Pen force emulating robotic writing device and its application

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Abstract

The paper describes our studies on the influence of physical and biomechanical processes on the ink trace and aims at providing a solid foundation for enhanced signature analysis procedures. By means of a writing robot, simulated human handwriting movements are considered to study the relation between writing process characteristics and ink deposit on paper. Since the robot is able to take up different writing instruments like pencil, ballpoint or fine line pen, the type of inking pen was also varied in the experiments. The results of analyzing these artificial ink traces contribute to a better understanding of the underlying interaction processes and will find its applications in the teaching, training, and medical diagnostics. It comes out that position, velocity and pen force suffice to produce high quality ink traces, hardly distinguishable from original probes.

1 Introduction

Signature pattern are characterized by the *behavioral* writing process. Each sample is influenced by situational factors such as writing position and pen grip, by physical properties of the writing material, like the ink liquidity [5, 11, 17], and, by psychological factors as stress and the use of psychofarmaca (coffee, alcohol, drugs) [29]. For this reason, signature specimens display variations in each individual sample. In systematic experiments and investigation, like in forensic sciences, the variability intrinsic to human's behaviors needs to be handled seriously. Exemplary, forensic handwriting experts have to distinguish whether specific characteristics of the ink traces are caused by individual characteristics of the writing movements or by a defect of the writing intrument. Thus, human handwriting and ink traces have to be studied under strictly controlled conditions, whereby the variability of the human writer is preferably excluded, e.g., due to the utilization of an electro-mechanical device.

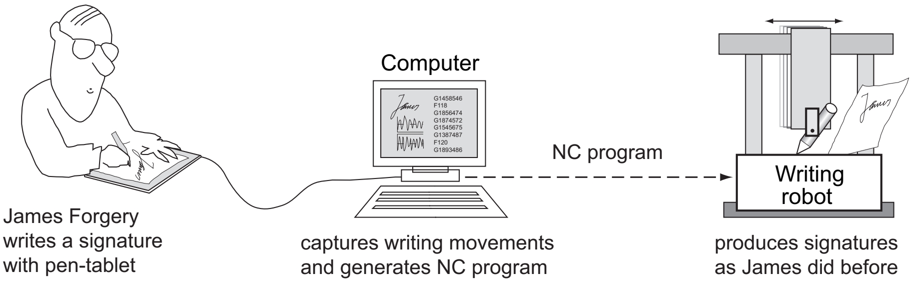

Figure 1: Schematic overview on the replication of human handwriting movements.

This paper presents a new approach for the robotic simulation of human handwriting and its potential applications. In this scenario an electronic pen-tablet to capture human writing

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movements is used. Recorded pen movements are considered for the *replication* and systematic study of writing behaviors and its resulting ink traces on paper. Time series of temporal pen trajectories, which comprise pen positions, pen tip forces, and writing velocities, are translated into machine commands to control an electro-mechnical device, the writing robot (Figure 1). Subsequently, the writing robot becomes able to repeat exactly the same movement multiple times and to *synthesize* ink trace specimens under controlled conditions. The artificial ink traces can be exploited in a dedicated *analysis* afterward [9].

In our studies, a highly accurate 3-axis CNC-machine [15] is being used. This robot is able to simulate pen displacements but also natural pen tip forces, pen lifts and landings. Moreover, it comprises a penholder that allows for "writing" with variable writing instruments as ballpoint, fine line or felt tip pen. Software simulations of handwriting and ink deposition processes are purposely not addressed in the current scenario, rather an appropriate experimental setup for the derivation and the cross-validation of such software models ought to be provided. Since the robot system proposed here is freely programmable, it will allow for the production of ink traces by means of peripheral handwriting models [16], too.

In order to reveal the intricate relationship between biomechanical writing and physical ink deposition, the characteristics of the human signing process are studied and experiments with a writing robot are conducted. The experimental results of the artificial ink traces contribute to a better understanding of the underlying interaction processes and allow for the formulation of a so-called *Ink Deposition Model* [7]. According to findings from the field of motor control theory [25, 30] as well as forensic studies [3, 18] the applied pen tip forces are most significant in recovering disputed or forged handwritings. The effects of applied pen tip forces can be investigated. Particularly, its impact on the amount of ink deposits and the inner line quality of ink traces on paper is studied. Research questions in this context are: (i) What are the effects on the residual ink trace by performing similar movements yet using different pens? (ii) Are there significant characteristics of ink deposits for a particular pen type? (iii) What are the changes in ink deposit according to changes in applied pen forces?

