clearly that if the controller C is chosen as the inverse of the model, the feedback of the IMC realizes a perfect transfer between the reference y_c and the output of the process, y_p . In this case, the controller can realize a good pursuit.

The new proposed handwriting internal model control is shown in Figure 7.

$$y_p = \frac{C \cdot P}{1 + C(P - M)} y_c \quad (1)$$

$$x_e(k) = -\sum_{i=1}^4 (a_{ix} y_e(k-i) - b_{ix} x_e(k-i)) + \sum_{i=1}^5 (c_{ix} e_1(k-i+1) + d_{ix} e_2(k-i+1)) \quad (2)$$

Figure 7. Handwriting Internal Model Control.

3.1. Handwriting process (P)

We propose a linear fourth order model to generate the movements of the pen-tip in (x, y) plane, from two integrated electromyography signals, IEMG1 and IEMG2, and from the positions of the pen-tip moving on the digital tablet at delayed moments. The model's inputs are x and y coordinates delayed at the instants: $k-1, k-2, k-3$ and $k-4$ and two IEMG calculated muscular signals at the instants: $k, k-1, k-2, k-3$ and $k-4$. The outputs are x and y coordinates at k instant. The handwriting models have the following forms:

$$y_e(k) = -\sum_{i=1}^4 (a_{iy} x_e(k-i) - b_{iy} y_e(k-i)) + \sum_{i=1}^5 (c_{iy} e_1(k-i+1) + d_{iy} e_2(k-i+1)) \quad (3)$$

x_e and y_e : Estimated position relative to x and y directions respectively,

e_1 and e_2 : IEMG1 and IEMG2 signals,

$a_{ix}, b_{ix}, c_{ix}, d_{ix}, \hat{a}_{iy}, \hat{b}_{iy}, \hat{c}_{iy}, \hat{d}_{iy}$: estimated parameters relative to the estimated coordinates x_e and y_e respectively.

Some simulation results of this model are presented in Figure 8.

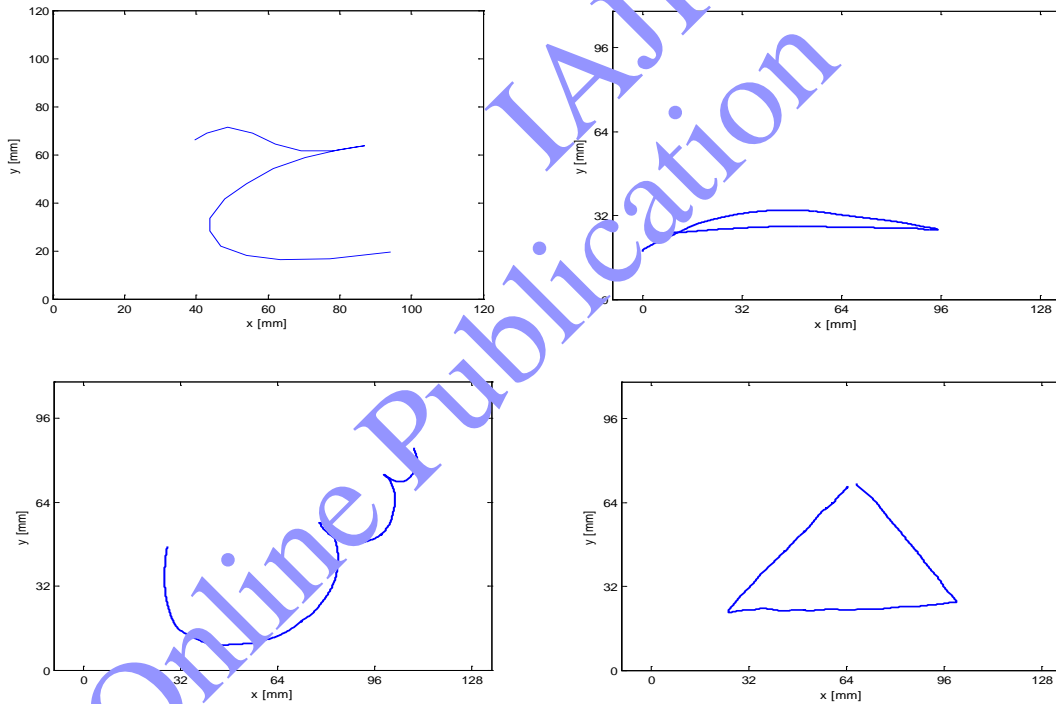


Figure 8. Handwriting model (P) responses

3.2. Direct and inverse handwriting velocity models

Basing on the handwriting velocity analysis and its relationship with IEMG signals to generate the pen-tip movement, in this section, the presented direct and inverse models are used to define Internal Model Control for the handwriting process.

