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PERSPECTIVES ON USING INNOVATIVE DIGITAL TECHNOLOGIES IN ARCHITECTURE FOR FORENSIC HANDWRITTEN INK ANALYSIS

Klaudiusz FROSS[1*], Adam BUCZEK[2], Krzysztof GROŃ[3], Tomasz SZULIŃSKI[4], Roxana FROSS[5]

[1] Silesian University of Technology, Faculty of Architecture; klaudiusz.fross@polsl.pl, ORCID: 0000-0002-0013-7619
[2] Upper Silesian Academy, Department of Law and Administration, Katowice; a.buczek@op.pl, ORCID: 0000-0003-1395-7541
[3] Silesian University of Technology, Faculty of Architecture; krzysztof.gron@polsl.pl, ORCID: 0000-0002-5152-0167
[4] Silesian University of Technology, Faculty of Architecture; tomasz.szulinski@polsl.pl, ORCID: 0000-0001-6005-3786
[5] Silesian University of Technology, Faculty of Architecture; frossroxana@gmail.com, ORCID: 0000-0003-2783-5086
* Correspondence author

Purpose: The paper aims to explore the application of modern 3D digital imaging tools, originally developed for architectural design, in forensic handwriting analysis and technical document examination. It seeks to provide objective, quantitative methods for assessing ink layer thickness in handwritten signatures, a parameter reflecting individual writing pressure and psychomotor characteristics.
Design/methodology/approach: An interdisciplinary research team, comprising experts in law, forensic science, architecture, software, digital technologies, and design, conducted the study. The approach combined 3D digital imaging techniques, image processing algorithms, and quantitative analysis to measure ink layer thickness in handwriting samples. The theoretical scope integrates architectural digital modeling methodologies with forensic document examination.
Findings: The study demonstrates that algorithms derived from 3D architectural imaging allow precise, quantitative measurement of ink layer thickness. This method provides reliable, reproducible data for assessing individual writing pressure, reducing subjectivity in traditional forensic handwriting evaluation. The approach also enables population-level analysis of writing characteristics.
Research limitations/implications: The research is limited to the types of handwriting samples and ink used in the study. Future studies could expand to different pen types, substrates, and larger population datasets. The methodology suggests potential for integration with automated forensic handwriting systems.
Practical implications: The developed techniques offer forensic experts' objective, reproducible tools for evaluating ink layer thickness, improving the accuracy and reliability of handwriting analysis in legal proceedings. The approach could inform the development of software solutions for document examination and digital evidence processing.

Social implications: By improving the accuracy of forensic handwriting analysis, the research contributes to the integrity of legal proceedings and public trust in forensic evidence. Enhanced reliability in document examination could influence law enforcement practices, judicial outcomes, and public confidence in the justice system.
Originality/value: The paper introduces a novel interdisciplinary approach by applying architectural 3D imaging techniques to forensic handwriting analysis. It provides new methodologies for objective, quantitative evaluation of ink layer thickness, valuable to forensic scientists, law enforcement, and researchers in digital forensics and document examination.
Keywords: forensic science, digital forensics, architecture, 3D imaging tools, handwriting analysis.
Category of the paper: Research paper.

1. Introduction to research

In recent decades, modern digital methods for architectural design have developed rapidly, extending into the virtual realm. Virtual environments can be created using platforms such as Unreal Engine. Software including Autodesk 3ds Max, Foundry Modo, Substance Designer, Rhino, Adobe Photoshop, and Adobe Fuse support modelling, texturing, lightmapping, and UV mapping, among other tasks. Animation can be produced using programs such as Premiere Pro or Mixamo. The combination of Rhino and Grasshopper enables the creation of parametric scripts and spaces. Virtual reality (VR) can be experienced through devices such as Meta Quest, Oculus, HTC Vive, Google Daydream, Samsung VR headsets, touchscreens, and mobile applications on iPads or iPhones, and is increasingly integrated into design workflows. VR-enhanced projects may include apartment sales presentations for developers or furniture design proposals. Mixed reality devices, such as Microsoft HoloLens 2, allow for presenting building models and inspecting structures during construction.

3D scanners, often paired with drones or smartphone apps, are increasingly used to inventory rooms, objects, or entire areas. Applications include grayscale numerical analysis, computational design, and parametric modelling based on CAD software, as well as algorithmic design. Widely used software for generating and processing 3D models includes Quad Remesher, Reality Capture, Moi3D, Fusion360, 3DCoat, Adobe CC, and Houdini. Graphical algorithm editors are particularly important; for example, the Grasshopper editor integrated with Rhinoceros 8 allows users to create form-generation algorithms without coding, generate geometry with custom attributes, and arrange hatches and annotations efficiently.

