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Forensic Science International 164 (2006) 102–109

Forensic Science International

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# Potentiality of 3D laser profilometry to determine the sequence of homogenous crossing lines on questioned documents

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Received 19 July 2005; received in revised form 30 November 2005; accepted 5 December 2005
Available online 20 January 2006

## Abstract

The determination of the sequence of line crossings is still a current problem in the field of forensic documents examination. Optical examination, lifting technique, ESDA technique, and electron microscopy are the most widely used methods for the determination of the writing order of crossing texts. However, at present many examinations of intersecting lines result in an inconclusive opinion, particularly if the same type and colour of ink is involved. This paper presents the potentiality of the 3D laser profilometry, which has been to determine the chronological sequence of homogenous "crossing lines". The laser profilometry, illustrated in this paper, has been developed on a conoscopic holography based system. It is a non-contact three-dimensional measuring system that allows producing holograms, even with incoherent light, with fringe periods that can be measured precisely to determine the exact distance to the point measured. This technique is suitable to obtain a 3D micro-topography with high resolution also on surfaces with unevenness reflectivity (usual for the paper surface). The proposed technique is able to obtained 3D profile in non-invading way. Therefore, the original draft are not physically or chemically modified, allowing a multi-analysis in different times. The experiments performed with line crossings database show that the proposed method is able of "positive identification" of writing sequence in the majority of the tests. In absence of a positive identification, the result has been "inconclusive" (no false determination did occur in this work).
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*Keywords:* Forensics; Questioned documents; 3D laser profilometry; Topography; Crossing line; Determination of writing sequence

## 1. Introduction

Even with the advent of electronic communication, electronic signatures and a whole array of electronic business transactions, the paper based document remains widely used and trusted for any business and legal documents. Besides, the problem of forgery remains an ever present problem and is still of great interest in forensic science. There are occasions when documents used in criminal activities or in the course of civil litigation are either altered or created specifically for the purpose of deception.

A difficult problem in questioned document examination is the determination of the order of crossed line.

The determination of the order of crossing lines is appropriate in cases of suspicions that the content of a document has been altered at a later date by adding a part to it, for instance in a will or signed legal agreement (blank signature). Therefore, the determination of sequence of crossing strokes [1–3] can provide important information when investigating fraud.

A variety of techniques can be employed to view an intersection. Optical examination, lifting technique, ESDA technique, and electron microscopy are the most widely used methods for the determination of the writing order of crossing texts. Unfortunately, many examinations of intersecting lines result in an inconclusive opinion, particularly when two inks are similar in colour and composed of the same type of ink. For these reasons, one of the most appealing challengers for questioned document examiners is the improvement of techniques, which can be used for determination of sequence of lines of homogenous intersection (crossing lines made by the same type of ink or media).

Handwriting on a common paper sheet allows to observe how, the pen-tip, besides releasing the ink, deforms the paper. In other words, the writing pressure leaves some impressions; several or less deep ones according to:

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doi:10.1016/j.forsciint.2005.12.004

- writing pressure (amount of pressure exerted on the point of a pen during the act of writing);
- underlying material (sheet of paper lying on a metal surface or on a paper block);
- writing material (fountain, pencil, ball point pen interact in different way with the paper);
- type of paper used (the production process determines the size and the morphology of the layers of fibers in the paper).

Therefore, a three-dimensional analysis of handwriting gives information on stroke sequence and on the pressure applied to the paper during writing, so as pen-up (stroke end vertex) and pen-down (stroke start vertex). The process of writing on a common paper sheet is similar to the writing on the sand (the paper sheet, for the writing, behaves as plastic material).

In Fig. 1 we see two eight drawn on the sand. The writing dynamics of two different 'eight' symbols is evident. The second stroke, when crosses the first stroke, modifies the produced groove in the sand according to the object used for the writing. In particular, it is possible to note the presence of some 'bumps' along the first stroke. These bumps are located at the sides of the second stroke that crosses the first one. The presence of these irregularities is localized in the strokes' crossing zone, along the first stroke line.

In this paper, we propose the use of the 3D laser profilometry, realized by means of the conoscopic holography, to transform seemingly flat handwritten letters into landscapes of hills and valleys that reveal the pressure and stroke sequence used to create each word documents. Conoscopic holography is a non-contact three-dimensional measuring technique that makes possible to produce holograms, even with incoherent light, with fringe periods that can be measured precisely to determine the exact distance to the point measured. It is suitable to obtain 3D micro-topography with high resolution also on surface with unevenness reflectivity (this situation is usual on the surface of the handwritten document). The technique is able to obtained 3D profile in non-invading way. Therefore, the system leaves the investigated surface unaltered so that the questioned document can be studied by means of other destructive or non-destructive technique in different time, also in case of forensic analysis with the necessity to preserve the original sample.