In order to minimize the error of prediction, a parametric identification is used to estimate parameters of the direct and inverse models to generate outputs response as close as possible to the real system. We

choose Recursive Least Square algorithm, because it has the advantage to be executed on real time and requires less memory resources in terms of calculation.

3.2.1. Correspondence between trajectory and velocity of the pen-tip

From the described experimental approach considering horizontal, vertical, complexes, rapid and slow movements, the relationship between the velocity of the pen-tip during the handwriting motion and the trajectory of this last one can be analysed.

Velocities of the pen-tip movements according to x and y directions are calculated as follow:

$$\|V(k)\| = \sqrt{V_x(k)^2 + V_y(k)^2} \quad (6)$$

with:

$$V_x(k) = \frac{x(k+1) - x(k)}{t(k+1) - t(k)} \quad (7)$$

$$V_y(k) = \frac{y(k+1) - y(k)}{t(k+1) - t(k)} \quad (8)$$

and:

- $V(k)$: Pen-tip velocity,
- $V_x(k), V_y(k)$: pen-tip speeds according to x and y axis, respectively,
- $x(k), y(k)$: pen-tip displacement according to x and y axis, respectively,
- $t(k)$: discrete time.

The velocity profiles relative to different measurements of pen-tip displacements are conserved and occur as bell-shaped whatever the kind of movement. Figure 9 (a) presents an Arabic letter, "SIN", written according to (x,y) plane. The handwriting velocity of this letter has three main areas, different in durations and amplitudes, formed by a

superposition of bell-shaped forms and corresponding to three primitives of the considered letter: two small half circles and a largest third one.

The velocity of writing can be interpreted as a superposition of bells distributed by area with different durations and amplitudes. Each zone corresponds to a primitive of the written letter, figure 9 (b).

Figure 10 shows other handwriting shapes. The first form is an horizontal line relative to go and back movement (left/right/left). In this case, the handwriting velocity profile presents two separate bell shapes with different amplitudes and nearly equal during. The first bell shape is the result of left/right movement while the second bell is relative to the right/left movement. The velocity is equal to zero at the beginning, the end of the movement and when the movement according to x axis changes direction. The second form shown by figure 11, allows to present the velocity profile of the geometric form "triangle". This profile includes three bell shapes corresponding to three segments of the triangle. Therefore, the writing velocity can be interpreted as a superposition of bells distributed by area with different durations and amplitudes. Each zone corresponds to a primitive of the written letter.