These technologies enable the creation of highly precise, photorealistic 3D models, which have applications beyond architecture, including industrial design, mechanics, geology, archaeology, and medicine. 3D digital imaging methods are increasingly employed in a wide range of expert practices within law enforcement and the justice system, covering areas such as biomechanics, molecular biology, toxicology, thanatology, forensic traumatology, ballistics, trace analysis, and accident reconstruction.

2. Methodology, purpose and scope of research

The research presented here is innovative, pioneering, and groundbreaking, representing some of the first effective attempts to apply modern 3D digital imaging tools from architecture to the forensic analysis of handwritten signatures (Fross, Buczek, Groń, 2024). This study focuses specifically on analyzing digital images of ink layer thickness in handwritten notes using grayscale numerical analysis. Determining ink layers is a critical component of forensic technical document examination and encompasses issues such as the analysis of inks, ballpoint pens, gels, stamps, seals, computer printouts, and xerographic copies.

In expert practice particularly in the context of forgery detection questions often arise regarding whether specific records (e.g., individual components of a will) were written using one or multiple ink layers, the chemical composition of these layers, whether the records were created simultaneously, and the sequence of recording. Although pilot in nature, the research described in this article offers a valuable supplement and a fresh perspective on standard methods used in forensic science.

Traditional forensic approaches to ink analysis include specialized workstations such as the Foster+Freeman QDE VSC8000/HS, which combines advanced digital imaging, multi-wavelength illumination, and a built-in microspectrophotometer. Spectroscopic methods, including Raman and infrared spectroscopy, as well as chemical approaches such as thin-layer chromatography and high-performance liquid chromatography, are widely employed. Additional research explores advanced techniques such as time-of-flight secondary ion mass spectrometry (ToF-SIMS), laser micro-sampling coupled with inductively coupled plasma mass spectrometry (LA-ICP-MS), and capillary electrophoresis (CE), among others.

The present research focuses on a single parameter the ink layer thickness which can be used to infer individualized writing pressure. Other properties, including the color of the ink coating and the indentations or reliefs created in the ink layer, are investigated in separate studies using different methodologies.

2.1. A concise description of the research methodology

The experimental method involved the use of Rhino 7.34.23267.11001 in combination with Grasshopper 1.0.0007 for all computational analyses. The research was conducted in two stages. In Stage 1, a single signature was analyzed, and an algorithm was developed to numerically characterize the degree of saturation of its ink lines. The outline of the signature was visualized, incorporating numerical values representing the saturation and thickness of the ink lines in the base signature. In Stage 2, the initial algorithm was expanded into a script that enabled comparative analysis of ink thickness distribution, represented on a grayscale, across multiple graphic structures. In this stage, four signatures by one of the co-authors, created with four different ink layers, were analyzed, and the results were visualized. A detailed description of the research procedure is provided in Section 4.

2.2. Theoretical background and foundations of research

Extensive literature exists on the forensic examination of documents, including studies addressing the application of concealing agents. The most important authors in the world include: Joy T. Kunjappu (Joy, 2003), Raj Kumar, Wiszal Sharma (Raj, Sharma, 2017), Yao Wu, Chun-Xi Zhou, Jing Yu, Hai-Ling Liu, Meng-Xia Xie (Wu, Zhou, Yu, Liu, Xie, 2012), Agnieszka Koenig, Celine Weyermann (Koenig, Weyermann, 2018), André Braz, Maria López-López, Carmen García-Ruiz (Braz, López-López, García-Ruiz, 2013), Jay Siegel, John Allison, Donna Mohr, Jamie Dunn (Siegel, Allison, Mohr, Dunn, 2005), Georgina Sauzier (Sauzier, 2023), Anastasia V. Kravchenko, Daria V. Makeeva, Ilja Tumkin, Andrei V. Kalinichev (Krawczenko, Makeeva, Tumkin, Kaliniczew, 2024), Nikolai Ju. Tyuftyakov, Andrei V. Kalinichev, Nadezhda V. Pokhvishcheva, Maria A. Peshkova (Tiuftiakow, Kaliniczew, Pochwiszczewa, Peszkowa, 2021), Matías Calcerrada, Carmen Garcia-Ruiz (Calcerrada, Garcia-Ruiz, 2015), L. Ortiz-Herrero, M. I. Maguregui, L. Bartolomé (Ortiz-Herrero, Maguregui, Bartolomé, L. 2021). In Poland, the following authors publish, among others: Klaudiusz Fross, Adam Buczek, Krzysztof Groń (Buczek, 2006; Buczek, Groń, 2015; Fross, Buczek, Groń, 2024), Andrzej Łuszczuk, Krystian Łuszczuk, Mieczysław Goc, Tadeusz Tomaszewski (Goc, Łuszczuk, Łuszczuk, Tomaszewski, 2012; Łuszczuk, Goc, Łuszczuk, 2014, 2015), Roman Ptak, Bartosz Żygadło (Ptak, 2006, 2012; Ptak, Żygadło, 2014), Jacek Reiner, Mariusz Mrzygłód, Grzegorz Rusek, Mirosław Owoc, Rafał Cieśla, Michał Januszkiewicz (Reiner, Mrzygłód, Rusek, 2014; Rusek, Cieśla, Ptak, Januszkiewicz, 2019; Rusek, Reiner, Ptak, Owoc, Mrzygłód, Cieśla, 2012), Jacek Jarnicki (Jarnicki, 2012).