The determination of the 3D micro-topography, in the field of forensic document examination, can be obtained using the scanning electron microscope (SEM) [4,5] or atomic force microscopy [6]. SEM and AFM are promising 3D-techniques, but have a limited range in the vertical direction (~5 μm) and in the scanning area (<2 cm$^2$); while by means of laser profilometry a 3D micro-topography overcoming the limits imposed by the use of the techniques SEM and AFM is possible. In fact, with the laser profilometry technique non-destructive examination of "wide" zones of documents can be made.

The 3D laser profilometry has been introduced, as a useful tool for the examination of crossing lines, in Refs. [3,7]. The aim of this paper is to study the potentiality of this method and, despite of complicating inhomogeneous structure of the paper and the writing impression, determine the writing sequence when the inks are chemically and optically mixed at the crossings (homogenous crossing lines).

This paper is organized as follows: in Section 2, the conoscopic holography and used conoscopic range finder are briefly described. In Section 3, the proposed method is described and the experimental results are presented. The conclusions are presented in Section 4.

## 2. Conoscopic holography and conoscopic range finder

A conoscopic range finder (based on conoscopic holography) is well suited to provide an accurate 3D profile of handwritten documents. At present, cheap conoscopic systems, well adapted to work in the field, are available.

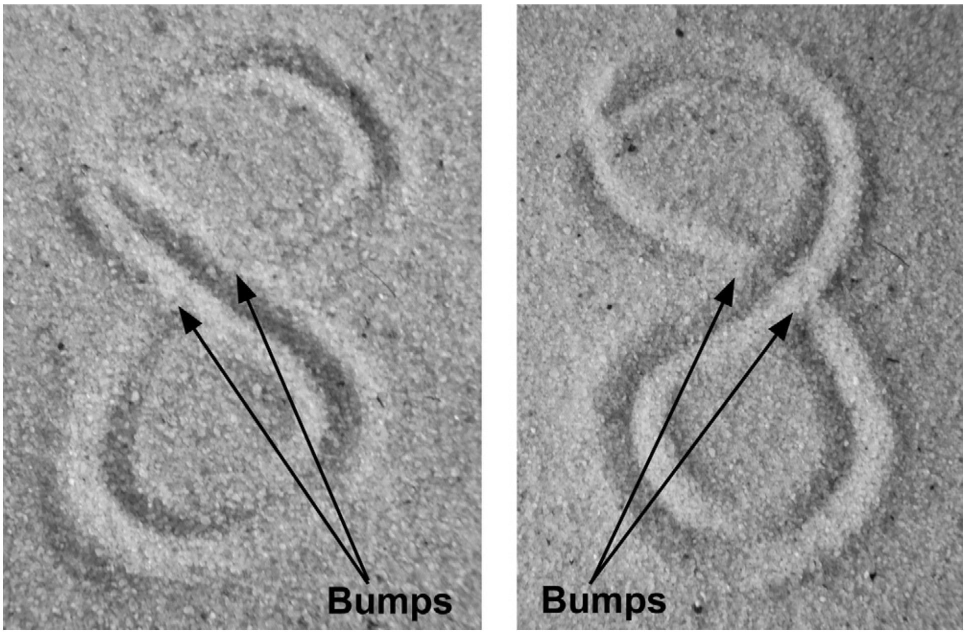

Fig. 1. Eight drawn, with different dynamics, on the sand.

Conoscopic holography has already been described in depth many times [7–9], here we present only what is necessary to understand the following discussion.

Based on crystal optics, conoscopic holography is a simple implementation of a particular type of polarized light interference process. In the basic interference set-up, a light beam is projected on a diffusive object. The reflected beam creates a light point source, which is dispersed in all directions. A complete solid angle of the diffuse light is analyzed with the conoscopic optical system. The measurement process corresponds to the retrieval of the distance of illuminated point from a fixed reference plane.

In order to obtain a better understanding of the system functionality the behavior of a single ray needs to be comprehended.

A single ray, emitted by light point source at a given angle is polarized using a polarizer.

This wave polarized at 45° to the principal axes of the crystal is incident on it (see Fig. 2). The wave is separated into two polarization components. In a uniaxial crystal the two polarized waves propagate at different velocities. The velocity of one ray is isotropic and it is designated as an ordinary ray, while the other one has an anisotropic velocity, i.e. it is designated as an extraordinary ray. Thus, two super-imposed rays emerge from the crystal with a phase difference and with orthogonal polarizations to each other. In order to obtain interference between these two rays, an analyzer (polarizer) is inserted at the point for which the rays emerge from the crystal.

