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## The influence of physical and biomechanical processes on the ink trace. Methodological foundations for the forensic analysis of signatures

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# Summary / Samenvatting

Handwritten signatures play an important role in daily life. They are widely accepted and frequently used to verify the claimed identity of a person. Consequently, there is a strong need for objective and automatic signature evaluation. The dissertation at hand aims (i) to provide a scientific basis for procedures applied in the forensic analysis of signatures and (ii) to derive advanced computational methods for the machine processing of signatures written on paper documents. Special emphasis will be put on methods for inferring writer-specific behaviors from the residual ink trace. The respective micro-patterns, caused by biomechanical writing and physical ink-deposition processes, provide important clues for the analysis. These inner-ink-trace characteristics of signatures, which are determined by the individual movements of a person, will be studied in depth, taking into account the effects of writing materials, such as the type of pen used. The studies work towards a fundamental understanding and a comprehensive multidisciplinary approach to the forensic, computer-based analysis of signatures.

This technological research is conducted under consideration of perspectives and findings from a number of other fields, namely forensics, human-movement science, image processing and pattern recognition as well as robotics, and also hopes to contribute to these disciplines. The research method is *Analysis by Synthesis*. Recorded pen movements are used to program a *Writing Robot* in order to ensure the production of ink traces on paper under strictly controlled conditions. The behavioral characteristics of the signing process and the characteristics of the synthesized ink trace are systematically studied, drawing conclusions for forensic analysis and computational method designs. The concept of *Soft Biometrics* is proposed in order to deal with the variability of the available signature data. It denotes the use of Soft Computing in biometrics, in the current case for signature preprocessing, feature extraction and analysis. The variability of shape and inner-ink-trace morphology is a result of the signing behavior itself and the variety of situations in which it is performed.

The thesis is divided into four parts. Part I (Chapters 1, 2) introduces forensic signature analysis and provides theoretical foundations, which will be further elaborated in the remaining parts. Part II (Chapters 3-5) presents empirical studies on the calibration of the writing robot and the measurement instruments used. It also includes studies on the human-biomechanical signing process and the characteristics of ink traces, particularly those synthesized by the robot. Part III (Chapters 6, 7) focuses on the design of computational methods, including preprocessing, feature extraction and the analysis of ink traces. Finally, Part IV (Chapters 8, 9) discusses the implications of the previously conducted empirical studies and the newly designed computational methods.

**Chapter 1** gives an overview of the demands and challenges of forensic signature analysis and specifies the research questions that this thesis aims to answer:

1. What are the interactions between the writing materials used and writing behaviors?

2. How can an analytical model describing these interaction processes be formulated?
3. How can writer-specific characteristics be deduced from ink-trace patterns?
4. How can superimposing material influences be dealt with during a computerized analysis?

**Chapter 2** provides the necessary theoretical basis. The concept of Soft Biometrics is proposed as the appropriate toolset for the new computational methods to be designed. It is shown to facilitate local, adaptive data processing and tolerance mechanisms in the analysis. Various aspects are pointed out in order to provide a solid basis for the upcoming chapters, i.e. the neuro-physiological and biomechanical signing process, the physical properties of writing utensils, such as paper, pen, ink and writing pad, and subsequently, characteristics of the residual ink trace on paper. Especially the micro-patterns of the inner writing line, which are caused by the interaction of biomechanical writing and physical ink-deposition processes, are described in detail.

**Chapter 3** describes the calibration and the feasibility study of the writing robot. The mechanical construction and dynamic behavior of the robot are evaluated in order to enable it to replay human-like pen movements and pen-tip forces. Reliable value ranges for parameters like writing velocity are derived by means of experiment. For the simulation of realistic pen-tip forces, the transformation of the robot's vertical movement into elastic spring forces is mathematically and empirically derived. In addition, the calibration of measurement instruments, such as electronic writing tablets and digital image scanners, is described. Writing tablets are used to record pen movements, which will later be replayed by the robot. Thus, a physical ground truth for captured data, mainly for the pen-force records, is established. The accuracy of superimposed on- and offline data is evaluated, given that recorded pen movements are also used for tracing and analyzing ink traces. In consequence, a procedure is proposed for correcting misaligned pen-tip coordinates.

**Chapter 4** presents empirical studies of the biomechanical characteristics of authentic and forged signing behavior. It focuses on kinematic, kinetic and pen-orientation characteristics, in order to identify significant factors for the upcoming signature analysis. It is shown that the signing behavior of genuine writers and forgers is only likely to differ in terms of local characteristics. Global characteristics can easily be imitated by skilled forgers. A study on pen-orientation characteristics, which is the first of its kind, is described in detail. It reveals four primary categories of pen-tilt variations, which is not only highly relevant for the analysis of signing behaviors and residual ink traces, but also for the improvement of current tablet technologies. The signing behavior of 55 genuine writers and of 32 writers mimicking three different signature samples is analyzed in order to identify process parameters for the upcoming experiments with the writing robot.