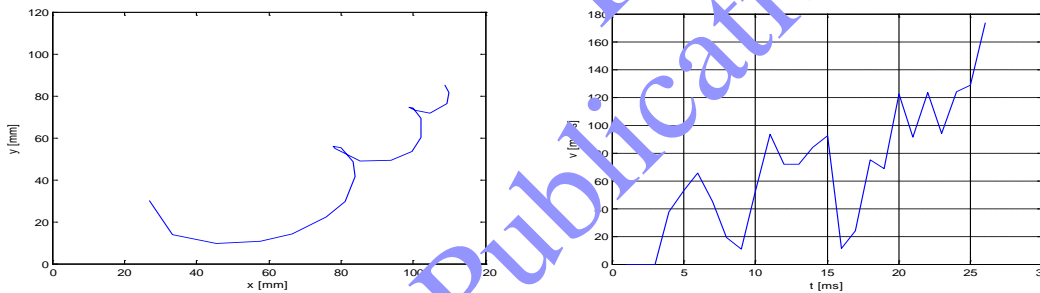


Figure 9. Simple movement (Arabic letter "SIN"), (a) Form, (b) velocity profile

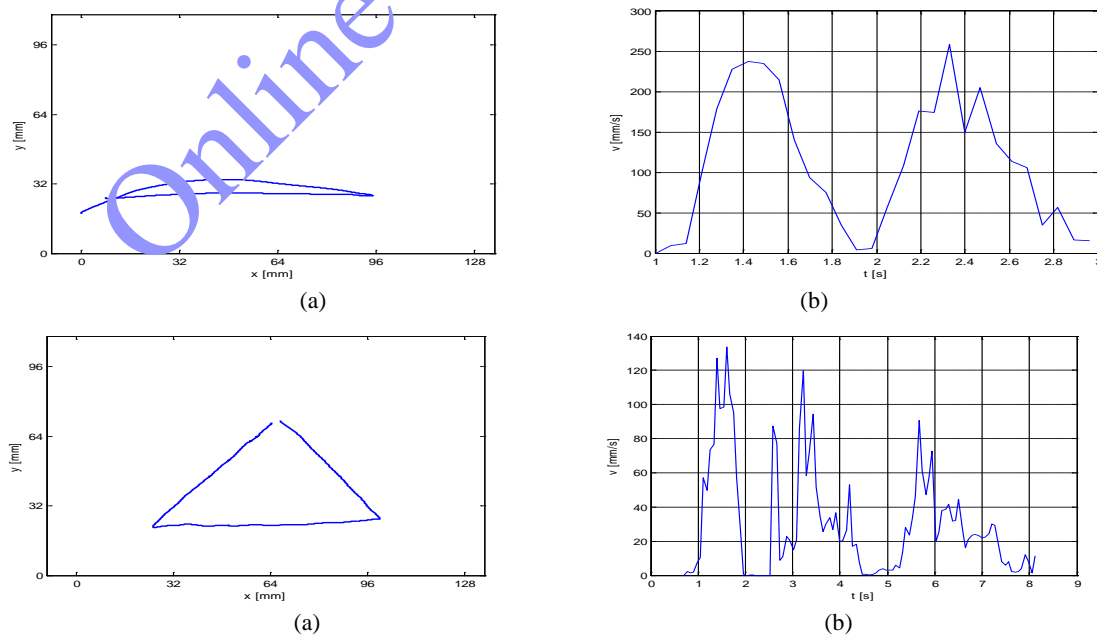


Figure 10. Handwriting movements, (a) Form, (b) velocity profile

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3.2.2. Direct handwriting model (M)

The direct mathematical model consists in generating an Arabic letter or a geometric shape written by a specific writer. The inputs of this model are IEMG signals of the forearm muscle (IEMG1 and IEMG2).

The proposed structure is a third order model. It generates as outputs V_{xe} and V_{ye} at instant k and admitting, as inputs, V_{xe} and V_{ye} delayed at $k-1$, $k-2$, $k-3$ and $k-4$ instances and the ElectroMyoGraphy signals at k , $k-1$, $k-2$ and $k-3$ instances. The following equations characterize the handwriting velocity direct model:

$$V_{xe}(k) = \sum_{i=1}^4 -[\hat{a}'_{ix} V_{ye}(k-i) + \hat{b}'_{iy} V_{xe}(k-i)] + [\hat{c}'_{ix} e_1(k-i+1) + \hat{d}'_{ix} e_2(k-i+1)] \quad (10)$$

$$V_{ye}(k) = \sum_{i=1}^4 -[\hat{a}'_{iy} V_{xe}(k-i) + \hat{b}'_{ix} V_{ye}(k-i)] + [\hat{c}'_{iy} e_1(k-i+1) + \hat{d}'_{iy} e_2(k-i+1)] \quad (11)$$

with :

- V_{xe}, V_{ye} : Outputs vectors, relative to the estimated velocities according to x and y movements respectively,
- $\hat{a}'_{ix}, \hat{b}'_{ix}, \hat{c}'_{ix}, \hat{d}'_{ix}$: parameters relative to the estimated velocities V_{xe} and V_{ye} ,
- $\hat{a}'_{iy}, \hat{b}'_{iy}, \hat{c}'_{iy}, \hat{d}'_{iy}$: parameters relative to the estimated velocities V_{xe} and V_{ye} , respectively.

