The Application of Profilometry in the Analysis of the Lines Crossing

Jan De Kinder and Veerle Berx

Nationaal Instituut voor Criminalistiek en Criminologie, Vilvoordsesteenweg 98/100, B-1120 Brussels, Belgium

A new approach for the problem of lines crossing was developed in this research project: laser profilometry was applied to crossing texts on questioned documents to determine the sequence of writing. Four major parameters influenced the presence of the crossing lines: the pressure exerted during the writing process, the kind of writing material and thus the kind of ink deposits, the type of paper used, and the angle between the crossing texts. In this paper, the writing pressure of both lines, together with the substrate (soft or hard), was controlled and varied through the tests. Homogeneous as well as heterogeneous writing pressures were evaluated. For the majority of the samples, 3-D topography gave conclusive information about the writing order, based on the presence of a complete intersection of 1 of the lines or an oval impression in the direction of the last-applied stroke. This research makes the laser profilometry a promising technique for questioned document examination.

Introduction

The problem of lines crossing is still an ongoing challenge in questioned document examination. The investigation of intersecting texts on documents can provide details that allow one to determine the order in which pieces of information were added on documents. The latter can be crucial in fraud detection. To this purpose, several analytical techniques that are common to a number of forensic disciplines have been applied to determine the writing sequence. Lines crossing can be characterized by a set of variables which determine the available techniques for solving the question. These include the type of paper and its surface characteristics (determined by roughness parameters), the writing material used (ballpoint pen, pencil, typewriter, printer, etc.), and the treatment of the questioned document after it was written on. The most widely used techniques are Scanning Electron Microscopy (SEM), lifting techniques (in which solvent, wax, lift-off tape, or other adhesive materials are used), and chemical treatments.

SEM is a powerful technique that is useful in cases of writing materials with distinctive surface morphologies (heterogeneous strokes). The order of pileup of ink deposits is used to determine the writing sequence. It fails when the ink is absorbed into the cellulose fibers of the paper as happens when a fountain pen or a fiber-tipped pen is used. The preparation of the samples for examination by SEM requires a coating by a conductive material and, frequently, a reduction of the size (Kasas, Khanny-Vital, & Dietter, 2001). This subsequently hampers the application of other techniques. Lifting techniques are based on the principle that the order of writing can be deduced from the existence of continuing edge marks.

Optical examinations and scanning probe microscopy have the advantage over previously mentioned techniques of leaving the surface unaltered. The optical methods may suffer from several disadvantages inherent in the appearance of interference between the light and the searched surface and from low magnification possibilities. One of the most appealing techniques of scanning probe microscopy (SPM) is atomic-force microscopy (AFM). This 3-D technique is promising but has a limited range in scanning area of 2 square centimeters, so that the questioned document has to be reduced in size. Moreover, measurements are limited within a range of 5 µm (15 µm in case of the so-called Bioscope) which, as shown during this research, is about the same range as the roughness parameters R_{ap} and R_{ake} for commonly used paper. These techniques are successful in a number of the cases but act in a more or less destructive way, thereby rendering a 2nd opinion impossible or seriously hampered.

Laser profilometry allows one to measure the 3-D topography of the surface without altering the evidence material (Stout, 1994). A new point of view is taken by analyzing the topography of the area of the crossing lines and by not analyzing the superposition of ink deposits at the surface. The resulting 3-D profile shows the pen strokes as an impression in the paper. The analysis of the profiles consists of a 3-D visualization and curve-fitting procedures to investigate the mutual influence of the crossing strokes in width and depth. The authors' research results show that in a number of cases, 3-dimensional measurements of intersecting lines provide additional information about the writing order. More importantly, they may bring a solution when commonly applied techniques fail.

Methods and Materials

Laser Profilometry

The surface of the questioned documents was measured by means of a laser profilometer (UBM Messtechnik GmbH). It is based on a noncontact technique, leaving the surface unaltered. The surface height is determined by a detection of the reflected light intensity. The apparatus consists of a Laserfocus® sensor. The emitted laser light is focused on a point at the document surface by means of a lens. The reflected light beam is collected by the same lens and is measured by a photodetector. Laser profilometry is a dynamic intensity focusing detection method, which means that the intensity of the reflected light is at its maximum when it is focused on the surface. The vertical position of the lens is altered to fulfill this condition, using the analogue signal from the photodetector as a feedback signal. The dynamical range in the vertical direction mounts up to 1000 µm, which allows one to research documents with rougher surfaces, contrary to, for example, AFM. Nevertheless, the resolution in the z-direction is as low as 0.1 µm.