The reminder of this paper is organized as follows: Section 2 recalls biomechanical handwriting characteristics and introduces our electro-mechanical device for the robotic emulation of human handwriting (Section 3). Selected applications for the writing robot are discussed in Section 4. Section 5 concludes on the studies presented here and points to further research.

2 Biomechanical handwriting characteristics

Performing handwriting movements means to act and to behave in a specific manner. More precisely, handwriting is a motor act using writing materials. It is a physical activity in the 3-dimensional space, requiring linguistic and cognitive abilities [33]. Typical for handwriting are the motor processes involved in the letter / word formation, size and slant control as well as their anatomical and biomechanical implications [26]. It is a learned behavioral pattern and depends upon everlasting and situational intentions. Handwriting is not just a complex psychophysiological behavior, it's resulting product, e.g., the ink trace on paper, is also a material object which is shaped by that behavior.

Our perspective on handwriting is from an engineering point of view. The focus is on biomechanical processes involved in performing the motor task and the physical-technical influences by utilized writing materials. A fundamental study of the neurophysiology of handwriting processes is not addressed in the communication at hand. An appropriate representation of the movement trajectory ought to be provided in order to *analyze* the writing behavior and to *replay* captured human movements under controlled conditions. Hence, we abstract from the finger-thumb and hand-wrist joint movements, and focus on the pen point *kinematics* and *kinetics* only.

For abstraction, we consider the motor system as a *mass spring with friction system* (compare Figure 2). This is the most direct analog, with physical parallels in the motor system [24].

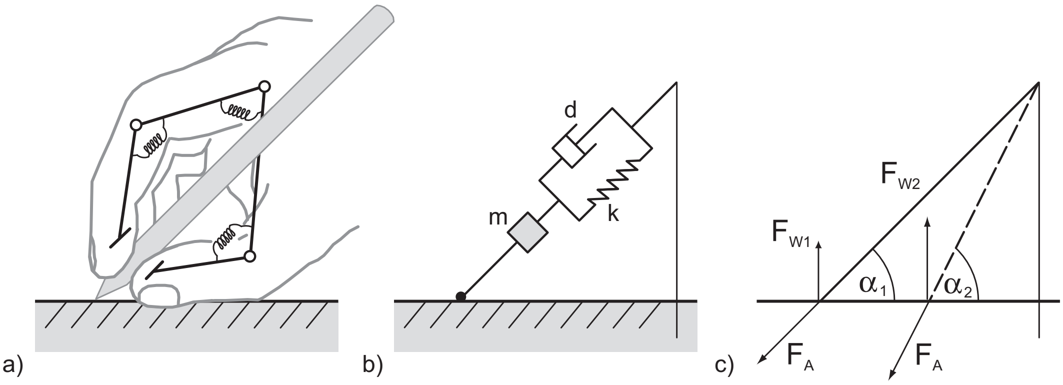

Figure 2: Biomechanical model according to Schomaker et al. [25] and adapted by the author. (a) The mass spring system, as a direct analog for the biomechanical behavior of the motor system, relates pen tip movements and resulting force. (b) The axial pen tip force F_A is determined by writing velocity, acceleration, pen point displacement and constants (m, d, k) for mass, damping and stiffness, respectively (eqn. 1). (c) The normal pen tip force F_W is a function of axial force F_A and pen tilt α.

Particularly, measurable physical aspects of the pen point trajectory, as displacement, velocity, acceleration and pen tip forces, are addressed. One has to carefully distinguish pen forces that yield movements with varying velocities in the xy-writing plane and the normal pen tip force activated in z-direction (perpendicular to the writing plane), which pushes the pen into the paper and possibly produces pen grooves. Forces are expressed by the equations of motion:

$$F(t) = m\ddot{s} + d\dot{s} + ks \quad (1)$$

$$\text{with} \quad s(t) = \sqrt{(x(t) - x_0)^2 + (y(t) - y_0)^2 + (z(t) - z_0)^2} \quad (2)$$

$$\text{we denote} \quad \dot{s} = \frac{\mathrm{d}s}{\mathrm{d}t} \quad \text{and} \quad \ddot{s} = \frac{\mathrm{d}^2 s}{\mathrm{d}t^2} \quad (3)$$