Using the identification technique, Recursive Least Square algorithm (RLS) presented by equation (12) to (14), the direct model is based on the computing velocities of the pen-tip, according to x and y coordinates (V_x and V_y). The forgetting factor is equal to 0,95. RLS algorithm performs the following operations to update the parameters of the researched model, [5], [6], [8] and [16]:

$$\hat{\theta}(k) = \hat{\theta}(k-1) + P(k) \sum_{i=n+1}^k y(i) \Psi(i) \quad (12)$$

$$P(k) = P(k-1) - \frac{P(k-1) \Psi(k) \Psi^T(k) P(k-1)}{1 + \Psi^T(k) P(k-1) \Psi(k)} \quad (13)$$

$$\varepsilon(k) = y(k) - \hat{\theta}(k-1) \Psi(k) \quad (14)$$

with:

- $\hat{\theta}(k)$: Vector of estimated parameters,
- $P(k)$: adaptation matrix,
- $y(k)$: actual output of the system to identify,
- $\Psi(k)$: observation matrix,
- $\varepsilon(k)$: estimated error.

The model structure used to identify the handwriting system dynamics for multi-inputs-multi-outputs is given as follows:

$$V_{xe} = \psi_x^T \theta_x + \varepsilon_x \quad (14)$$

$$V_{ye} = \psi_y^T \theta_y + \varepsilon_y \quad (15)$$

ε_x and ε_y : Error vectors, relative to the velocities according to x and y movements respectively,

ψ_x^T and ψ_y^T : matrices which elements are the delayed inputs and outputs components, relative to the velocities according to

x and y movements respectively.

$$\hat{\psi}_x^T(k) = \begin{bmatrix} -V_{ye}(k-1) & -V_{ye}(k-2) & -V_{ye}(k-3) & -V_{ye}(k-4) \\ -V_{xe}(k-1) & -V_{xe}(k-2) & -V_{xe}(k-3) & -V_{xe}(k-4) \\ e_1(k) & e_1(k-1) & e_1(k-2) & e_1(k-3) \\ e_2(k) & e_2(k-1) & e_2(k-2) & e_2(k-3) \end{bmatrix} \quad (16)$$

$$\hat{\psi}_y^T(k) = \begin{bmatrix} -V_{xe}(k-1) & -V_{xe}(k-2) & -V_{xe}(k-3) & -V_{xe}(k-4) \\ -V_{ye}(k-1) & -V_{ye}(k-2) & -V_{ye}(k-3) & -V_{ye}(k-4) \\ e_1(k) & e_1(k-1) & e_1(k-2) & e_1(k-3) \\ e_2(k) & e_2(k-1) & e_2(k-2) & e_2(k-3) \end{bmatrix} \quad (17)$$

Variations of parameters in time show that they converge to constant values, characterizing the studied handwriting model, as shown in figures 11 and 12. The estimated parameters of velocities vectors $\hat{\theta}_x$ and $\hat{\theta}_y$ according to x and y movements, respectively, will take the following forms:

$$\hat{\theta}_x = \begin{bmatrix} \hat{a} & \hat{a} & \hat{a} & \hat{a} & \hat{b} & \hat{b} & \hat{b} & \hat{b} & \hat{c} & \hat{c} & \hat{c} & \hat{c} & \hat{c} & \hat{d} & \hat{d} & \hat{d} & \hat{d} \\ 1x & 2x & 3x & 4x & 1x & 2x & 3x & 4x & 1x & 2x & 3x & 4x & 5x & 1x & 2x & 3x & 4x & 5x \end{bmatrix} \quad (18)$$

$$\hat{\theta}_y = \begin{bmatrix} \hat{a} & \hat{a} & \hat{a} & \hat{a} & \hat{b} & \hat{b} & \hat{b} & \hat{b} & \hat{c} & \hat{c} & \hat{c} & \hat{c} & \hat{c} & \hat{d} & \hat{d} & \hat{d} & \hat{d} \\ 1y & 2y & 3y & 4y & 1y & 2y & 3y & 4y & 1y & 2y & 3y & 4y & 5y & 1y & 2y & 3y & 4y & 5y \end{bmatrix} \quad (19)$$

Figure 13 shows some examples of comparison between the real trajectories and the handwriting direct model's outputs. The solid line presents the recorded experimental data and the dotted line is relative to the answer given by the estimated parameters of the obtained model.

The validation of the proposed direct model consists on, integrating parameters of a model characterizing a letter or a geometric form with data saved from another example of the same kind of drawing trace and of the same writer, figure 14.

Compatibility between the prediction results of pen-tip speed and the experimental data is shown.