For modern equipment used in handwriting identification examinations, including issues such as determining the chronology of entries (relative age) and absolute age analysis, see, for example, E. Gruza, M. Goc, and J. Moszczyński, Kryminalistyka. *Czyli o współczesnych metodach dowodzenia przestępstw*, Wolters Kluwer, Warsaw 2020, pp. 462-471. In the context of examining concealing agents, forensic science employs numerous methods described in Analityka sądowa (Kościelniak, Król, Wietecha-Posłuszny, Woźniakiewicz, 2023).

Similarly, modern digital methods developed for architectural design have been widely described, including software for 3D visualization, 3D scanning, 3D printing, virtual reality (VR) (Urbanowicz, Szuliński, 2020, 2021) and mixed reality (MR) (Fross, Fross, Szuliński, 2022). It is important to emphasize the rapid development and significant variability of architectural software in recent years, evolving from early CAD programs such as AutoCAD and ArCADia, through complex 3D visualization programs like 3ds Max, then to more user-friendly solutions such as ArCon and ArchiCAD, and currently widely used programs including Revit, SketchUp, and Blender (Szuliński, 2022). Achieving high-quality 3D visualizations often requires the use of multiple programs, culminating with graphics software such as Photoshop. The market drives the demand for creating 3D drawings, visualizations, and models, with current trends emphasizing project digitization and design integrated with BIM software (Fross, Fross, Szuliński, 2022).

In forensic science, the transition from conventional to digital 3D imaging methods has created disproportionately greater opportunities for inference and assessment. Modern 3D laboratories offer extensive technical and technological capabilities for mapping and analysing the complex biology of the human body and its surrounding environment within a virtual three-dimensional space. Key technologies employed include 3D laser scanning, photogrammetry, modelling, texturing, and 3D animation (Maksymowicz, Tunikowski, 2018).

The primary objective of forensic handwriting and document analysis is the identification of the writer. The scope of such research encompasses comprehensive examinations of wills, continuous texts, signatures, anonymous letters, and phenomena collectively referred to as 'handwriting pathology.' This includes the handwriting of individuals affected by various conditions, such as mental illness, Parkinson's disease, Alzheimer's disease, aging (particularly in the context of drafting wills), and other relevant factors.

2.3. Description of the research and methods

Items Using Rhino 7.34.23267.11001 and Grasshopper 1.0.0007, we first developed an algorithm to quantitatively assess the degree of saturation of the writing lines with the covering material (Fig. 1).