Here, (x_0, y_0, z_0) represents a reference position. Each term is determined by a kinematic factor for (pen tip) acceleration $\ddot{s}$, velocity $\dot{s}$ and displacement s, respectively, and a constant (m, d, k) for mass, damping (viscosity), and stiffness, respectively. According to the resulting direction of the pen tip trajectory in the 3-dimensional writing space, the applied forces might lead to pen displacements in the writing plane (xy-direction) or to the pen pushing onto the writing pad (z-direction). In order to avoid ambiguities in our discussions the definitions of writing kinematics and kinetics ought to be recalled. Kinetics refers to the study of the role of force as a cause of motion, while kinematics refers to descriptors of motion without concern for the cause of that motion. Kinematics and kinetics are tightly connected, in particular if transitions of pen point trajectories in the air to movements where the pen is pushing into the paper are considered.

Modern capture devices as electronic writing tablets and appendant pens allow for the recording of human handwriting movements, e.g. [32]. Pen tip trajectories are sampled at the very peripheral end of the effectors. Thus, the devices allow for the acquisition of *time series*. Depending on tablet's technological design the data records comprise x, y pen position in the writing plane, pen tip force and pen orientation records that contain pen tilt and pen azimuth. From these raw data, further kinematics and kinetics of the writing behavior can be derived and exploited in specific studies, as the generation of NC-program codes that control the robot.

3 Robotic emulation of handwriting

3.1 Related Work

Much research has been done on the modeling of handwriting [19]. Most of the peripheral models [16] were validated by software emulations [20, 24]. In 1961 the first electro-mechanical model based on the use of two pairs of DC motors was presented [28, 27]. Later attempts [31, 13] on the robotic synthesis of handwriting were still without the modeling of applied pen forces. Even models of anthropomorphic robots were developed that perform rather natural pen point kinematics, yet are not able to apply time-varying pen force [1, 2, 21, 22]. Besides application in research, electro-mechanical devices for the production of ink traces are predominantly used for quality inspection during the manufacturing of writing instruments [10]. Likewise, these machines are only able to perform pen displacements, which follow some kind of LISSAJOUS pattern, with constant pen tip forces. Previous forensic studies [10, 18] tried to employ such devices in the synthesis and the analysis of ink traces, yet they had to encounter difficulties. Since the variation of the pen tip forces was missing, the so produced ink traces were insufficiently.

3.2 Writing robot

Our writing robot, in particular the CNC [1] flatbed machine *isel GFY 44/48* [15] was chosen after an intensive market analysis. The reported accuracy of $1\,\mu$m, the maximal movement velocity of 12.8 m/min (214 mm/s), and not at least the purchase price where in favor for this specific model. The application area of the machine tool is primarily intended for manufacturing of high-complex aluminum and copper components, for industrial wood machining and for model making. The machine construction comprises three linear axes: x, y and z. They are driven by AC-synchron motors and allow for three-dimensional positioning. During the processing of one command, all axes can move simultaneously [15]. The original tool mounting was replaced by a new pen carrier, which was especially designed at the Fraunhofer IPK. The pen holder is mounted on a sliding bed (compare Figure 3). This unit comprises two fixed slide rails and four movable rollers. It allows for displacements in perpendicular z-direction with respect to the machine table. Moreover, the sliding bed is elastically supported by means of a spring. The spring enables the transformation of deflection into force. Due to the current design of the pen holder, only three degrees of freedom for pen tip movements are possible: x, y for movements in the writing plane and z to simulate pen tip force (Figure 3). Pilot studies were conducted in order to calibrate the transformation of robot's z-displacement into applicable pen tip forces [9]. Due to the linear behavior of the spring one can consider linear force increase per one mm spring deflection with $\Delta\bar{F}|_{\Delta z=1\,\mathrm{mm}} = 0.38\,\mathrm{N}$. Note that the maximal movement velocity is currently restricted to $v_{\max} = 33\,\mathrm{mm/s}$ due to an insufficient attenuation of the penholder, which might cause vibrations and subsequently disturbances on the ink trace [9]. Not supported so far, are pen orientation variations during pen movements, as they are intrinsic for natural human handwriting. Nevertheless, pen orientation can be preset for a particular writing experiment. For the experiment described here a fixed pen tilt of $\alpha = 55^\circ$ was used, which is the most natural for human writers [8].