**Chapter 5** details the validation of residual ink trace and stroke phenomena that were produced under controlled conditions. The purpose of these empirical studies is to provide a scientific basis for inferring writer-specific behaviors from the ink trace. In particular, the stability and reproducibility of the micro-patterns of inner ink traces are validated. The interrelation of writing and ink-deposition processes for pens with different ink types is studied as well. A so-called Ink-Deposition Model is formulated, which describes the

change of ink deposition as directly related to the applied pen-tip force. The systematically conducted experiments clearly show that ink traces produced by viscous ballpoint-pen paste are most likely to represent writer-specific information, in contrast to liquid water-based inks of roller ball and fine-line pens, where inner-ink-trace characteristics do not reflect the writing process. Furthermore, it is revealed that inner-ink-trace characteristics and stroke phenomena caused by different ballpoint pens are similar for ink traces produced by the same writing movements. Thus, it is possible to infer behavioral characteristics from the residual ink trace. The procedure of regenerating robotic pen trajectories from recorded human-writing movements is described in detail in order to demonstrate the accuracy of the robot's movements. The precision of emulated pen-point kinematics / kinetics is examined and cross-validated with natural data. It is shown that the robotic simulation of handwriting is feasible, and that synthesis is the appropriate method for ink-trace analysis.

**Chapter 6** introduces new computational methods for signature and document preprocessing. The segmentation of the signature from the document background has to be done without impairing the quality of the ink-trace line. Several methods are presented for removing the document background and foreground. The methods differ depending on the amount of available a-priori knowledge. However, in view of the great variety of document types the procedure will not always be the appropriate one. Therefore, Evolutionary Computation is investigated in order to generate adapted image filters as and when required. It will be shown that such an approach makes it possible to deal with the vast amount of different document types that are investigated in forensic casework. In addition, conclusions regarding the feasibility of basic image operations are drawn. Local, adaptive image operations are needed to preserve fine ink-trace details, while simultaneously removing complex backgrounds. It is described at length how the introduction of concepts from Fuzzy Logic, such as Triangular Norms, can be used to extend well-established operations of Mathematical Morphology, and how these approaches of so-called Fuzzy Morphology outperform other methods with regard to filtering textured backgrounds.

**Chapter 7** proposes new computational methods for the shape and stroke-morphology analysis of signatures. The so-called region approach is presented as a reliable analysis technique for comparing the spacing between ink strokes. This approach for deriving regions from the contour-shadow strokes is described in detail. The method yields a 98% recognition rate for single region matching on the basis of fuzzy rules derived by means of a Neuro-Fuzzy approach. It will be shown that these automatically derived rules outperform other methods used for function approximation, particularly hand-coded rule-based classifiers, the Multi-Layer Perceptron and the Support-Vector Machine.

In a next step, the feasibility of texture-analysis methods for computer-based ink-type recognition is tested, in particular second-order statistical features of the co-occurrence matrix. The selection of class-discriminant features is alternatively done by Fisher Discriminate Analysis and by exhaustive search. It will be shown that the selected features are particularly suitable for distinguishing between different types of ink traces. By using Artificial Neural Networks, recognition rates of more than 98% are obtained for samples produced by 62 different pens/refills. Thus, the ink type used can be recognized automatically by applying methods of texture analysis and Artificial Neural Networks.

The relative ink deposition along the trace is sensed by means of recorded and superimposed pen movements, and subsequently analyzed by applying the method of Derivative Dynamic Time Warping. It will be shown how recorded pen movements can be used for sensing ink deposits, and which preparative steps are necessary in order to ensure reproducible analysis results. The approach is validated by synthesized signature specimens, produced with 24 different ballpoint pens, yielding recognition results of 92%.

**Chapter 8** summarizes the introduced concepts and primary results of the performed empirical studies of the biomechanical signing process and the robotic ink-trace synthesis. In addition, new computational methods for signature preprocessing, feature extraction and analysis are presented. In brief, the main contributions of this thesis are:

1. The formulation of a so-called *Ink-Deposition Model*, describing the interaction of biomechanical writing and physical ink-deposition processes. Experiments with natural human handwriting as well as simple, ballistic movements were conducted, providing a scientific basis for inferring writing movements from residual ink traces.
2. The establishment and proof-of-validity of a *Writing Robot* that replays recorded pen movements in order to exclude the variability intrinsic to human behavior and, consequently, to enable the analysis of handwriting under controlled conditions.
3. The introduction and feasibility study of *Soft Biometrics* as a toolset for computer-based signature processing. New approaches for the extraction and analysis of writer-specific signature and ink-trace patterns are revealed. The computational methods proposed here establish objective and reproducible testing procedures for forensic investigations.