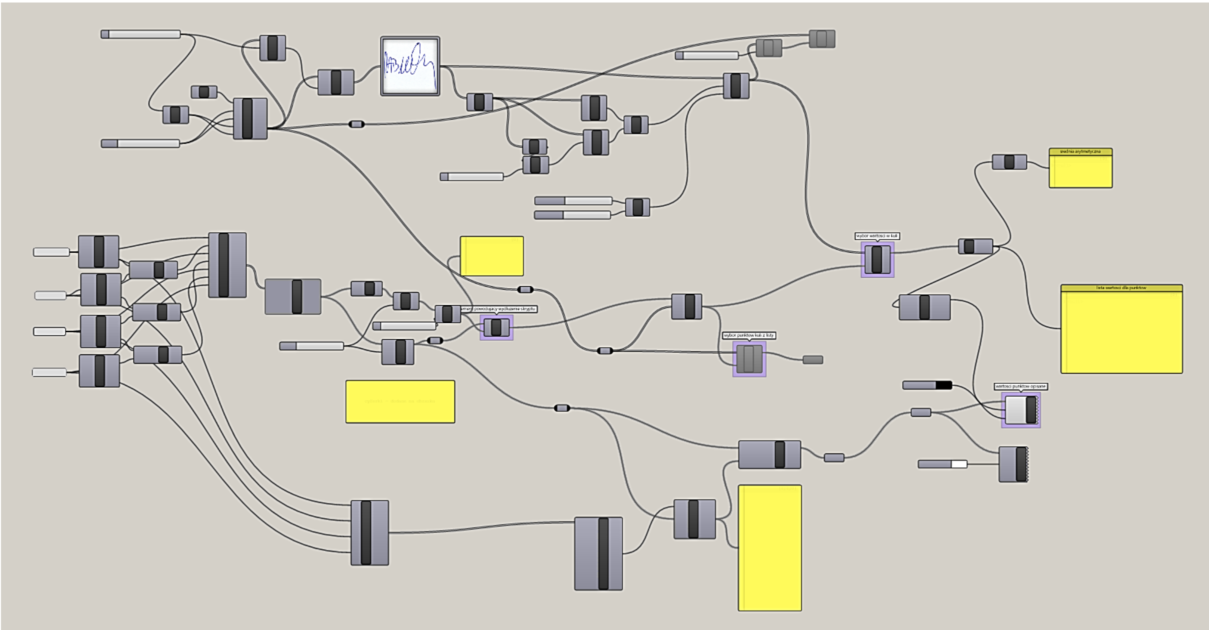

Figure 1. Algorithm providing a numerical characteristic of the digital image of the degree of saturation of the writing lines with the ink.

At the current stage of research, the algorithm remains semi-automatic and has been tested primarily on short graphic structures, including signatures and initials[1]. After scanning the analysed structure, the procedure began by manually tracing a line through the centre of the writing, across the entire surface of the signature, to define the pixel analysis area. In the present case, the algorithm was configured to divide this defined outline into 300 sets. It then sampled pixels along the traced line and calculated arithmetic means for each set, corresponding to the degree of line saturation (see Figures 1 and 2).

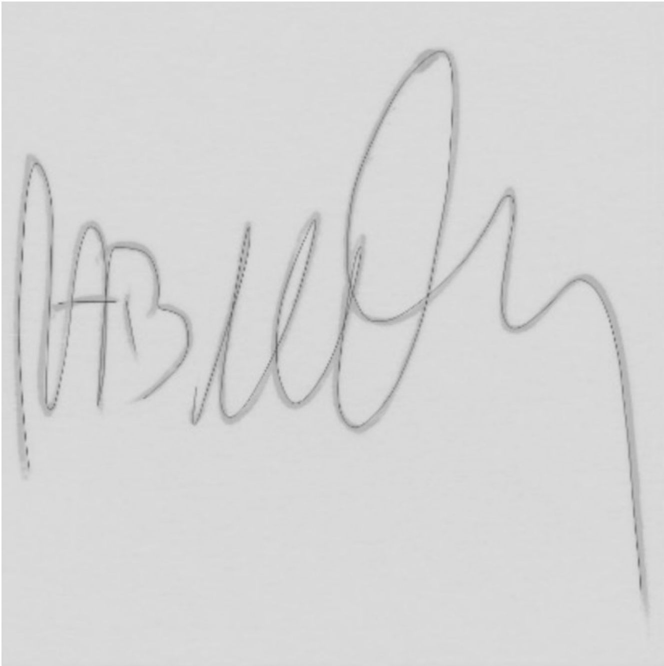

Figure 1. Manually drawn line/outline of the base signature scan.

Figure 3 defines a 1-100 grayscale based on scan brightness. This scale enables the quantification of the signature's pressure sensitivity, representing the shade (value) of the line across its 300 divided sections.

A precise, numerical characterization of handwriting line thickness was obtained, allowing the identification of extreme values from the minimum to the maximum and the calculation of the average value. This approach facilitates the quantitative determination of a highly personalized, and therefore diagnostically significant, handwriting parameter that can support individual identification. Figures 4 and 5 illustrate a visualization and a 3D model of the procedure as applied to the page containing the analyzed signature.

[1] The graphic structure (visible in Fig. 1) described later in the text is the signature of one of the co-authors of this publication.