The document is resting on a translational support made of porous copper. Through microscopic holes, air is evacuated in order to keep the position of the document unaltered. The laser profilometer is equipped with both stage scanning and beam scanning. The sensor, as well as the translational table bearing the questioned document, can be moved during measurement in orthogonal directions (X and Y). For each sample, a square area around the crossings is measured with a scanning speed of 400 points per millimeter. The resulting raw data consist of a 2001 by 2001 matrix, which is further analyzed and visualized using the software package IDL (by Research Systems, Inc.). The whole instrument rests on a vibration-free stage to isolate it from environmental disturbances. No size reduction of the sample is necessary.

Experimental Parameters

One may expect the appearance of the intersecting lines in 3-dimensional measurements to be influenced by the following factors:

a. **Writing Pressure** — The writing pressure is defined as the amount of pressure exerted on the writing instrument during the act of writing. During this study the support of the paper is also of importance, as part of the mechanical pressure can be absorbed by the underlying material, indirectly influencing the profile in the upper sheet. During the application of a handwritten line on a document, the pressure exerted by the pen point is not homogeneous throughout the whole line and varies from 1 point to another. The grip of the hand, together with the movements during the writing process, influences the final amount of pressure exerted on the ballpoint pen.

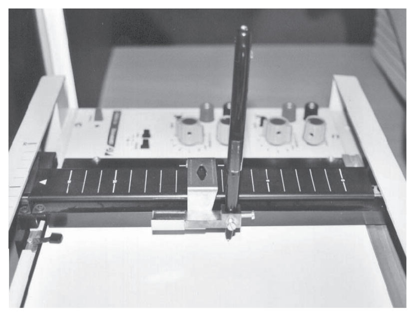

Figure 1. Experimental setup made of a XY recorder with the ballpoint pen kept in the pen support.

An experimental setup by means of a XY recorder was constructed to create lines with reproducible pressures (Figure 1) and to quantify the pressure applied by hand. The ballpoint pen, which is kept in the pen support, can be manually displaced using the "offset" button. Three different amounts of writing pressure were generated by attaching 3 different weights of lead on the writing pen. In Table I, an overview of the different pressures is given. Homogeneous strokes (same writing pressure applied to both lines) as well as all possible combinations of heterogeneous strokes were

	Weights (g)	Writing pressures (MPa)
Low	240.6	210
Medium	503.6	440
High	728.8	630

Table 1. Overview of the different writing pressures carried out by means of weights of lead.

produced. During the experiments, a soft substrate—specifically 0.1 cm paper sheets of 80 g/m2—was used, as well as a hard support formed by a metal block.

b. **Writing Material** — A printer, typewriter, fountain pen, pencil, and ballpoint pen interact in different ways with the paper. A classification can be made between writing materials with a static impression, such as typewriters, printers and faxes, and writing material with dynamic characteristics, such as ballpoints and pencils. The inks used by these different kinds of writing materials are different, which consequently result in different deposits. A 2nd classification can be made depending on whether both strokes were made by different or similar types of writing materials—heterogeneous as well as homogeneous.

   In this paper, a common black ballpoint pen (Bic® E25) was used as writing material. The impression made by such a pen is caused by a small sphere located in the ball housing and attached to a long hollow ink column. The sphere is made of hard metal and fits in a sort of enclosed cage (Leung and Leung, 1997; Morris, 2000). During the writing, the ball rotates along an axis that is perpendicular to the direction of the pen stroke and parallel to the surface. Ink-flow channels are present to allow the ink in the column to be transferred to the ball and the paper. When it comes into contact with the paper surface, the ink flows out of the pen due to gravitational and capillary forces. Contrary to fiber-tipped pens and roller balls, the ink of ballpoint pens is not spread throughout the adjacent fibers in the paper, and an indentation is left in the paper by the ball. Regarding the ballpoint strokes, the rotating ball has a diameter of 650 µm. Due to the limited contact between the sphere and the paper surface, the widths of the ink lines on the paper were found to vary from 300 µm to 400 µm on a soft and a hard support respectively. An impression can be observed in the middle of the ink line, having a width of about 120 µm.

c. **Type of Paper** — The writing process influences the topmost fibers of the paper in 2 ways: by deposition/absorption of ink and by the mechanical pressure of the writing tool. An impression is made on the inhomogeneous structure of the paper, which results from the manufacturing process. This production process determines the size and the morphology of the layers of fibers in the paper. The surface of different papers shows much variation in physical properties (Poulin, 1996). Apart from that, the inhomogeneous distribution in size and orientation of the fibers within the same piece of paper also causes an important variation in local topography of the paper surface. As laser profilometry is able to visualize individual fibers, special attention has to be paid to the reproducibility of the results obtained.