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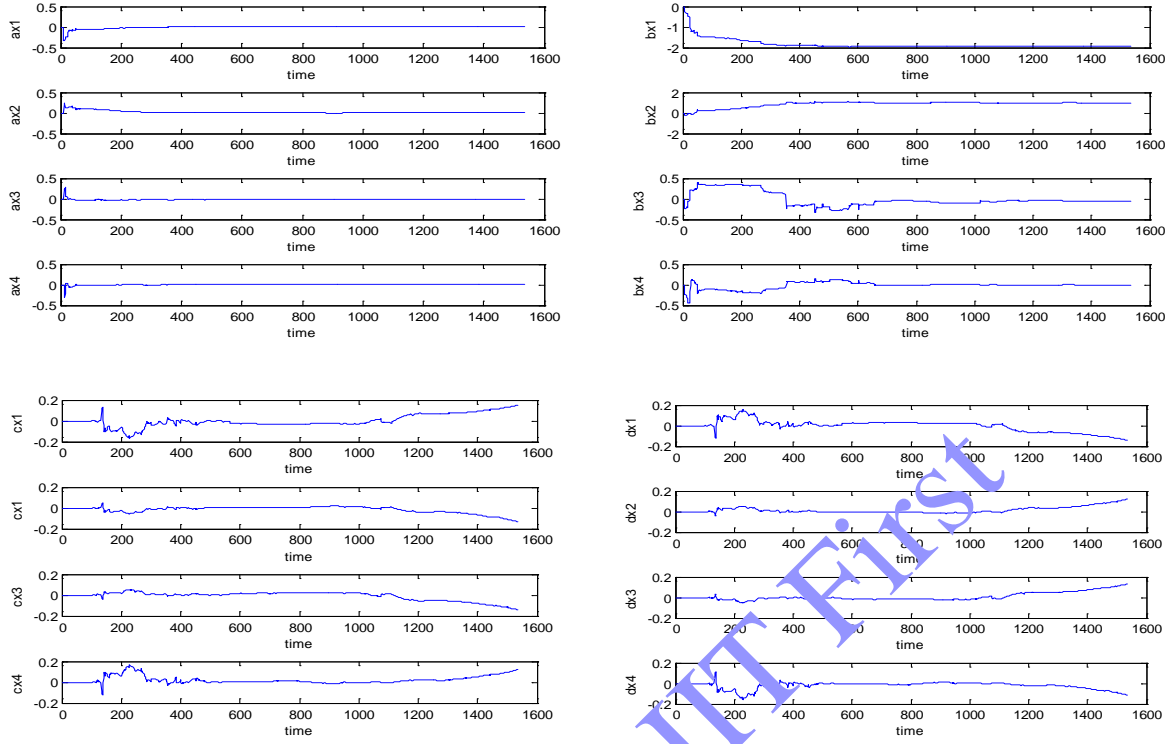


Figure 11. Parameter's evolutions relative to the estimated velocity according to x direction