Three primary actions have to be performed to derive a NC-program that controls the robot pen movement and consequently "writes" a particular signature specimen: (i) Device calibration for the writing robot and the electronic pen-tablet, in particular with respect to captured / applied pen displacement and pen force. (ii) Acquisition of real human handwriting by means of the electronic writing tablet. (iii) Generation of the NC-program code taking the calibration results into account. The NC-program generation has to be performed separately for each particular signature or handwriting sample. To give an example of signatures produced

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[1] CNC - Computer Numerical Control

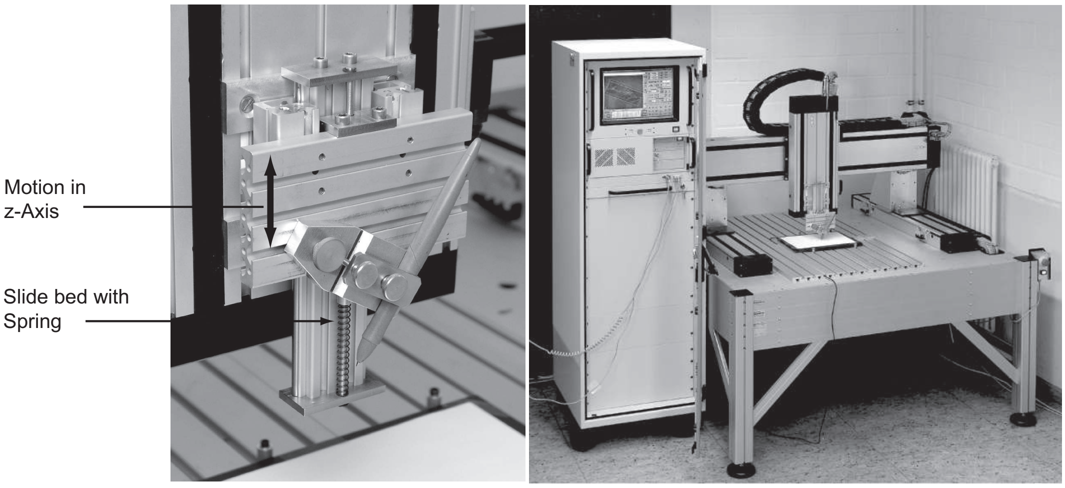

Figure 3: Writing robot and detail view on the newly designed pen holder. The sliding bed is elastically supported by means of a spring enabling the transformation of deflection into force.

by the robot, Figure 4b displays three specimens that were sequentially “written” by the robot. Additionally, a small piece of the employed NC-program is provided in Figure 4a.

3.3 Feasibility study

The reproducibility of the artificial writing traces with respect to pen displacement is extremely high. Since the CNC flatbed machine is designed for tool manufacturing, position accuracy by the three movable axis of at least 1 μm is guaranteed [15]. The pen is also tidily connected to the pen slide at robot’s z-axis. So, variations in the pen displacement and spatial characteristics of the ink trace are not expected in the first instance. However, due to the limited damping of the pen carriage, vibration could be stimulated for movement velocities above 33 mm/s (2 m/min) [9]. Such vibrations may cause pen displacements and thus disturbances on the ink trace. It has to be taken into account that for some writing instruments the pen tip, in particular for chargeable refill, is also moveable. Thus, the reproduction accuracy of ink traces on paper may be affected. Note that the steadiness of the pen tip is also referred to as tip switch stroke.

Next, we examined the pen force signals that were simultaneously captured with the electronic pen and tablet. An example for the pen force signal for human and robot signatures is given in Figure 5. The average standard deviation of the synthesized signal is 2 % (13.2 pressure levels) with respect to the median of the average synthesized signal (698.9 pressure levels). The slightly higher pressure levels were explicitly chosen in order to operate the tablet in a linear working domain. The superimposed pressure signals by the machine trajectory are so similar that it is difficult to identify single curves. Therefore, the reproducibility of the pen force signal is also given, regardless of the mentioned vibrations. Beside the insufficient attenuation, the fixed pen orientation may also contribute to slight falsifications of the applied force signal during ink trace synthesis. Although the current setup can be further improved, it appears obvious that the robot is able to simulate many important aspects of the natural variation in pen forces.

