Ink-Deposition Model: The relation of writing and ink deposition processes

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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 allow for the formulation of a so-called ink-deposition model (IDM). Particularly, we present IDMs that analytically describe the relation of applied pen tip force and relative ink intensity distribution for solid, viscous and fluid ink types. These IDMs might be employed in computer-based analysis of ink trace line quality to recognize skilled forgeries.

Keywords *forensic handwriting examination, pseudo-dynamic signature analysis, line quality, stroke phenomena, writing instruments, robotic writing trace synthesis*

1. Introduction

The limited amount of graphical characteristics in signatures requires a fundamental understanding of the writing and ink deposition process if one aims at developing advanced algorithms for signature preprocessing, feature extraction, and evaluation. So, the presented study is linked with our research on methods for the computer-based analysis of signatures written on paper documents. Of particular interest are those signature characteristics, which are determined by individual writing movements of a person. In the analysis, it is argued that writing process dynamics can be inferred from specific ink-deposits along the writing trace [2, 5, 9, 11, 12, 24]. Rather the line quality, which is represented by micro patterns of the inner trace [7] and stroke phenomena [10], is taken into account than the temporal ordering of strokes [1, 3, 14, 15] or stroke shapes [4, 18, 19].

Although already exploited in forensic practice, there were only few attempts to systematically proof the concurrence of writing processes and ink deposit [11, 7]. Previous studies from the forensic field focused primarily on the change of depth of the pen grooves [6, 16]. 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 [16]. 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 [9]. In order to study the interaction processes and the resulting graphical characteristics of the ink trajectory, a mechanical device, in particular a writing robot that is able to simulate natural human handwriting can be employed. Such a device allows for the synthesis of ink traces under controlled conditions, e.g. high precision repeatable writing velocity, pen force or pen inclination, yet using different kind of pen, paper and writing surface support. The so produced artificial ink trace can be systematically analyzed and conclusions about the interaction processes of applied writing process parameters and ink deposits can be drawn. Particularly, the profound knowledge on the relation of writing and ink deposit processes further promotes the development of adequate, computer-based methods for signature line quality analysis. In previous works [2, 20, 22] the ink intensity variations, particularly the regions of high intensities, be it locally for a trace segment or globally for a whole signature, were extracted by different kinds of threshold operators, which were loosely adapted to the specific efforts of ink traces. This loose adaptation did not consider the influence of material such as inking pen, paper or writing pad. Other proposed approaches [12, 24] base on the analysis of variations in the ink intensity profiles that are determined from ink traces, in particular in normal direction to the writing direction. These approaches, however, give little attention to the employed writing instrument.

The aim of our line of research is to develop an approach,

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which is objectively and achieves reproducible results. It is therefore necessary to consider all of the main aspects involved in the production of the handwritten trace, as well as the conversion of the trace into a digitized image for a computer-supported analysis. The variations in the writer's handwriting, which are the result of numerous environmental or internal influences, are the focus of handwriting examination and signature verification, while the effects of the writing materials (paper, inks and writing pads) and the digitization process must be neutralized. The neutralization of these effects is the motivation for our current studies, particularly the establishment of an ink-deposition model that allows for the formulation of the relation of writing process parameters and the amount of ink deposit on paper.

Our recent efforts on the design and the feasibility of an electronic writing robot [10], allow us to produce ink trajectories on paper under controlled conditions. According to findings from the field of motor control theory [21, 23] as well as forensic studies [6, 16] the applied pen tip forces are mostly significant in recovering disputed or forged handwritings. So, we are going to investigate the effects of applied pen tip forces on the amount of ink deposits and the inner line quality of ink trajectories on paper, first. Major research questions in this context are: (1) What are the effects on the ink trace by applying similar writing dynamics yet using different writing instruments? (2) Are there significant characteristics of ink deposits for a particular writing instrument? (3) What are the changes in ink deposit accordingly to changes in the applied pen tip forces?