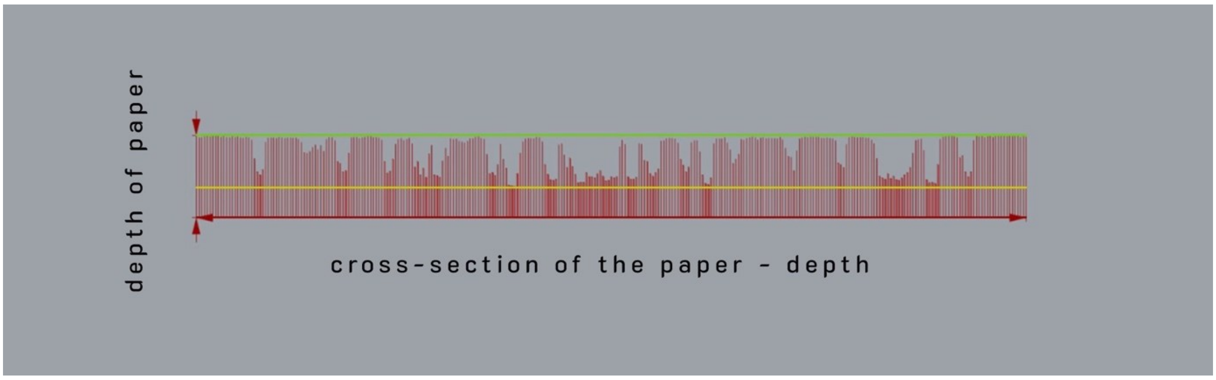

Figure 4. Visualization of the amount of coating agent applied to the background of the paper. Green line: top edge of the paper; red line (long arrow): base of the paper; yellow line: limit to which the coating agent layer thickness extends. This value ranges from 0 mm to 1 mm.

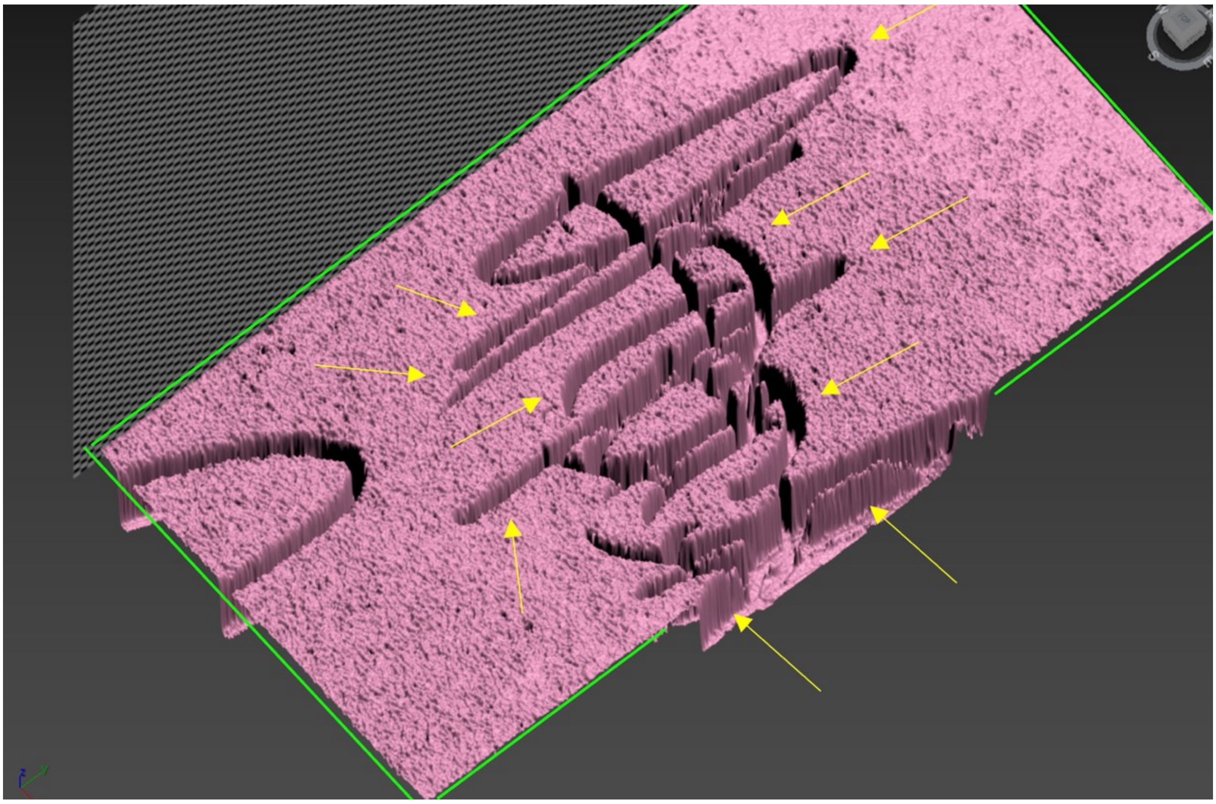

Figure 2. 3D model of the coating layer thickness in the base signature. Green line (border): top edge of the page. Arrows indicate the coating material (ink) thickness. Top view.