The following examinations focused on the ink traces on paper. We manually compared ten artificial writing traces per signature and writer with each other. These cross-validations were performed in two different ways: (i) the signatures were visually inspected with respect to stroke phenomena as well as the rhythms of the ink deposition, and (ii) the signatures were transformed in a pseudo-colorized representation, whereby each color segment corresponds to a relative amount of ink deposited on paper [6], and were compared afterwards. A high concurrence of ink depositions as well as stroke phenomena in kind and location was recognizable. More

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%
G17 G90
G0 Z-70
F0.6
G1 X0.566 Y8.316 Z-80.000
G1 X0.338 Y8.039 Z-80.000
F1.2
G1 X0.125 Y7.934 Z-80.000
F1.6
G1 X0.000 Y8.173 Z-81.000
F1.8
G1 X0.027 Y8.890 Z-81.000
F1.9
G1 X0.250 Y10.151 Z-81.000
G1 X3.174 Y18.506 Z-81.000
G1 X4.051 Y20.026 Z-81.000
…
F1.8
G1 X47.949 Y6.301 Z-75.000
F1.3
G1 X49.104 Y6.730 Z-75.000
F1.0
G1 X49.974 Y7.028 Z-75.000
G0 Z0
G0 X0 Y0
M30
%
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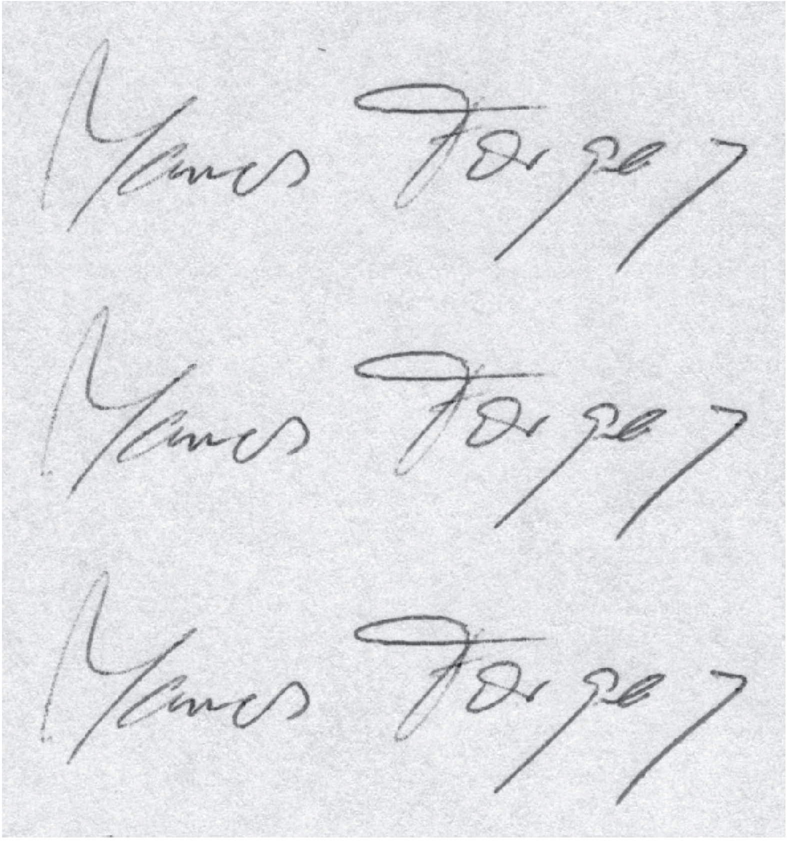
a)



b)

Figure 4: Signatures written by the robot: a) Code sample of a NC-program that controls the robot movements. Major commands are the *G1*-command and the *F*-command. The *G1*-statement determines robot's axis movement in x-, y- and z-direction. Due to the employed spring, the z-movements are transformed into pen tip forces. The *F*-command defines the actual movement velocity in [m/min]. b) On the right hand side three different signature samples are displayed, which were produced by the robot evoking one and the same NC-program.