The remainder of this paper is organized as follows: Section 2 describes the writing robot system briefly. The methods for the synthesis of ink traces with variable pen tip forces, as well as the analysis of digitized ink traces are outlined in section 3. The performed experiments and obtained results are described in section 4. Finally, we draw conclusions for the inspection of line quality as a means to analyze disputed and forged signatures (section 5).

2. Experimentation Device

For the synthesis of writing traces under controlled conditions the flatbed machine Isel GFY 44 / 48 [13] is being used (see figure 1). The application area of this CNC-machine 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-sychronous motors and allow for three-dimensional positioning. During the processing of one command all axes can move simultaneously with a position accuracy of 1 μm [13]. The original tool mounting was replaced by a new pen carrier, which was especially designed at the Fraunhofer IPK. The penholder

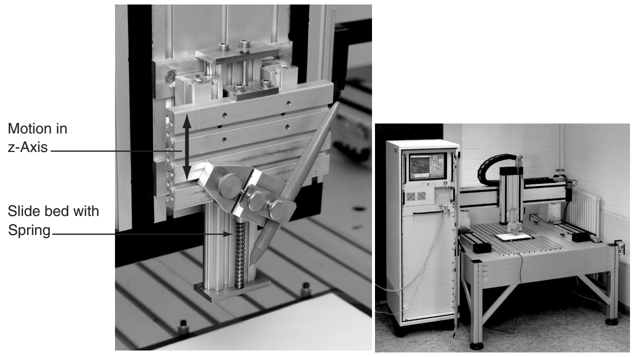

Figure 1. Flatbed machine iselGFY44/48 with assembled pen carrier that is used in the synthesis of writing traces.

is mounted on a sliding bed. 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 penholder, 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. Preparative studies were conducted in order to calibrate the transformation of robot's z-displacement into applicable pen tip forces. A conversion chart was determined that allows for the look-up of an applied force by given robot z-displacement and pen inclination [10]. For the here-described experiment we have used a fixed pen tilt of $\alpha = 55°$. And, due to the linear behavior of the spring we can consider linear force increase per one mm spring deflection with $\Delta \bar{F}_W|_{\Delta z = 1\,\mathrm{mm}} = 0.38$ N. Note: the maximal "writing" velocity is currently restricted to $v_{\max} = 33$ mm/s due to an insufficient attenuation of the penholder, which might cause vibrations and so disturbances on the ink trace. In the following, section 3 will briefly describe how to control the robot in order to produce ink trajectories on paper. Yet, we will focus on the simulation of variable pen tip forces only. The procedure to simulate natural human handwriting is detailed elsewhere [10].

3. Method

Step 1 - Synthesis of ink traces: In the domain of handwriting control theory pen tip forces of trained, genuine writers are considered as rather idiosyncratic, ballistic movements [21]. Hence, the writing robot was programmed to perform circular movements in the vertical x, z-plane. Due to the elastically supported pen carrier this movement yields to the simulation of pen's soft landing on paper. Further on, pen tips force F_i will increase continually until the maximum is passed, and will decrease until the pen is also softly lifting from the writing surface. Figure 2 gives a schematic

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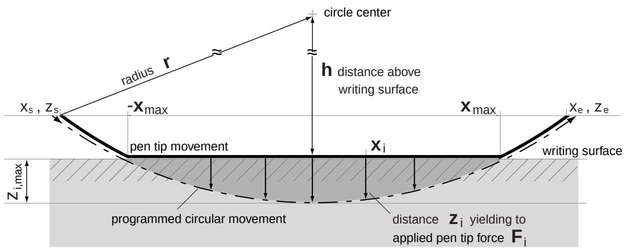
overview on robots programmed circular movement that is converted into pen tip movements with uniformly changing pen tip forces, while equations 1-3 describe the relation between of programmed circular movement and pen tip force. In order to produce multiple ink traces with different maximal pen forces the center point of the programmed circular movement is step-wisely shifted towards the writing pad. Hence, the distance h between circle center and surface is decreasing. Preserving the pen displacement parameters ensures similar admittance/exit angles (tangents) of the pen for tracings and applied maximal pen forces. However, the total lengths of the ink trajectory $(2 \cdot x_{\max})$ will increase. Since the inner line quality of the ink trace and not the shape characteristic will be studied in the experiment, this circumstance can be neutralized in upcoming computations by normalization. The relation of trace length $(2 \cdot x_{\max})$, pen displacement z_i in z-direction, and applied pen tip force F_i are determined by equations 1 - 3. The linear force increase per one mm pen displacement $(\Delta \bar{F}_W|_{\Delta z=1\,\text{mm}} = 0.38\,\text{N})$ was determined in advance during robots calibration. Thus, the ink trace synthesis with controlled pen tip forces can be particularized as follows:

1. Program circular robot movement with ISO command *G3*, and radius $r = 200$ mm,
2. Seek the pen tip at start position; distance $h = 199.5$ mm above the writing surface,
3. Produce an ink trace by means of the programmed movement,
4. Decrease pen distance from the surface by $\Delta h = 0.5$ mm, and
5. Repeat step 3 - 4 while distance $h = 187$ mm (about 25 repetitions).

Subsequently, the maximal pen tip force F_i was increased from 0.2 N to 4.8 N. The curvilinear writing velocity was kept constant with $v = 16.5$ mm/s, and the pen tilt angle was adjusted to $\alpha = 55°$.

Step 2 - Analysis of ink deposits: In order to perform a numerical analysis of the ink deposit characteristics, the trace images on the paper sheets were digitized by means of a calibrated flatbed scanner. The controlling parameters for spatial resolution were 300 dpi and 255 levels for color/gray intensities. Others, as brightness and contrast control were fixed, since only if all autonomous adjustments of the scanning device are switched off the different probes become comparable. Hence, the number N of ink trajectories written by one pen P on exactly one paper sheet are transformed into a digital image $I_P(x,y)$ with $0 \leq x \leq X$ and $0 \leq y \leq Y$. To allow for separations of the N ink traces within a digital image I_P, N rectangular, non-overlapping masks $M_1 \dots M_N$ with width W_i and height G_i were defined, whereby each mask M_i with $(1 \leq i \leq N)$ is constituted as a set of image coordinates



$$x_{\max} = \sqrt{r^2 - h^2} \quad (1)$$

$$z_i = \sqrt{r^2 - x_i^2} - h \quad (-x_{\max} < x_i < x_{\max}) \quad (2)$$

$$F_i = z_i \cdot \bar{F}_W|_{\Delta z=1\,\text{mm}} \quad (3)$$

Figure 2. Programmed circular movement for the analysis of ink deposit. Functional relations are given in equations 1-3.

$M_i = \{(m_{ij}^x, m_{ij}^y) | 1 \leq j \leq ||M_i||\}$. Homogenous background removal [13] was applied in order to filter a set T_{Pi} of image coordinates $(T_{Pi} \subset M_i)$ that belong to a digitized ink trajectory. For the analysis two primary representations of the intensity distribution along the ink trajectories T_{Pi} should be considered. (1) The intensity frequency plot $H_P(I_P, T_{Pi})$ which allows for a more general view of the ink intensity distribution, and (2) a surface plot $S_P(I_P, T_{Pi})$ that enables for assignments of applied pen tip forces to resulting ink deposit on paper. The computational procedure for both representations as well as their normalizations can be summarized as follows:
For each T_{Pi} compute the intensity frequency plot

$$h_{Pi}(k) = \#\{(x,y) | I_P(x,y) = k; (x,y) \in T_{Pi}\} \quad (4)$$

with $0 \leq k \leq 254$ and max-normalized to

$$H_{Pi} = \text{median}\{h_{Pi}(l) || k - l| \leq 5\} / \max_k(h_{Pi}(k)) \quad (5)$$