In the next stage, the output algorithm was extended with a script enabling comparative analysis of the coating thickness distribution of individual graphic structures in the grayscale (see Fig. 6).

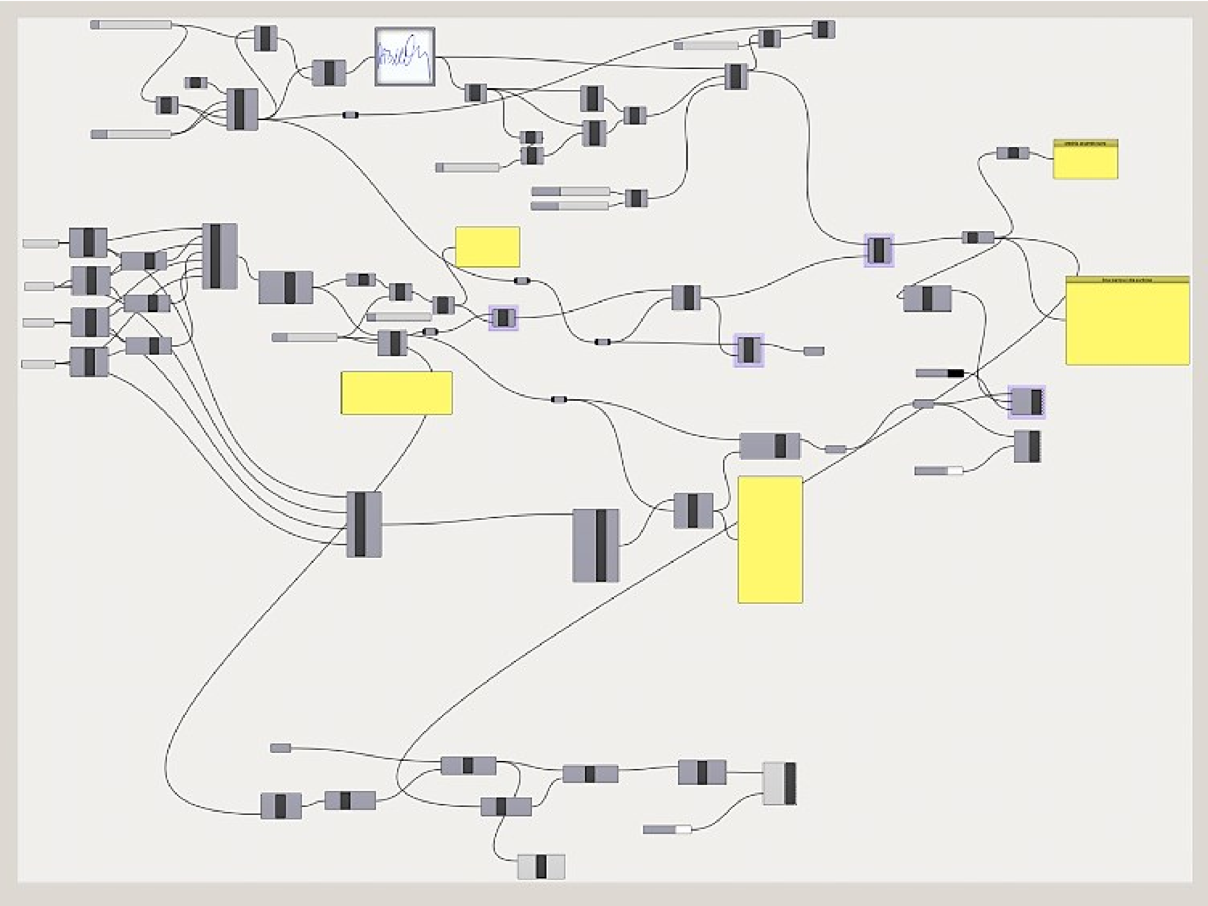

Figure 6. Script for analysing the coating thickness distribution on a grayscale.

At this stage, the analysis focused on four signatures produced by one of the co-authors, each written with a different ink layer. The thickness of the ink layer was automatically quantified by the program and represented as a spectrum. Each spectrum is based on differences in grayscale values corresponding to the scan brightness; for example, the grayscale can range from 0 to 100, with the range manually defined by the user. Consequently, the resulting spectrum of ink layer thickness reflects the corresponding grey saturation, with each original spectrum appearing in grayscale.