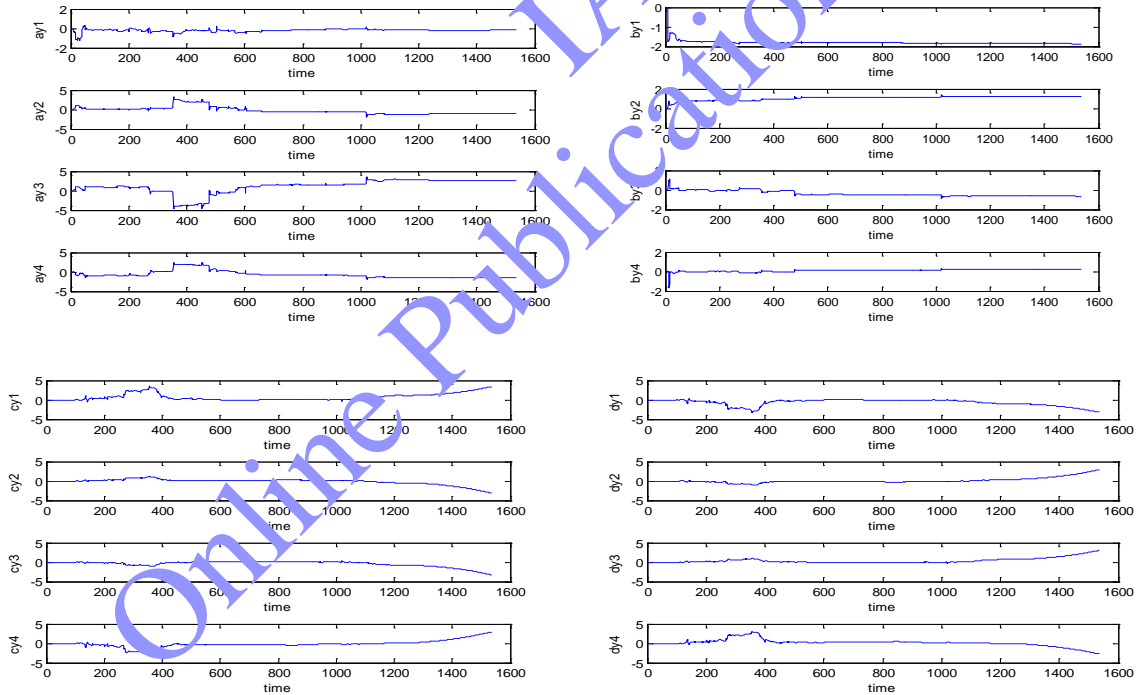


Figure 12. Parameter's evolutions relative to the estimated velocity according to y direction

3.2.3. Inverse handwriting velocity model (C)

The inverse handwriting velocity model which allows to reconstruct IEMG signals from the pen-tip velocity, according to x and y coordinates. This new third order model generates the ElectroMyoGraphic signals IEMG at k instance from the velocities, V_x and V_y at $k, k-1, k-2$ and $k-3$ instances and from IEMG signals at $k-1, k-2$ and $k-3$ instances, relations (20) and (21).

$$e_1(k) = \sum_{i=1}^4 -\left[\hat{a}_{i1} e_1(k-i) + \hat{b}_{i1} e_2 V_{xe}(k-i)\right] + \left[\hat{c}_{i1} V_x(k-i+1) + \hat{d}_{i1} V_y(k-i+1)\right] \quad (20)$$

$$e_2(k) = \sum_{i=1}^4 -\left[\hat{a}_{i2} e_2(k-i) + \hat{b}_{i2} e_1 V_{xe}(k-i)\right] + \left[\hat{c}_{i2} V_x(k-i+1) + \hat{d}_{i2} V_y(k-i+1)\right] \quad (21)$$

with:

$\hat{a}_{i1}, \hat{b}_{i1}, \hat{c}_{i1}, \hat{d}_{i1}$: Estimated parameters relative to the estimated e_1 and e_2 signals

\hat{a}_{2i} , \hat{b}_{2i} , \hat{c}_{2i} , \hat{d}_{2i} respectively.

Comparisons between the recorded IEMG signals and the reconstructed ones are shown in figure 15, which illustrates some identification's results for the Arabic letters "HA" and "SIN", written by different persons. For the first shape "HA", an important correspondence is shown between the proposed model outputs and the

recorded data. The solid line presents the recorded experimental data and the dotted line is relative to the answer given by the presented model.

Validation results of the inverse handwriting velocity model in monowriter case, is shown in figure 16. Indeed, good concordance is observed in this case.