For each T_{Pi} compute the intensity surface plot

$$s_{Pi}(k) = \frac{1}{G_i} \sum_{(k,y) \in M_i} I_P(k,y) \quad (6)$$

with $0 \leq k \leq W_i$ and max-normalized to

$$S_{Pi}(k) = \hat{s}_{Pi}(k) / \max(\hat{s}_{Pi}(k)) \quad \text{with} \quad (7)$$

$$\hat{s}_{Pi}(k) = \tilde{s}_{Pi}(k) - \min(\tilde{s}_P(k)) \quad \text{and} \quad (8)$$

$$\tilde{s}_{Pi}(k) = \text{median}\{s_{Pi}(l) || k - l| \leq 5\} \quad (9)$$

These plots are used for the statistical analysis of ink intensity distributions, in particular derived parameters as mean, deviation, mode, range and lower/upper quantile.

4. Experimental Results

For the production of ink traces we used 30 different pens. These pens were randomly taken out of our pen collection, which comprises 70 different pen and refills by various

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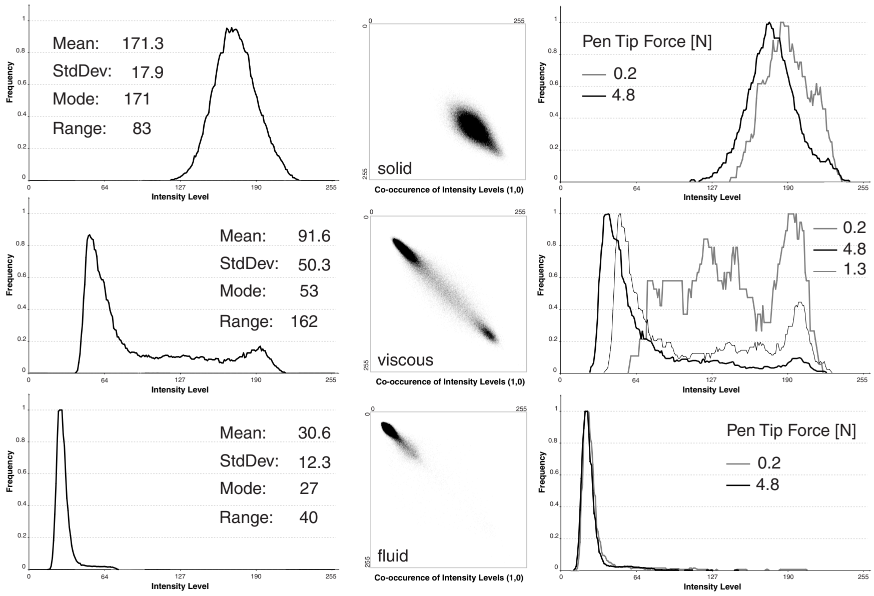

Figure 3. Average intensity frequency plots and co-occurrence matrices (distance (1,0)) for solid, viscous and fluid ink types are given on the left and middle, respectively. On the right, frequency plots for single traces produced with varying maximal pen tip forces are shown.

brands. The only criterion considered was the specific ink type of the pen [8]. Particularly, the *solid* ink type as in case of clay-graphite composites of pencils; the *viscous* ink type for ballpoint pen pastes that comprises resin and glycerin, and also the *fluid* ink type, which can be assigned to a wide variety of water-based inks, e.g., of roller ball, fine line or felt tip pens. For each ink type we considered 10 sample pens, which showed neither mechanical defects of the pen tip nor disturbances in the ink deposit due to ink aging or similar. For all chosen pens ink traces were synthesized by means of the writing robot applying the procedure described in the previous section. We used blank white paper (IBM Laser Papier, 80 g/m^2) to write on. Afterward, the trace images on the paper sheets were digitized and the ink intensity levels were analyzed separately for each pen.

Different pens, in particular differing by their ink types, can be easily recognized from the intensity plots (see figure 3). The typical characteristics can be observed for all examined ink trajectories and pen probes. Note: For discussions on ink properties and underlying physical processes of ink deposition, the interested reader is referred to [8]. The frequency plots displayed in figure 3 are given exemplary for each ink type class. It has to be noted that different ink colors yield just shifts of the intensity distribution and do not affect the general distribution.