For a complete solid angle, each emerging ray will have a different phase difference between the ordinary and extraordinary rays. At a given plane, the collections of all the rays will create an intensity figure—the conoscopic image. This image can be recorded by means of CCD array or matrix. The parameters of conoscopic image will depend on the angular distribution of the rays inside the crystal. The latter depends on the position of the point in space. Recording and analyzing the image, one is capable of retrieving the distance of the illuminated point from a fixed reference plane. An important point is that each detector of the CCD carries out an independent measure. Conoscopy is, in principle, a triangulation method of distance measurement duplicated many times. In particular, a standard triangulation system measures the angle of a single ray, while the conoscopic system measures the angle of each ray in a complete solid angle. Therefore, conoscopic procedure is much more precise, stable and robust, but requires more computations.

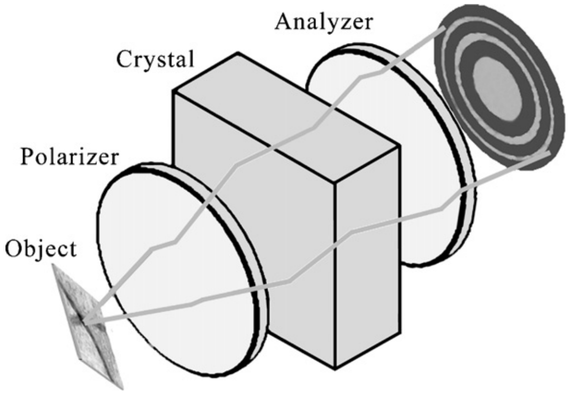

Fig. 2. Conoscopic principle.

Conoscopic range finder offer specific benefit:

- Simplicity in the set-up. This makes simple the procedure of measure.
- Much greater stability than classical interferometer because the geometrical paths of both split wavefronts are almost the same. The system is able to work outside laboratory (it is possible to work in field, in other words where the questioned document is kept).
- By switching the polarization axis of one polarizer (see Fig. 2), two complementary holograms of the same point can be obtained. Indeed, we will calculate the ratio between the difference and the sum of both interferograms ('contrast' calculation). Most of the intensity inhomogeneities (optical noise) can be in this way eliminated. So the conoscopic probe measurements are independent from intensity modulation induced by the object albedo and surface with unevenness reflectivity (which is usual on the surface of the handwritten document).
- Large range in vertical direction is possible.
- Collinearity and minimal aperture. The conoscopic techniques need a minimal angular aperture to recover the wavefront curvature and they can work in an on-axis configuration with respect to the projected laser beam. Therefore, measuring is also possible inside holes or cutting. This characteristic is very important when there is the interest to reconstruct the 3D micro-topography 3D micro-topography of crossing line with high resolution. In fact, only with a collinear measurement system it is possible to reconstruct all the characteristics present in the crossing zone.

All this characteristics make conoscopic holography well suited to reconstructing the 3D micro-topography of handwritten documents. As far as we know, for application on questioned document, no commercial micro-profiling equipment with potentiality of the conoscopic holography is available.

Our system (Optimet MiniConoscan 3000) has vertical resolution and the dynamical range of 0.2 and 2000 μm, respectively. The system used in this work is in the fix-probe configuration. The fix-probe configuration consists of keeping the conoscopic probe fixed and placing the questioned document to be analyzed on a translation-table. The maximum dislocation of the translation-table is 12 cm with a position accuracy of 1 μm/10 mm. The documents are resting on a support made of porous copper. By evacuating the air through the microscopic holes in this material, the position of the document remains unaltered throughout the measurement.

## 3. Three-dimensional analysis of handwritten documents

The conoscopic range finder determines the micro-topography of the examined surface. The resulting 3D profile shows the pen-tip strokes as an impression in the paper.

A typical handwritten document surface profile consists of roughness, pen-tip strokes (waviness) and form (in many cases the paper sheet may also contain significant form such as deformations) [10]. It is important to notice that:

- The paper roughness range is, usually, 2–8 μm. It depends on the type of paper used [11,12].
- The pen-tip strokes depth range is between 2 and 50 μm. This is the range of depth analyzed, with our conoscopic range finder, in our tests. The range of variability depends on writing pressure and used material.
- The deformations of paper sheets, present mainly when we use soft underlying support and when the paper is in no good condition (e.g. sheet humidified or rubbed), can be also 100 times greater than the pen-tip stroke impression.

Fig. 3a shows 3D view of raw data from the analysis of handwritten symbol ‘‘€’’.

This raw data contain information on pen-tip strokes, paper roughness and paper deformation. So, after the acquisition of the data, 3D image processing and filtering are necessary to obtain a surface model that can be used to identify the stroke that describes the handwriting [13].