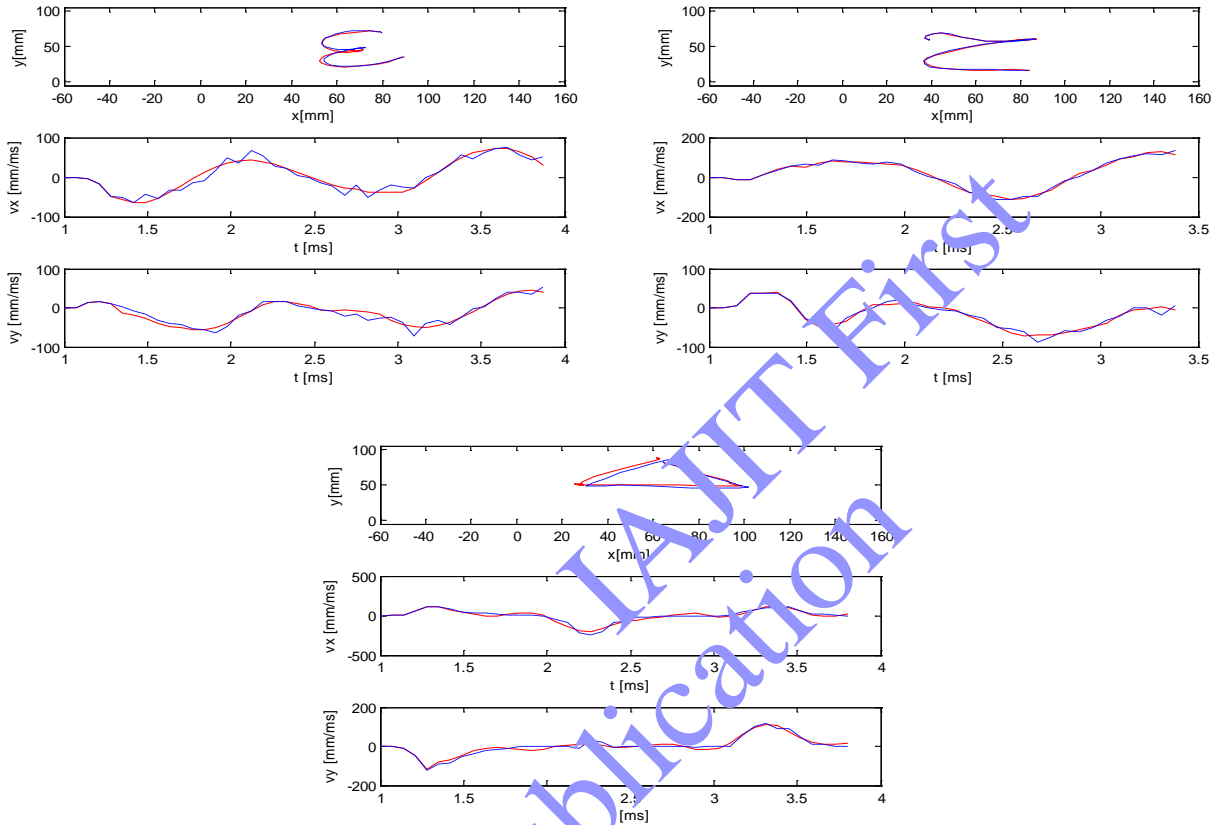


Figure 13. Comparison between experimental recorded data and the direct handwriting velocity model response

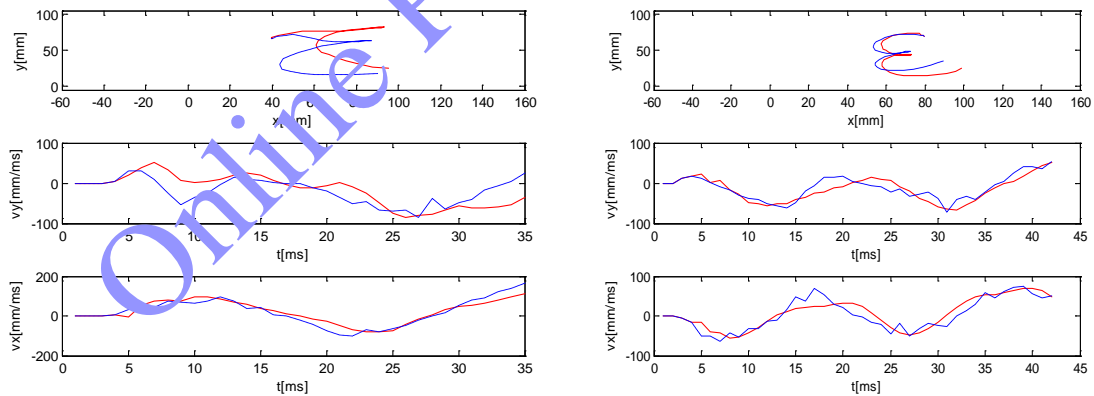
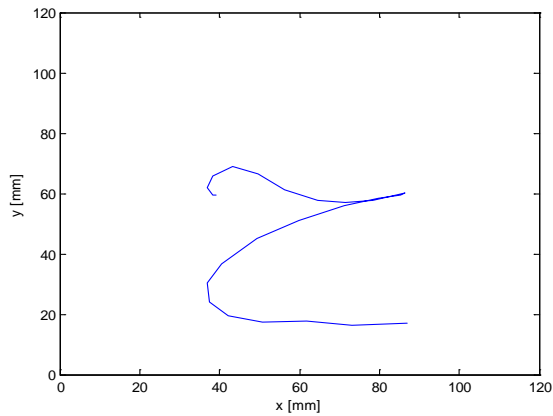
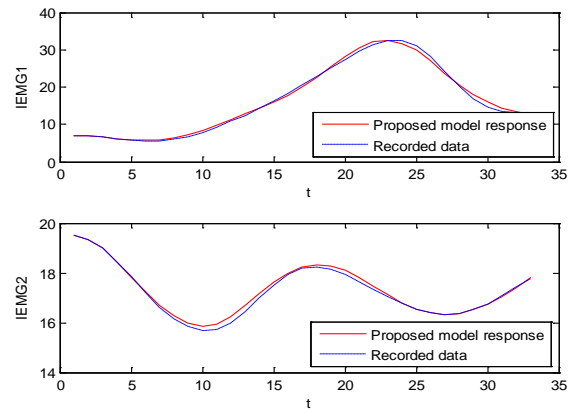