The methodology was as follows: first, each signature was scanned, and a separate grayscale spectrum representing ink layer thickness was generated for each. Second, for enhanced visualization, each spectrum was assigned a distinct color - red, blue, white, and green - and the colored spectra were then superimposed (see Figures 7 and 8).

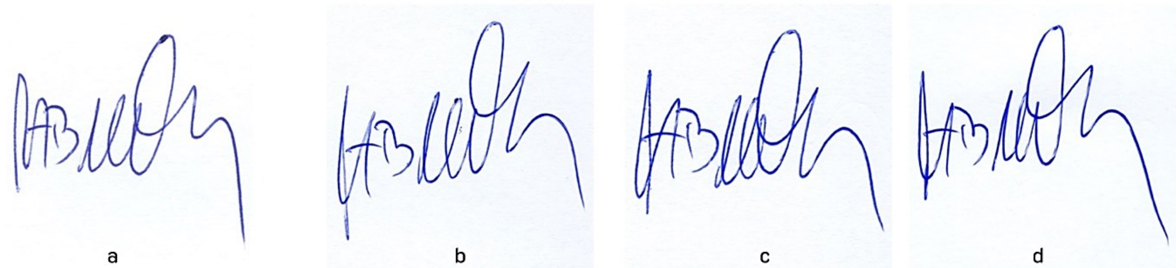

Figure 7. Signatures subject to analysis in grayscale - spectral colour designation; a. Red spectrum, b. Blue spectrum, c. White spectrum, d. Green spectrum.

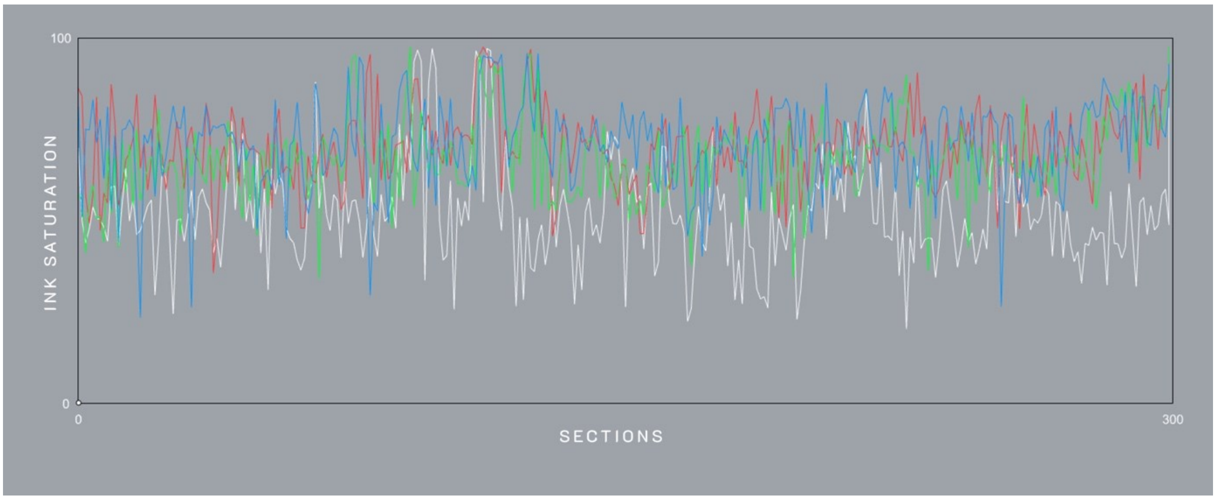

Figure 3. Superimposed image of spectra of signatures a, b, c and d.

Analysis of the spectra, focusing on the shape and distribution of peaks, indicates that the thickness of the covering material layer - a key pressure-sensitivity parameter - is highly consistent. A major advantage of the tested methods is the use of 3D visualization techniques, which provide significantly greater capabilities for displaying, analyzing, and presenting examined graphic structures compared to conventional methods commonly employed in judicial practice.

These techniques enable faithful reproduction of the graphic structure, preserving all proportions, details, and characteristics. Furthermore, through advanced lighting modelling, specular reflection, light dispersion, refraction, and shading solutions, many details that are difficult to capture using traditional handwriting analysis methods can be revealed, examined, and presented. This includes features related to both the texture of the substrate and the graphic structure itself. Additionally, once an accurate 3D model of the analysed graphic structure is created, further operations such as translation (moving the graphic in space), rotation, tilting, and scaling can be performed. Figures 9 and 10 illustrate two perspectives of the coating layer thickness visualization.