The first step is to identify and eliminate the paper deformation by means of suitable 3D filter. The handwriting of a word or symbol cause the incision of the sheet, besides, it causes a global deformation on the sheet. Fig. 3b shows the global deformation drawn out by means of ‘‘3D form removal’’ techniques. The 3D view of the symbol ‘‘€’’, after the operation of ‘‘form removal’’, is shown in Fig. 3c. The filtered data is then passed through a new elaboration to separate the roughness and waviness components of the surface. Fig. 3d shows the roughness component present on the paper sheet. The pen-tip strokes (waviness) impression is shown in Fig. 3e. Finally, 3D view of the pen-tip strokes, with a mirror along the $z$-axis, is shown in Fig. 3f.

Observing the reconstructed 3D image, strokes appear like furrows, but for recognizing the crossing dynamics the observer needs to pay attention to some particular characteristics. A first activity to perform is to verify the presence of some ‘bumps’, irregularities in the grooves produced in the paper by the pen-tip used for the writing. These bumps are located at the sides of the second stroke that crosses the first one. The presence of these irregularities is localized in the strokes’ crossing zone, along the first handwritten stroke line, and they have to stand out against the paper depression created by the double pen passage. The strokes’ and bumps’ visibility depend both on the kind of paper and used per.

However, when we are in presence of homogenous intersection with lines effected with similar writing pressure

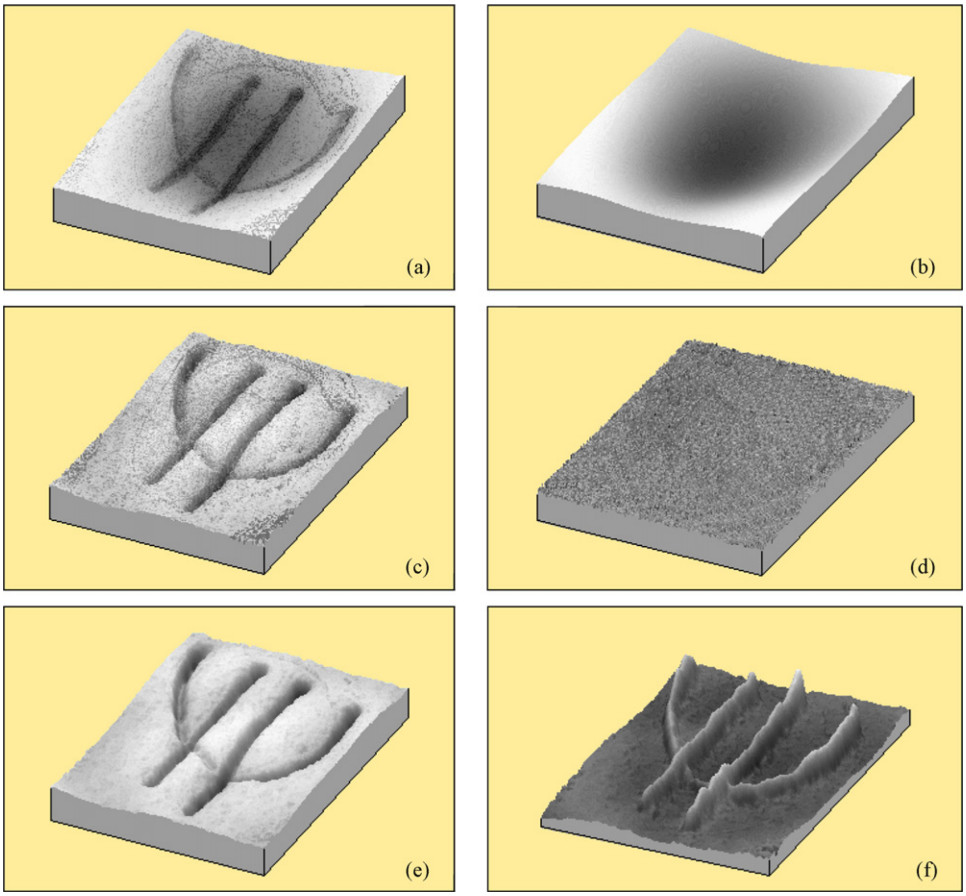

Fig. 3. 3D image processing for separation of roughness, waviness and form in a handwritten document. (a) 3D original data; (b) 3D form—deformation of sheet; (c) 3D profile of the euro symbol, after the operation ‘‘form removal’’; (d) paper roughness; (e) pen-tip strokes–waviness; (f) 3D view of the pen-tip strokes with a mirror along the $z$-axis.