More detailed: The ink intensity distribution for the solid ink type can be considered as rather symmetric Gaussian distribution. According to the friction between the refill and the paper surface, different amount of ink is deposited. An increase of the applied pen tip forces yields a significant left-shift of the intensity distribution. For fluid ink types the intensity distribution is almost symmetric too, yet spreads over a rather small range. The ink soaks the paper evenly, which also explains missing changes for the intensity distributions of traces written with higher pen forces. Little activations (less then five percent) of upper intensities correspond to paper fibers at the trajectory edges, which were partially colorized by the capillary effect within the paper fiber mat. The intensity distribution for viscous pastes is skewed, whereby a maximal peak is observable at lower intensity levels. The range of the distribution is the widest compared to others. The trajectories comprise segments of different ink saturation, which range from total colorizing as in the case of fluid inks up to partially colorized paper fibers that stick out like in the case of the solid ink type. This observation is supported by ink intensity distributions of traces, which were written with different pen forces. In case of lower applied pen tip forces the distribution is rather a Gaussian distribution, yet it somehow morphs into the typical skewed viscous-ink distribution if pen forces increase.

Since all ink traces were “written” from exactly the same robot program and pen tip forces, it has to be concluded that the ink type and the physical ink deposition process heavily effects the ink trace line quality, which is represented by the intensity distribution and the micro pattern of the inner trace structure. These results are in accordance with our studies on natural human handwriting [8]. Hence, for the computer-based analysis of ink trace line quality, an identification of the hypothetically used writing instrument is most important. Moreover, the kind of ink intensity distribution needs to be taken into account for the determination of high-pressure segments, since the underlying segmentation heuristic [17] might not be appropriate. Additionally, it might be possible that the range of an intensity distribution

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is too narrow, e.g. less than ten intensity levels for fluid, black inks, and an applied segmentation might fail, too.

Next, we were interested to relate changes in the applied maximal pen tip force F_{max} with $0.2\,\mathrm{N} \leq F_{max} \leq 4.8\,\mathrm{N}$ to changes in the intensity levels and to derive so-called ink-deposition models. Thus, we studied the superimposed surface plots of each ink trace and pen probe. Normalized surface plots for solid, viscous and fluid ink types are shown in figure 4. Beside selected trace plots, in particular for traces produced with a maximal pen force $F_{max} = \{0.2, 0.8, 1.3, 1.8, 2.5, 3.0, 3.6, 4.2, 4.8\}$ N, an ideal circle (broad, light gray line) is drawn. This is a kind of reference and corresponds to the programmed pen tip force variation. Plot lines for solid ink intensities along the trace increase/decrease steadily and are in accordance with the reference. Also recognizable is the rather equidistant decrease of minima intensities for increasing pen tip forces. In case of fluid inks the shape of plot lines are tubs and show the greatest deviation from the ideal circle. Just a few traces, which were written with limited pen forces, are roundly shaped. This effect can be also explained by the physics of the ink deposition process. As long as the capillary effect is not occurring, only single paper fibers are colorized. But once the effect is activated due to sufficient pen tip force, ink is evenly soaking the paper fiber mat. Rather fuzzy are the shape characteristics for surface plots of viscous inks. Traces written with less pen force are almost roundly shaped while for traces with higher pen forces the rectangular shape characteristics can be observed. We assume that analogously to solids only out-sticking paper fibers are colorized for small pen force values. But with pen force increase the applied pen force presses the paper fibers flat or even produces a groove. Additionally, ink smearing is caused which results in uniform ink deposits and no further changes occur in the intensity, once a certain saturation of ink is achieved.