   The paper used was 80 g/m2 white paper (Nopa Topâ), commonly used for printing and photocopying. All sheets originated from the same ream of paper. The type of paper used has a thickness which varies between 95 and 100 µm and was characterized by means of roughness parameters determined by the

Roughness parameter	Physical meaning	Value (μm)
R_a	Arithmetical mean of all profile values of the roughness profile	1.17
R_p	Maximum profile peak height	5.88
R_{zISO}	Arithmetical mean value of the amplitudes of the five highest profile peaks and the five deepest profile valleys	11.91
R_k	Depth of the roughness core profile	3.90
R_{pk}	Mean height of the peaks protruding from the core area	1.36
R_{vk}	Mean depth of the valleys extending from the core area	2.01

Table 2. Relevant roughness parameters characterizing the type of paper used.

profilometer. In Table 2 the values of the most relevant roughness parameters are given, together with their physical meaning. To separate out the waviness and roughness profiles, a Gaussian filter procedure was applied, together with crack suppression to eliminate the influences from extreme peaks and valleys.

d. **Angle Between the Intersecting Strokes** — The angle between the lines crossing will influence the algorithm to deduce the correct result from the experimental data. In this paper, angles of 90° between both lines were used.

The previously mentioned factors influence the morphology of the crossing lines on the questioned document. To research the impact of each single factor, only the effect of the 1st parameter (the writing pressure as well as the kind of support) was studied. Homogeneous as well as heterogeneous strokes were considered.

Results and Discussion

Profile from a Single Stroke

By visual observation, one can see that some of the written strokes show small variations in width throughout their length. The apparent shrinkage in width of the ballpoint lines appears to be due to the encounter of the mostly water-soluble ink lines with grease or oil stains in the paper surface. The inhomogeneous structure of the paper, composed of fibers, is expected to influence the depth of the ink strokes. In a 1st step, the profile generated by a single handwritten stroke was studied. The lines were written on a soft substrate and distributed in an anisotropic way to estimate the effect of possible anisotropic distribution of fibers in the paper. Cross-sections were taken perpendicular to the writing direction to determine the evolution of width and depth within a handwritten line. Each cross-section shows an indent left by the tip of the ballpoint pen. The width and depth of each indent were quantified by means of a Gauss-fitting procedure. For each written stroke, 500 cross-sections were taken and fitted

Ballpoint Stroke	Width (μm)	Depth (μm)
1	141 ± 34	27 ± 6
2	116 ± 34	21 ± 4
3	135 ± 31	27 ± 7
4	110 ± 17	32 ± 7
5	106 ± 15	26 ± 2
6	125 ± 19	24 ± 4
7	130 ± 24	24 ± 4

Table 3. Mean value and standard deviation of the widths and depths of 7 ballpoint strokes in paper. The lines were distributed around 360°.

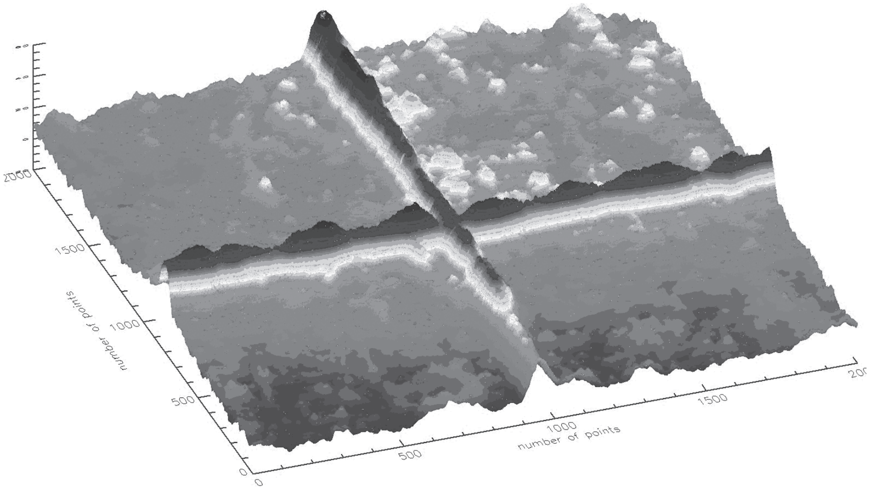

Figure 2. Presentation of a 3-D inverted written stroke, completely interesected by a 2nd written line. The variation in shades in the profile is a measure for the height of the profile.