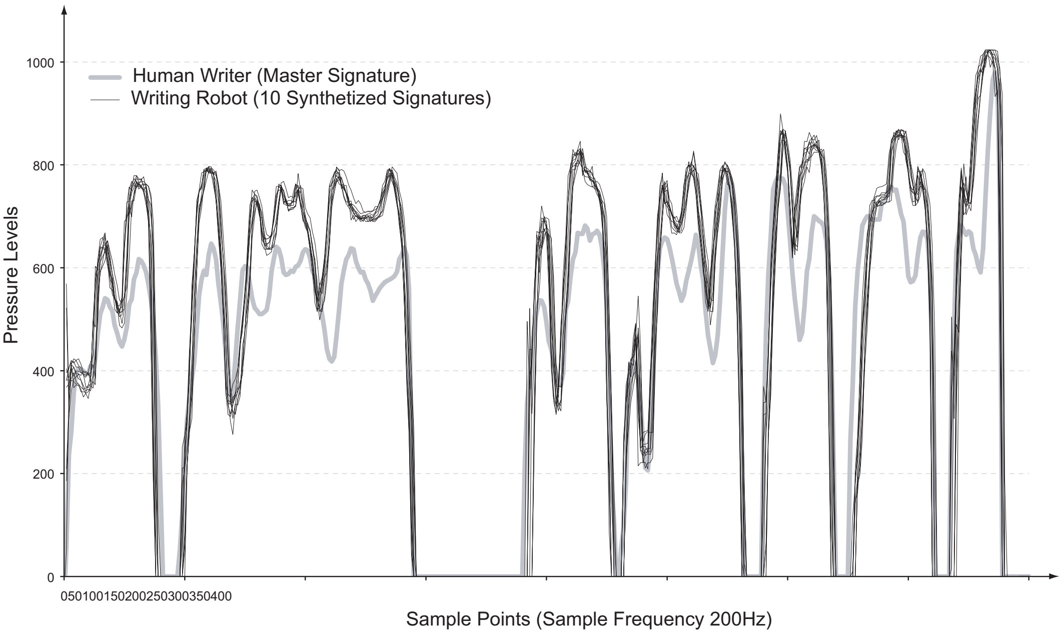


Figure 5: The captured writing force signals of human master-signature as well as 10 samples of signatures by the writing robot (see the text for discussions).

elaborated approaches are demanded to automatically examine the flow of ink along the writing trace.

4 Applications

4.1 Study of ink deposition processes

Although already exploited in forensic practice, there were only few attempts to systematically proof the concurrence of writing processes and ink deposits [10, 4]. Previous studies from the forensic field focused primarily on the change of depth of the pen grooves [3, 18]. However, these examinations also revealed that environmental condition as humidity might yield to deformations of the groove, and, that position accuracies of employed measuring devises, e.g., laser scanning microscope or mechanical surface sensing devices, are not sufficient for practical usage [18]. So, it's desirable to establish a systematically derived coherence of applied writing dynamics and amount of ink deposited on paper. Thereby, the different physical properties of the writing material have to be taken into account [6].

Our efforts on the design and the feasibility of an electronic writing robot, allow us to produce ink traces on paper under strictly controlled conditions. According to findings from the field of motor control theory [25, 30] as well as forensic studies [3, 18] the applied pen forces are mostly significant in recovering disputed or forged handwritings. So, the effects of applied pen tip forces onto the inner line characteristics of the ink traces on paper are investigated [7]. We considered 30 different pens that were chosen according to their specific ink type [5]. Three classes were elucidated: solid, viscous and fluid ink type. In order to ensure repeatable writing dynamics for all pen probes we have used the writing robot. The robot, which is able to simulate natural human handwriting, was programmed to perform ballistic movements with uniformly changing pen forces. The so produced realistic ink traces on paper were digitized and the intensity distributions for image elements representing the ink trace were analyzed with respect to evoked ink type and applied pen tip force.