Figure 9. Image of the coating layer thickness relative to the sheet of paper in the form of an indentation.

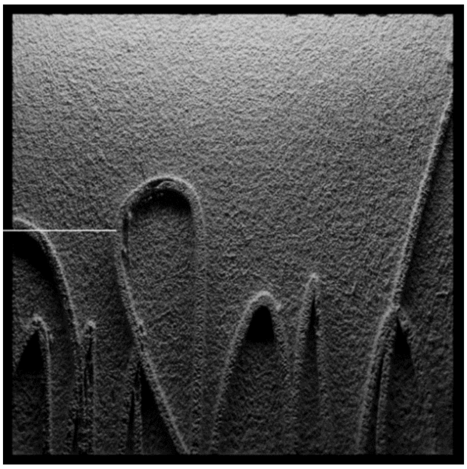

Figure 10. An inverted image of the coating layer thickness relative to the sheet of paper in the form of a convexity.

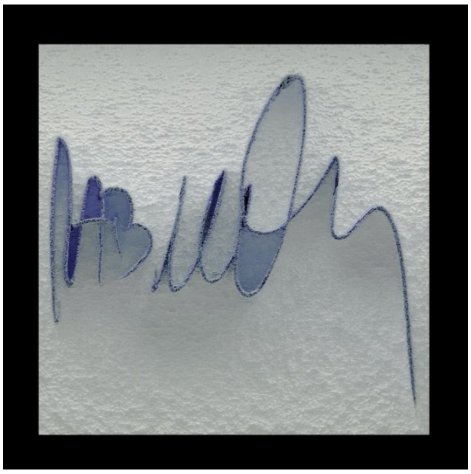

Figure 11. Visualization of a negative 3D model in colour.

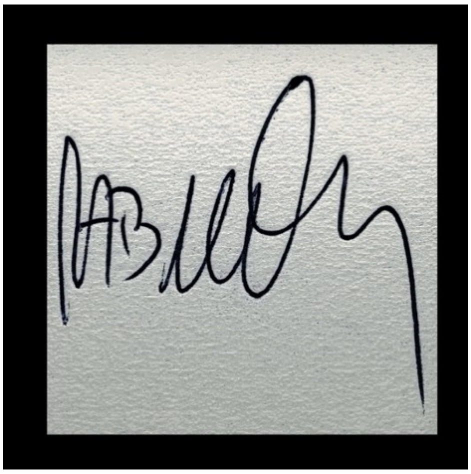

Figure 12. Visualization of a positive 3D model in colour.

Figures 11 and 12, in contrast, present a visualization of the signature analysed using the algorithm described in Figure 1.

3. Summary and conclusions

In summary, it should be emphasized that this research is of a pilot nature, and the algorithms described are still under development. At this stage, they cannot be considered fully validated tools for handwriting analysis. The authors aimed to explore the capabilities of digital technologies originally developed for purposes outside forensic identification, assessing their potential to form the basis of future supporting or alternative identification methods. To advance this work, more extensive experimental studies will be conducted using comparative materials from multiple individuals and a variety of ink types.

Based on the conducted research, the following conclusions can be drawn. The study demonstrated the extensive potential of applying modern digital techniques and 3D imaging tools, originally developed for architecture, in forensic handwriting and document examination. The algorithms developed by the authors are still under development and not yet ready for full implementation. Nevertheless, they represent a novel research direction, enabling the precise, numerical characterization of coating layer thickness distribution on a substrate. By providing a precise, numerical description of ink density distribution, these methods allow for accurate determination of handwriting parameters that are diagnostically important, which previously could only be described subjectively with vague terms such as "small", "medium", or "large" in reference to pressure force. The developed algorithms supply detailed information on features such as the shading of writing lines and the pressure exerted by the writing instrument on the surface. These characteristics are highly individualized, dependent on psychomotor abilities, and therefore critically important for personal identification. At the current stage, the tools are applicable to short graphic structures, such as legible signatures and initials, enabling analysis of both single signatures and comparative characteristics across multiple signatures. With further refinement and validation, the described algorithms could, in the future, be applied to broad population studies, not limited to forensic contexts, as a means of assessing individuals' psychomotor performance.

This research represents a pilot, pioneering, and groundbreaking effort, constituting one of the first successful attempts to explore the application of architectural digital technologies in forensic handwriting analysis. The study demonstrates that such technologies can be effectively applied in forensic practice. It is anticipated that the use of digital technologies will continue to develop dynamically, offering new opportunities across multiple fields, including modern forensics. The authors are actively continuing their research in this area, and the coming years are expected to mark a period of significant growth for digital forensics.

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