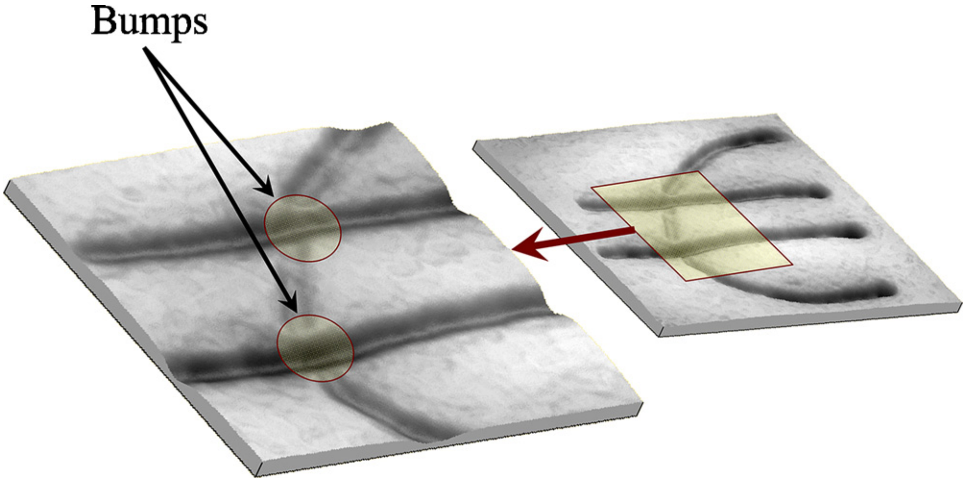

Fig. 4. 3D view of the strokes' profile. It is possible to note the regularity in the horizontal lines. The presence of bumps is evident.

and when indented impression of stroke is one or two times the roughness, the bumps are always present and evident.

Fig. 4 shows a typical example of analysis. This example was realized using a common black ballpoint pen on 80 g/m$^2$ white paper commonly used for printing and photocopying. It clearly shows that the horizontal lines, of symbol "€", were made after curvilinear stroke. Therefore, the shapes are continuous, whereas curvilinear stroke is interrupted. As can be noted, a characteristic of the second stroke is that it 'cuts' the first one. Using this assertion it is easier to reconstruct the crossing dynamic.

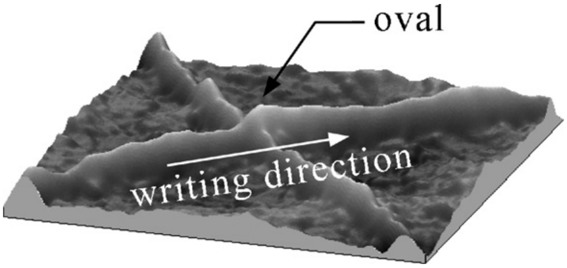

Fig. 5. 3D view, with a mirror along the $z$-axis, of crossing zone of two pen-tip strokes. In this image, it is possible to note the presence of an "oval".

Fig. 5 shows 3D view an other example of analysis. It shows 3D view of a crossing zone of two strokes, with a mirror along the $z$-axis. In Fig. 5, we note the presence of an "oval" structure, with its longitudinal axis in the direction of second line, where the two strokes are really crossed.

The oval structure is due to the additional impression left by the last written line leaves in the existing groove of the first pen stroke. Moreover, when the second line is less indented in comparison with the first, this "oval" is deformed along the writing direction of the second line. When the pen-tip arrives at the zone of crossing, where the first line is present, it downs within the groove already clear. Successively it goes up again smoothing the first groove (see Fig. 6). Therefore, from the

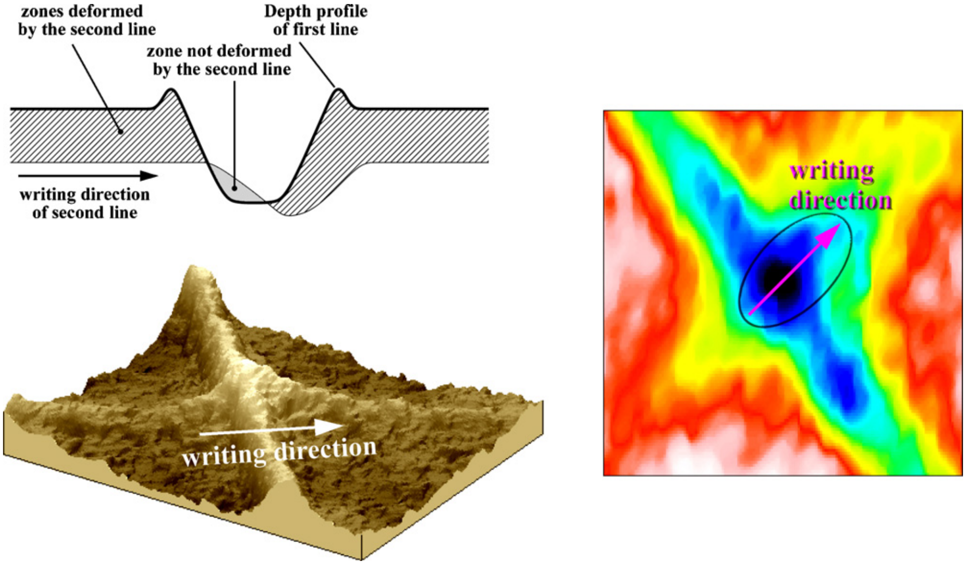

Fig. 6. Deformation of the "oval" in the direction of writing.