The ink intensity distributions for inks of the same type: solid, viscous and fluid, are highly

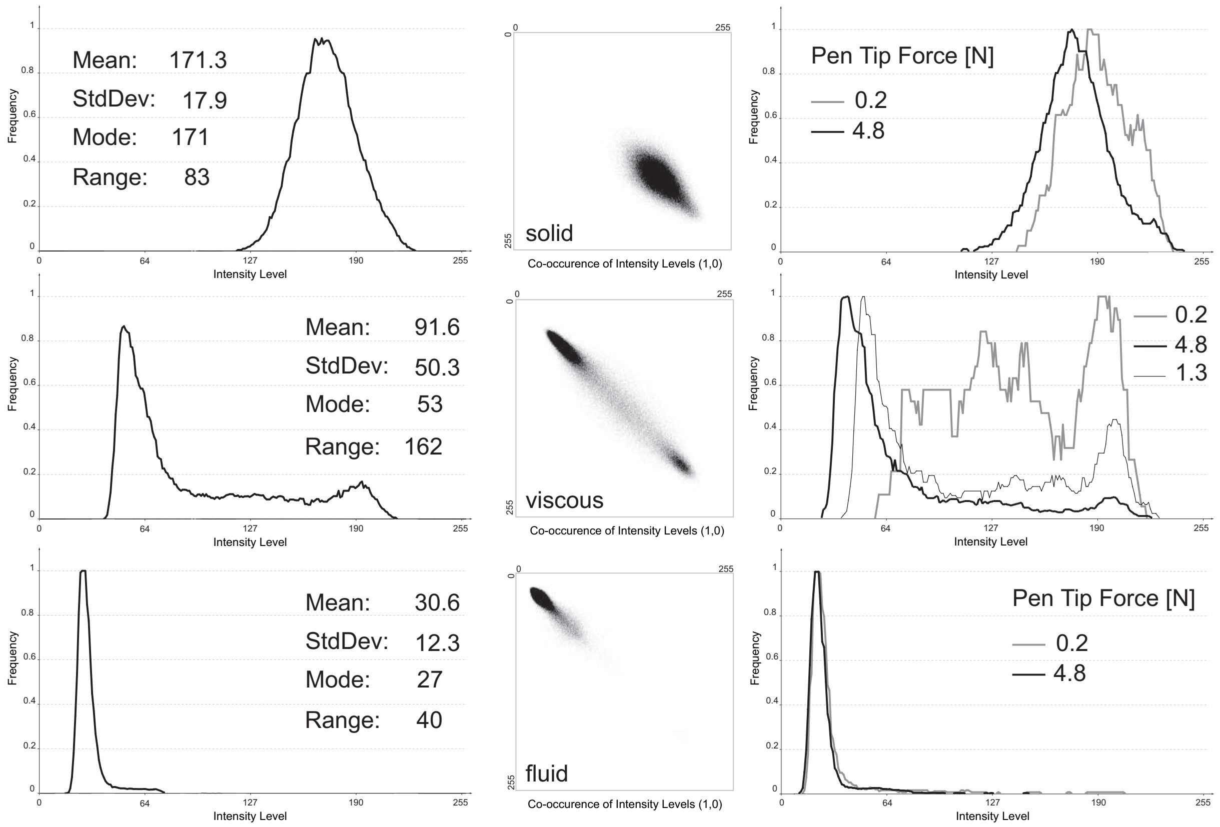


Figure 6: Average intensity frequency plots and co-occurrence matrices (distance (1,0)) for solid, viscous and fluid ink types are given on the left and middle, respectively. On the right, frequency plots for single traces produced with varying maximal pen tip forces are shown.

discriminate (compare Figure 6). Particularly, the ink fluidity yields to ink type specific micro-patterns of the inner writing trace. Increasing pen forces are rather linearly related to chances of ink intensities for solid ink types, which can be explained by the friction of the graphite refill and the paper fibers. Changes of pen forces show little influence on intensity distributions in case of fluid inks. Due to the capillary effect the paper is rather equally soaked with the water-based ink. Most distinguishable are ink intensity distributions effected by viscous ballpoint pen pastes. Ink intensities do not only cover the widest range, but also show characteristics ranging from colorizing just single paper fibers up to completely saturated ink traces. The relation of applied force and ink deposit is non-linear and thus the intensity distribution for viscous ink types is skewed.

The overall objective, and motivation for our detailed study, is the development of sophisticated algorithms for the computer-based analysis of ink trace line quality, mainly to recover disguised and forged signatures. The better understanding and analytical modeling of the interaction processes of writing movements, physical ink properties and ink deposition will allow for the design of appropriate algorithms, as for example for the segmentation of high-pressure regions. However, the ink-deposition models provided in this study, consider the effects of applied pen forces only. Writing dynamics of natural human handwriting are composed by additional parameters as writing velocity. Thus, ink traces produced by humans need to be analyzed in order to cross-validate our findings. Further work is directed at a more detailed analysis of algorithms for the allocation of high-pressure regions and their feasibility in the automatic detection of skilled signature forgeries.