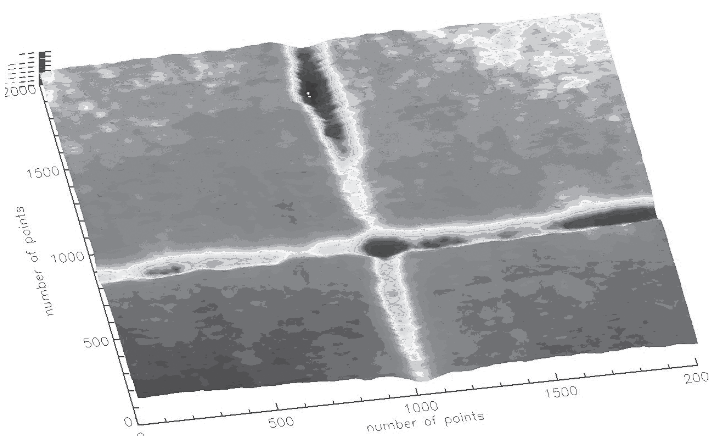

Figure 3. Presentation of an "oval" structure in the crossing. The longitudinal axis of the "oval" structure is in the direction of the 2nd written line.

by a Gaussian. The resulting width and depth were statistically evaluated, resulting in a mean width and depth, as well as their standard deviation (Table 3).

Although the structure of the writing material is inhomogeneous, these results show that consistent results can be obtained for the width and depth of the impression. No indications for a possible effect from anisotropically distributed paper fibers can be seen. The variation in standard deviation is due to the structure of fibers and possibly by the handwritten nature of the lines.

The mean values of the width and depth of the impressions of both the handwritten lines and the mechanically produced strokes were compared. Strokes written by means of a weight of lead of 503.6 g were found to leave a similar indentation as the handwritten texts.

Stroke 1	Stroke 2: Low	Medium	High
Low	Oval, +	Intersected, +	Intersected, +
	Intersected, +	Oval, +	Intersected, +
	Oval, +	Intersected, +	Intersected, +
	Oval, +	Intersected, +	Intersected, +
	Intersected, +	Intersected, +	Intersected, +
Medium	Oval, +	Oval, +	Intersected, +
	Intersected, +	Intersected, +	Intersected, +
	Smooth, inconclusive	Intersected, +	Intersected, +
	Smooth, inconclusive	Intersected, +	Intersected, +
	Smooth, inconclusive	Intersected, +	Intersected, +
High	Smooth, inconclusive	Oval, +	Intersected, +
	Smooth, inconclusive	Smooth, inconclusive	Intersected, +
	Smooth, inconclusive	Oval, +	Oval, +
	Smooth, inconclusive	Intersected, +	Intersected, +
	Smooth, inconclusive	Oval, +	Intersected, +

Table 4. Overview of the obtained results for strokes, both homogeneous and heterogeneous in pressure, and performed on a soft substrate. For each combination of pressures the experiment was repeated 5 times. "Intersected" = 1st line is completely intersected by the 2nd written stroke. "Oval" = presence of an oval structure with its longitudinal axis in the writing direction of the 2nd written stroke. "Inconclusive" = further examination is necessary. "-" = false determination. "+" = correct determination, possibly by 1 of the 3 phenomena.

Line-Crossing Problem

A square surface of 2001 by 2001 points was measured around each crossing to distinguish between the features particular to the intersection and those characteristic for the lines themselves or the inhomogeneous paper material. Five samples were generated for every combination (homogeneous pressure, heterogeneous pressure, and different types of substrate) to account for the inhomogeneous structure of the paper and to validate the technique. For the heterogeneous strokes, the experiments were set up as blind tests.

Three types of phenomena can be distinguished from the visualization of the data in a 3-D graph:

- A complete intersection of the 1st written line. The 1st line is broken up by the 2nd written ballpoint pen stroke (Figure 2).
- An oval impression is present in combination or not with a slight intersection of the 1st written stroke. That oval has its longitudinal axis parallel with the writing direction of the 2nd line (Figure 3).
- Smooth crossings demonstrate that a direct determination of the writing sequence from the 3-dimensional images is not possible. These samples