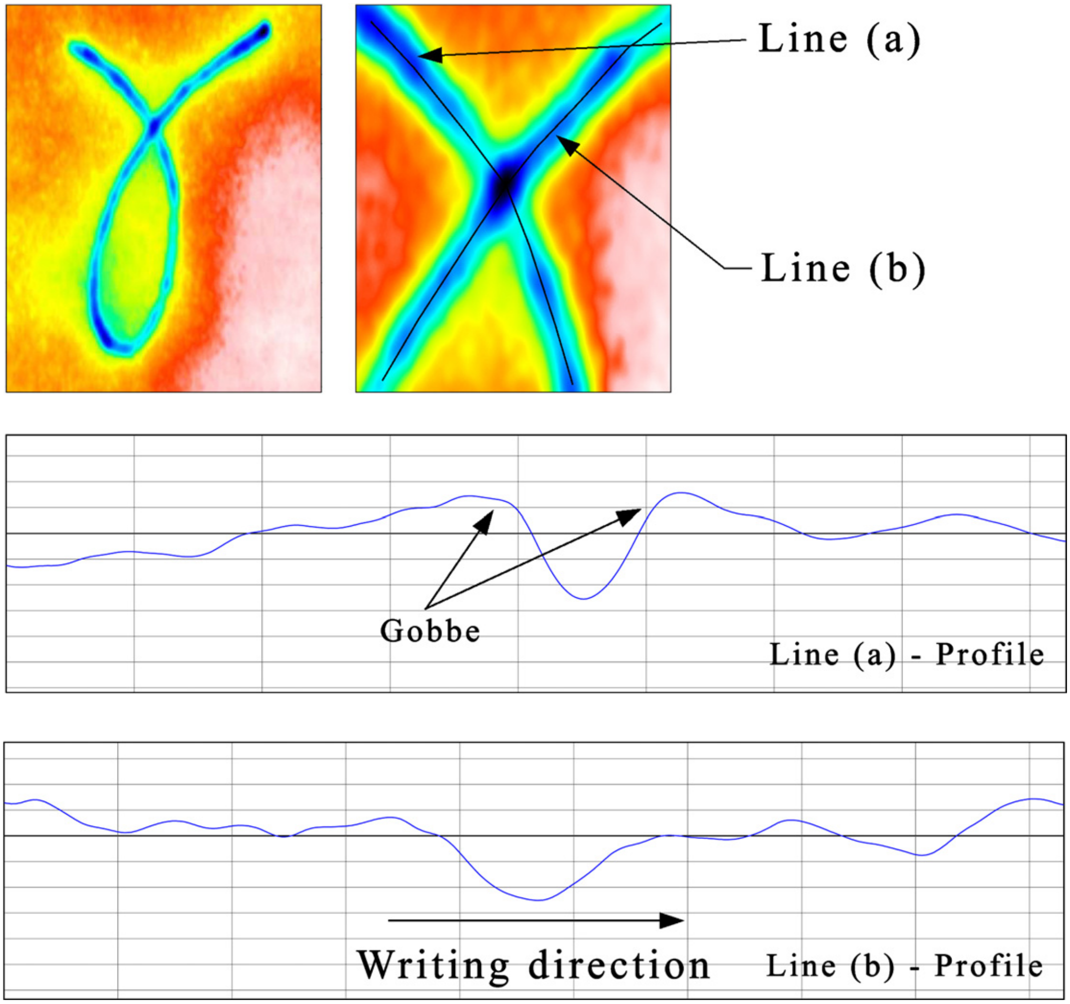

Fig. 7. Profilometry along the lines of writing.

analysis of the “oval” structure it is possible, at any time, to go back to the direction used for tracing the second stroke. The analysis of the direction of writing can be effected, with more effectiveness, by means of profilometry along the handwritten lines. Fig. 7 shows this type of analysis made on the geek “gamma”.