**Chapter 9** concludes with theoretical implications as well as practical considerations for computer-based signature analysis. The experiments with synthesized ink traces have shown that it is possible to infer behavioral characteristics from the residual ink trace. The application of the newly designed computational methods in a number of experiments has revealed that algorithms with learning, adaptation or optimization abilities are the appropriate means to deal with the variation and imprecision of signature data. The concept of Soft Biometrics has proved to be feasible, yielding valid results. Nevertheless, it must be taken into account that a handwriting digitizer is not reliable without calibration. In order to ensure reproducible data and analysis results, user interference with the settings of the digitizer must be prevented.

Finally, suggestions are made for further research. Information about writing movements, such as stroke order, pen displacement and pen-tip force, facilitates the advanced forensic analysis of residual ink-trace patterns. It is not only possible to deduce the writing sequence, but recorded pen movements can also be used in specific measurements and analyses. Open questions concern the direct assignment of temporal writing and ink-trace characteristics. There is clearly a demand for extensive experiments with artificially synthesized and naturally produced ink traces. Since the robotic simulation of pen trajectories can exclude natural variations of human behavior, it allows for strictly controlled studies of writing and ink-deposition processes. With the help of this machine, fine motor tasks and established peripheral models of human handwriting can be further evaluated. Ink traces and writing materials can be dealt with in a sophisticated manner, and it is even possible to train and examine forensic handwriting experts. This provides

a basis for the development of new computational methods for signature / handwriting analysis and recognition.

**In summary**, the thesis shows (1) that a multidisciplinary approach to forensic signature analysis provides fundamental insights, (2) that ink deposition and the resulting ink-trace morphology provide reliable information about the writing process, (3) that the robot simulation of signatures requires pen-force control in order to ensure a precise signature synthesis, and (4) that the paradigm of Soft Biometrics, comprising methods of Soft Computing, is applicable in forensic signature analysis.

## Samenvatting

### De invloed van fysische en biomechanische processen op het inktspoor - Methodologische fundamenteen voor de forensische analyse van handtekeningen

De handtekening speelt nog steeds een belangrijke rol in het zakelijk verkeer. Er is een toegenomen behoefte aan objectieve biometrische technieken zoals automatische handtekeningverificatie. Dit proefschrift heeft tot doel (i) om een wetenschappelijke basis te bieden voor methodes die gebruikt worden in de forensische analyse van handtekeningen, en (ii) om geavanceerde computationele methoden af te leiden voor de automatische analyse van handtekeningen zoals die op papier zijn vastgelegd.

Hierbij ligt de aandacht op methoden waarmee schrijver-specifieke gedragingen kunnen worden afgeleid uit het vastgelegde, statische inktspoor. Methoden waarbij de vorm van elementen in een handtekening worden gebruikt bestaan al langer. De aanleiding voor de hier voorgestelde analyse bestaat echter uit de gevonden aanwezigheid van micropatronen binnen het inktspoor. Deze morfologische patronen zijn het resultaat van biomechanische processen gedurende het schrijven en van de specifieke inktafzettingsprocessen die typerend zijn voor het gebruikte schrijfinstrument. Door gebruik te maken van analyse door synthese, middels een robot-arm, kon een systematische analyse worden gemaakt van de intrinsieke eigenschappen van het inktspoor van een handtekening als functie van bewegingsparameters. Er werd hierbij rekening gehouden met de invloed van het type schrijfinstrument.

De multidisciplinaire benadering (beeldbewerking, patroonherkenning, robotica, forensisch en bewegingswetenschappelijk onderzoek) van deze studie heeft geleid tot een beter fundamenteel begrip van het schrijfproces. De verworven inzichten worden gebruikt voor een geautomatiseerde forensische analyse van handtekeningen. Hierbij is het nodig gebleken dat automatische methoden robuust zijn in het verwerken van ruis en variabiliteit. Voor de oplossing van dit probleem wordt het paradigma *Soft Biometrics* voorgesteld. In deze aanpak worden methoden uit het gebied van *Soft Computing* ingezet bij de voorbewerking en analyse van biometrische signalen. Bij de automatische handtekening-analyse worden de meeste problemen veroorzaakt door de variabiliteit van de fysische, biomechanische en psychologische context waarin het tekengedrag verloopt. Hierdoor zal het gebruik van een eenzijdige en rigide deeltechniek niet mogelijk zijn in de realiteit van het forensisch schriftonderzoek.