Stroke 1 \ Stroke 2	Low	Medium	High
Low	Oval, +	Intersected, +	Intersected, +
	Intersected, +	Oval, +	Intersected, +
	Oval, +	Intersected, +	Intersected, +
	Smooth, inconclusive	Intersected, +	Intersected, +
	Oval, +	Oval, +	Intersected, +
Medium	Smooth, inconclusive	Smooth, inconclusive	Intersected, +
	Smooth, inconclusive	Smooth, inconclusive	Intersected, +
	Smooth, inconclusive	Smooth, inconclusive	Intersected, +
	Smooth, inconclusive	Smooth, inconclusive	Oval, +
	Oval, +	Oval, +	Smooth, inconclusive
High	Oval, +	Oval, +	Intersected, +
	Oval, +	Intersected, +	Smooth, inconclusive
	Smooth, inconclusive	Smooth, inconclusive	Oval, +
	Smooth, inconclusive	Smooth, inconclusive	Intersected, +
	Smooth, inconclusive	Smooth, inconclusive	Intersected, +

Table 5. Overview of the obtained results for strokes, both homogeneous and heterogeneous in pressure and performed on a hard substrate. For each experimental setup the experiment was repeated 5 times. "Intersected" = 1st line is completely intersected by the 2nd-written stroke. "Oval" = presence of an oval structure with its longitudinal axis in the writing direction of the 2nd-written stroke. "Inconclusive"= further examination is necessary, "-" = false determination, "+" = correct determination, possible by 1 of the 3 phenomena.

necessitate a complementary mathematical analysis based on the hypothesis that the passage of the 2nd line undeniably changes the morphology of the 1st written line, but the former remains generally unaltered. The change in morphology would appear by a difference in width and depth of the 1st pen stroke inside and outside the actual crossing. Therefore, 2000 cross-sections (situated before, in, and after the crossing) of each written line, implicated in the crossing, are fitted by means of a Gaussian curve. This way the evolution of width and depth of both applied strokes can be followed throughout the crossing.

Soft Substrate

The results from the data are given in Table 4. All homogeneous writing sequences could be correctly determined. In the majority of the cases, the 1st written line is completely intersected by the 2nd written stroke. In the rest of the samples, an oval structure was present, indicating the direction of the last applied text. For heterogeneous strokes and as indicated in Table 4, the writing order can correctly be determined by means of the 3-D measurements when the 2nd written stroke was applied with a greater writing pressure than the

1st written line. Difficulties arise when the pressure of the 1st applied stroke exceeds the pressure of the later stroke. In these cases, smooth crossings are seen. The larger the pressure difference, the more likely no conclusion can be drawn based on the established criteria. The formerly described Gaussian analysis procedure was applied to determine the influence of the 2nd written stroke on the width and depth of the 1st written line, in and outside of the crossing. For these smooth crossings, the Gaussian fitting procedure unfortunately suffers from its own rigidity and the inherent inhomogeneity of the surface of the paper; therefore, these samples were classified as inconclusive. Further mathematical analysis is needed to analyze this situation. It is important to note that no false determinations were made on the basis of the established criteria.

Hard Substrate

A correct conclusion results from homogeneous strokes on a soft substrate. For a hard substrate, the established criteria could only be applied in a reduced number of cases. A larger frequency of oval impressions was observed. Similar to the data for the soft substrate, a correct determination of the writing order for heterogeneous strokes becomes more difficult when the pressure of the last-applied stroke is less than the pressure of the 1st stroke. For higher pressures of the last-applied line, the established criteria can almost apply without exception. Overall, no false conclusions were drawn. Although the Gaussian fitting procedure, when applied on samples showing an oval impression in the direction of the latest written line, gave satisfying results, it remains too rigid to determine the writing order for samples with smooth crossings. The results for the data are given in Table 5.

Conclusions

The problem of lines crossing is approached from a different point of view—by topography of the paper surface. The measurements were performed by means of a laser profilometer, which has for document investigation several interesting characteristics: measurement under ambient conditions, easy positioning of the samples in the apparatus, no size reduction, and no destructive nature of the tests. Several parameters influence the appearance of crossing strokes: the type of paper, the kind of writing material, the angle between the written texts, and the pressure exerted during the writing process. In this paper, the researchers investigated the influence of the pressure in combination with a variation in substrate. Three different writing pressures and 2 types of substrate—homogeneous and heterogeneous—were investigated.

The sequence of writing was determined in 64 cases out of 90 examined samples, based on 2 criteria, and no false determinations were made. In the remaining samples, the 3-D graphs did not provide enough information to conclude the writing order. If the last-applied stroke is written with less pressure than the first, the probability of providing a result decreases substantially. Based on these results, one can conclude that laser profilometry can be a useful tool to questioned document examiners.

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