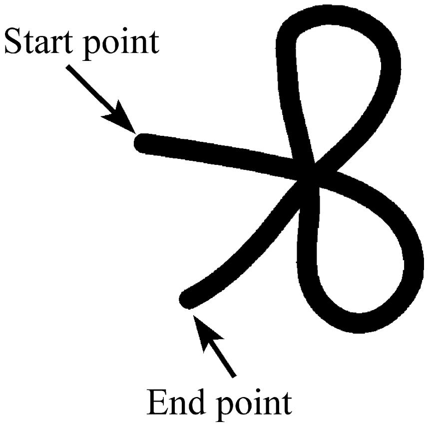

Fig. 8. Scrip with more two lines intersecting.

Analyzing Fig. 7 it is possible to note that along the firth line are present two “evident” bumps. The presence of these bumps, in the profile along the line (a), assures that this line is what we have traced for first. The presence of these bumps, in our example, assures that the line (a) is what has been traced for first. The profile along the line (b) shows an interesting characteristic. The pen-tip “falls” in the furrow (impression) done by the first line. This fallen deforms, even, the paper (increases the impression in the cross point). Subsequently, the peak of the pen, going up from the hole, smoothes the slant. The side of the profilometry that shows a softer profile indicates the writing direction.

Our method is also able to resolve complex stroke sequence. Fig. 8 shows a handwritten script with more than two lines intersecting. The 3D view, relating to this script is shown in Fig. 9. It is possible to see that, even in this case, the correct sequence of drawing order is recovered.

Our method allows to analyze cross lines marked with different pressure. In Fig. 10, we show an analysis done on the geek “gamma” handwritten with a non-constant pressure (the first part has high writing pressure, instead the second part has low pressure). The example shows crossing lines with the first written line more marked compared to the second. Analyzing

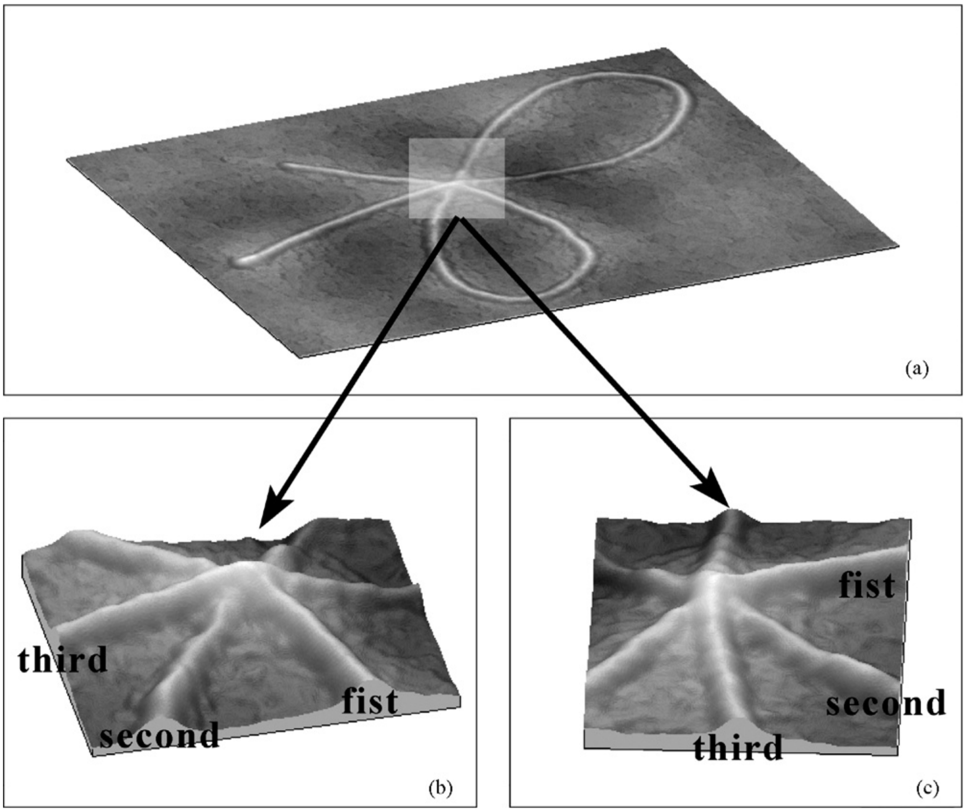

Fig. 9. 3D view of script with more two lines intersecting. (a) The micro-topography of the symbol. (b and c) The 3D reconstruction of the intersection from two different geometrical points of view.