Figure 14. Validation results of the direct handwriting model



(a)



(b)

Figure 15. Results of the identification of the inverse model, (a) Form (Arabic letter “HA”), (b) IEMG signal according to x and y directions.

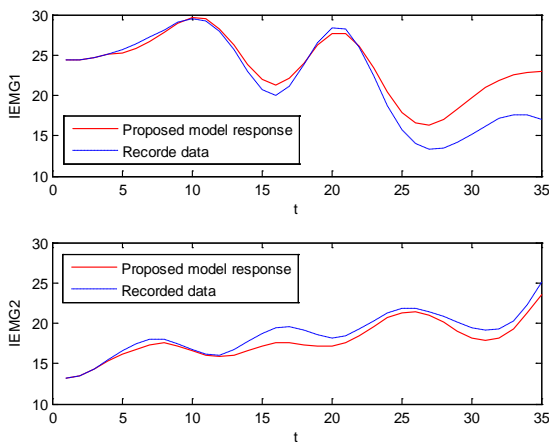
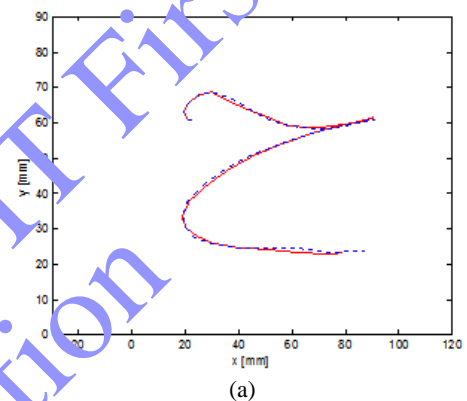


Figure 16. Validation's result of the inverse handwriting model

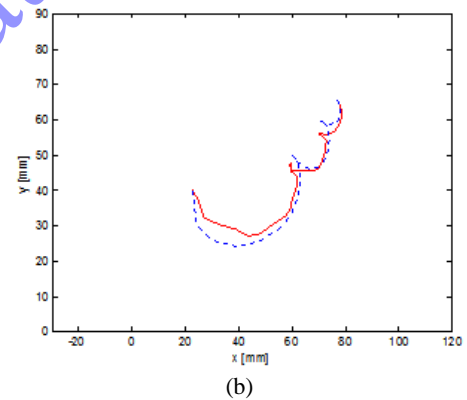
4. Results of the handwriting internal model control structure

In order to characterize the handwriting process, the inverse handwriting velocity model acts as the controller C . The direct model represents the model M . The process P is replaced by the handwriting model based on computation of the positions of the pen-tip moving on (x,y) plane.

The results illustrated in figure 15 confirm the ability of the proposed Internal Model Control to follow the form of the writing traces but with a very negligible error between the experimental recorded data and the answer of the proposed command structure, for some Arabic letters, figure 17 (a). For other Arabic letters, an acceptable error is shown, figure 17 (b).



(a)



(b)

Figure 17. Responses of the Internal Model Control of handwriting process

5. Conclusions

The study of the handwriting process and its modelling by Internal Model Control approach, constitute the main contributions of this paper. To characterize this approach, a direct and inverse handwriting models are proposed. Each one is based on the relationship between the pen-tip velocities according to (x,y) plane. Recursive Least Squares Algorithm was used to estimate the parameters of both models.

The various developed approaches for modelling and control of the handwriting system are led with success and good results are obtained. The proposed structure can be ameliorated to obtain good results valid on (x,y,z) plane.

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