4.2 Forensic investigation and training

The unlimited reproduction of one and the same writing movement offers new perspectives in the forensic examination of questioned handwriting specimens and writing instruments. Handwriting and ink trace can be produced under strictly controlled conditions. As known from other disciplines of forensic science, such as tool mark and fire weapon investigation, a technical device as the robot allows for the reconstruction of a particular situation under which a specimen was hypothetically produced. Thus, potential side effects that might be caused by the operating writing surface support or the defect of a writing instrument can be studied, e.g. [12, 14, 23].

Handwriting specimens can be generated in order to provide adequate training and reference samples. The samples can be produced with arbitrary paper, pen and ink, or even writing surface support. Additionally, it is relatively easy to manipulate the robot NC-program in order to generate new "phantom" handwritings, e.g., by rather straightforward transformations applied to the online signal [16], but also by replacing / adding selected parts of the writing trajectory with captured-natural or artificially-synthesized data. These samples can be employed in a criminal investigation or preferable just for education and training of forensic handwriting experts. The production of sample material for audit tests, which can replace controversial photos or copies, is just another application example. Note that the inspection of pen grooves is only possible if a writing robot produces the specimen as it is proposed in this paper. The exclusive utilization of photos, digital images or similar reproduction of ink characteristics is strongly criticized among European forensic handwriting experts from governmental and police organizations that have already established quality assurance guidelines for forensic casework, training and expert evaluation.

4.3 Handwriting robot: A biometric camouflage?

So far neglected are the potential risks that arise with the availability of such a writing robot. History has shown multiple times that a technology, which was developed to support professionals or mankind, has been abused by irresponsible individuals. We definitely do not want to promote such developments. Therefore, we would like to mention a few ink trace characteristics that may help to identify a technical reproduction. There may be evidence for reconstruction if the artificial movements did not incorporate variations in the applied pen force. Strokes with an unlikely reduction in ink deposit may not appear natural. The same holds for overly regular ink deposition at pen lifts and landings. Furthermore, a writing trace may look like a composition of linear segments, and third, resonating vibrations of the mechanical device may cause disturbances in the ink trace. Note that this latter kind of ink trace characteristic could be mixed up easily with natural tremor caused by illness or aging. As usual, the consideration of additional context-related information is advisable.

5 Conclusions

Due to a precise modeling of the applied pen tip force, and in contrast to all previously available systems, the robotic simulation of human handwriting presented in this study is going to result in most natural ink traces on paper.

– Teaching of handwriting skills: The proper development of writing skills in childhood is more and more considered an important pre-requisite to develop language and communication abilities. Nowadays the higher deployment of electronic communication facilities, like the internet, email, electronic organizers and mobile messaging, is repressing the development of such abilities in the younger generation, and we may not see at the moment whereto this tendency will lead us. At least, devices like a writing robot will provide a compatible and supporting means to foster the teaching of writing skills also in this upcoming e-learning era.

- Application in medical diagnostics: We see a multitude of diagnostic approaches, like the treatment of Parkinson disease or any other disease having a representation in and influence on the writing skills. Also the support of rehabilitation, as in stroke recovery, unreveals important application fields for such devices.

Since the robotic simulation of pen trajectories can exclude natural variations of human's behaviors, it allows for strictly controlled studies of writing and ink deposition processes. By means of the machine, fine motor tasks, and established peripheral model of human handwriting can be further evaluated. Ink traces, writing materials can be handled in a sophisticated manner, and, even forensic handwriting experts can be examined and trained. From that, new computational methods for signature / handwriting analysis and recognition can be derived. The major outcome of the presented study is as follows: Its the consideration and inclusion of the pen tip force time series, in addition to the positional and velocity time series, that makes a writing device capable of producing handwriting that is hardly distinguishable from the original probes even by forensic experts. In conclusion, enthusiasts who are dreaming of anthropomorphic robots can be provided with electro-mechanical devices that produce human-like ink traces.

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