In order to compare and formulate the relation of applied pen tip force and deposited ink on paper, the intensity variations for all surface plots were merged into one graph. For each trace plot the lower 10-%quantiles are printed in a bar chart, see the sub-figure on top of figure 4. As one might expect, the curves for solid ink types are rather linear, while those for viscous inks show definitely a non-linear behavior. At the first glance surprisingly, is the given intensity decrease for fluid inks. One has to take into account that values in the plots are normalized. The overall intensity range for fluids, however, comprises just 40 levels. Additionally, the plot lines are average values considering also the trace edges. So, a more realistic visualization of the intensity changes might be provided by the synthesized gray-ragtimes that also considers the overall intensity range (figure 4). In the synthesis we considered the regression results for 10%-quantiles per trace that are formulated in equation 10 - 12. These regressions model the relation of relative ink intensity to applied pen tip forces, denoting them as *Ink-Deposition Models*.

$$i_\mathrm{s} = -0.0008f^3 + 0.0157f^2 - 0.1498f + 0.7462 \quad (10)$$

$$i_\mathrm{v} = -0.0011f^3 + 0.0027f^2 - 0.2376f + 0.7537 \quad (11)$$

$$i_\mathrm{f} = -0.0006f^3 + 0.0116f^2 - 0.0902f + 0.3713 \quad (12)$$

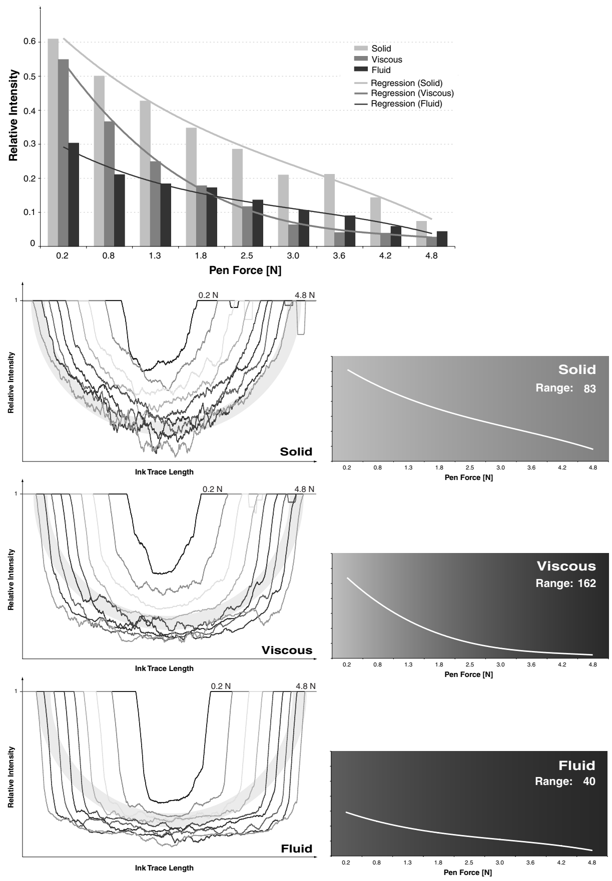

Figure 4. Derivation of Ink-Deposition Models for solid, viscous and fluid ink type: Lower 10%-Quantil of intensity surface plots of ink traces written with variable pen tip forces were analyzed. Further on, the analytic regression results considering relative ink intensity as function of applied pen tip force (equation 10 - 12) and ink type specific distribution ranges.

So far however, these models consider the applied pen tip force only. For a comprehensive description of the interaction processes between writing and ink deposition processes other characteristics of the human handwriting process, in particular writing velocity, needs also to be taken into account. Unfortunately, such investigations cannot be performed by means of the currently available writing robot. Initial tests with varying writing velocity did not give trustworthy results. Particularly, the mentioned insufficient damping of the penholder and so excited vibrations cause recognizable disturbances on the ink trace for writing velocities above 33 mm/s. Subsequently, we have to postpone such experiments until a redesign of the robot was performed, or, preferable a writing robot with six movable axes is at our disposal.

5. Summary

This paper presented a systematical study on the relation of writing and ink deposition processes. Particularly, the effects of applied pen tip forces onto the inner line characteristics of the ink traces on paper are investigated. We considered 30 different pens that were chosen according to their specific ink type. Three classes were elucidated: solid, viscous and fluid ink type. In order to ensure repeatable writing dynamics for all pen probes we have used a 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 discriminate. These results are in accordance to our previous studies. 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.

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