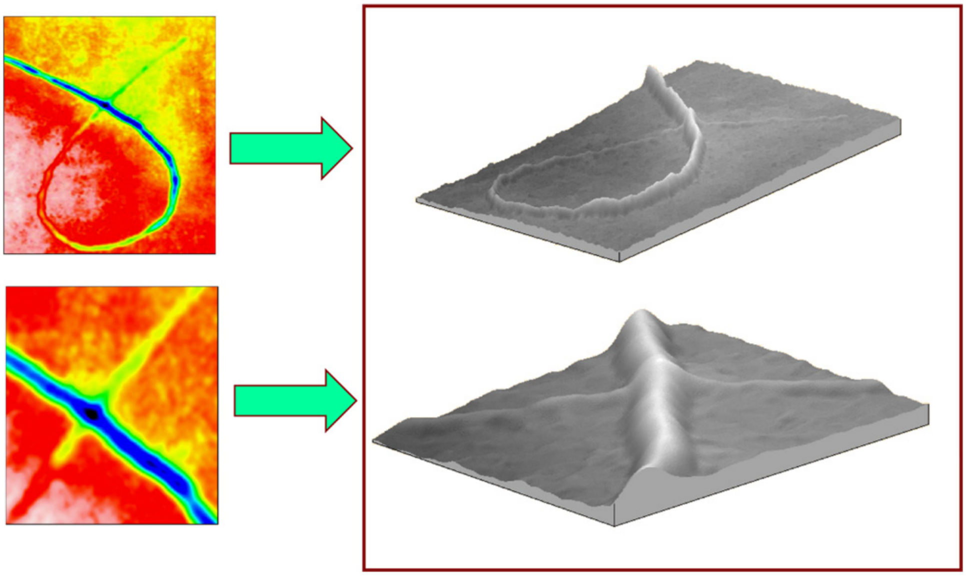

Fig. 10. ''Crossing lines'' problem of intersection when the lines have very different depth profile.

Fig. 10, the possibility to determine the writing sequence in unambiguous way is evident. Also in this case the second line changes the morphology of the first stroke. It is possible to note a second impression over the deformation caused by the first line.

To confirm the potentiality of the proposed technique, to detect the dynamics of the strokes' superposition, we have used 120 homogeneous intersections made by 120 different persons of different age. Every single intersection has been done using the same pen. We have used six different types of pen, two different types of paper (80 and 120 g/m$^2$ white paper commonly used for printing and photocopying) and two different underlying supports. On one hand, the strokes were

Table 1
Synthesis of results obtained for each kind of pen

| Category of pen | Positive identification (correct classification) (%) | Inconclusive (%) | Number of experiments |
|---|---|---|---|
| BIC pen | 98 | 2 | 45 |
| Ballpoint pen with fine point | 90 | 10 | 10 |
| Fountain pen | 45 | 55 | 15 |
| Liquid ink pen | 65 | 35 | 20 |
| Felt pen | 35 | 65 | 20 |
| Felt pen with fine point | 75 | 25 | 10 |

made on a ‘‘soft’’ underground consisting of pile of 0.3 cm of 80 g/m$^2$ paper; on one hand, the strokes were made on a ‘‘hard’’ underground consisting of metal plate. In particular, we have realized five samples for every single combination pen-paper-support. The five different intersections have been carried out using the symbols: €, +, ×, $\gamma$, and $\alpha$. In this way we have simulate homogeneous intersection made in different direction. Subsequently, the sample data has been tested, with our method, in blind way, by two different persons independently. The two scientists have achieved similar results. These results are reported, in a synthetic way, in Table 1.

From the results reported in the table, is possible to notice that under no circumstance a false determinations has been effected. Besides, it is possible to notice that the cases of inconclusiveness relate to a depth profile.

Generally, by means of the tests effected it is possible to conclude that if the profile, left by the writing media, is at least two times the mean roughness of the paper, the determination is possible with success.

## 4. Conclusion

In this paper, we have presented the potentiality of the 3D micro-topography to study the sequence of homogenous crossing lines on questioned documents. The method is applicable where the questioned document is an original and contains a crossing between two media that will allow the determination of the sequence of introduction onto the paper. In this work, 3D micro-topography is obtained by means of conoscopic holography, which has same advantages over other 3D profile techniques. In particular, greater stability; large range of measure in vertical direction; ‘‘wide’’ zones of documents can be analyzed; measurements are independent from intensity modulation induced by the object unevenness reflectivity.

The method works well and it allows, in most of the cases, to recover correct stroke sequenced of a handwritten script. Besides, the method is able of analyzing the pressure variations used during the writing. The main potentiality over the ‘‘traditional’’ methods and is that it allows to determine, with success, the sequence intersection made by two mixed inks of similar colour (e.g. when the inks are chemically and optically mixed at the crossings).

The principal limit is the inability to analyze intersection if the profile, left by the writing media, is similar to the mean roughness of the paper. Other limit is the time consumed to acquire data. For this reason, it is essential to carry out studies for the improvement of the used hardware.

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