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Nicola Senin,[1] M.S.; Roberto Groppetti,[1] Ph.D.; Luciano Garofano,[2] M.S.; Paolo Fratini,[2] M.S.; and Michele Pierni,[2] B.S.

Three-Dimensional Surface Topography Acquisition and Analysis for Firearm Identification

ABSTRACT: In the last decade, computer-based systems for the comparison of microscopic firearms evidence have been the subject of considerable research work because of their expected capability of supporting the firearms examiner through the automated analysis of large amounts of evidence. The Integrated Ballistics Identification System, which is based on a two-dimensional representation of the specimen surface, has been widely adopted in forensic laboratories worldwide. More recently, some attempts to develop systems based on three-dimensional (3D) representations of the specimen surface have been made, both in the literature and as industrial products, such as BulletTRAX-3D, but fundamental limitations in achieving fully automated identification remain. This work analyzes the advantages and disadvantages of a 3D-based approach by proposing an approach and a prototype system for firearms evidence comparison that is based on the acquisition and analysis of the 3D surface topography of specimens, with particular reference to cartridge cases. The concept of *3D virtual comparison microscope* is introduced, whose purpose is not to provide fully automated identification, but to show how the availability of 3D shape information can provide a whole new set of verification means, some of them being described and discussed in this work, specifically, visual enhancement tools and quantitative measurement of shape properties, for supporting, not replacing, the firearm examiner in reaching the final decision.

KEYWORDS: forensic science, firearm identification, ballistic fingerprinting, cartridge cases, three-dimensional surface topography acquisition and analysis

In firearms identification, experts try to associate evidence bullets or cartridge cases to a suspect weapon. Typically, test specimens are produced by firing the suspect weapon under controlled conditions; then the toolmarked areas produced on the test ammunition are compared with those found on the actual evidence (as an alternative, different evidence specimens are compared if the firearm is not available).

The underlying assumption is that microscopic shape imperfections that are peculiar to the firing chamber, barrel, etc., of each individual weapon are imprinted on the ammunition surface during firing, thus constituting a signature or fingerprint of the weapon itself.

However, the identification and comparison of such signature marks are not trivial tasks: pressures and velocities involved in the physical interaction between the weapon and the ammunition at firing are subjected to intrinsic variation from shot to shot, thus resulting in variations of the shape, orientation, and localization of the signature markings, even for the same combination of firearm/ammunition type. Moreover, meaningful markings are often mutilated, sometimes even obscured, by other surface shape features, such as class-characteristic markings, or like random scratches, bumps, or other types of damage because of postfiring interaction of the specimen with the environment.

For these reasons, currently, a complete comparison and a successful final identification of characteristic shape features can only be performed by highly skilled and trained examiners, involving a very time-consuming process that is generally based on visual analysis of a pair of specimens at a time, through the careful use of a comparison microscope.

In the last decade, computer-based systems have been introduced for bringing the competitive advantages of Information Technology to the domain of firearm identification. The main benefits that have been exploited so far are concerned with the capability of storing large amounts of evidence-related digital information, through the use of databases, and with the capability of performing large amounts of numerical analysis and processing tasks on evidence data, thanks to the computational power made available by computers.

Current mainstream computer-based systems, most notably the Integrated Ballistics Identification System (IBIS) by Forensic Technology Inc. (Montreal, Quebec, Canada) (1), are based on digital imaging; digital images acquired from the specimens under controlled conditions are used for storing evidence-related information in databases. Support to the comparison process is provided through powerful digital image analysis and processing techniques.

On the one hand, the choice of adopting a digital format to store evidence information, in particular two-dimensional (2D) still images, confers a definite advantage to the documentability and reproducibility of the results of the firearm identification process. On the other, it implies an inevitable loss of information if compared with direct observation of the real specimen through a microscope, where viewpoint, lighting conditions, orientation, magnification, etc., can be changed during observation. In turn, the reduced amount of information available from digital images places intrinsic limitations to the capabilities of any identification/comparison technique based on such an approach. These limitations add up to the fundamental problems introduced above and related to the intrinsic variability of the shape features to be identified and compared, making the whole problem extremely

[1] Dipartimento di Ingegneria Industriale Università di Parma, Parco Area delle Scienze, 181/A, I-43100 Parma, Italy.
[2] Sezione di Balistica, Reparto Carabinieri Investigazioni Scientifiche, Parco Ducale, 3, I-43100 Parma, Italy.

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difficult to cope with by means of algorithmic approaches such as those available currently for digital images.

Thus, if on the one hand the introduction of computer-based solutions seems to bring some more determinism, and thus traceability and reproducibility, in an otherwise basically subjective and qualitative human decisional process such as firearm identification, on the other, no algorithmic solution available currently seems to be able to provide the same flexibility of a skilled, knowledgeable operator, and ultimately achieve comparable results.

For these reasons, current ballistic imaging systems are mostly used for screening large amounts of evidence data with the purpose of reducing the total amount of candidates to be compared manually, while expert firearm examiners are still in charge of the final identification.

More recently, approaches based on three-dimensional (3D) digital representations of evidence surface topography have begun to appear, both in the literature, see for example Breitmeier and Schmid (2), Kinder and Bonfanti (3), and Bachrach (4), and as industrial products, such as BulletTRAX-3D, again by Forensic Technology Inc. (1). The introduction of 3D surface topography solves some of the limitations typical of digital imaging systems, but raises some new issues to be solved as well. A significant advantage derives from the reusability of methodologies and techniques originally developed in different, heterogeneous application domains, ranging from the studies of large-scale features over terrain (e.g., orography) to the characterization of microscopic roughness features on high-precision surfaces in engineering applications. In particular, the scale of the shape features to be acquired in ballistic fingerprinting makes the technical solutions developed for the measurement of surface roughness in engineering applications more suitable to be transferred to ballistic fingerprinting. An overview of the main measurement techniques that can be adopted to acquire the 3D topography of engineered surfaces can be found in the work by Sherrington and Smith (5,6).

Once the 3D surface topography has been acquired, there are many approaches that could be followed in order to investigate shape properties: to this end, a broad set of techniques for data analysis and processing is available from the literature (7–11). Most of these techniques have proven to be useful in several application domains including, but not limited to, the mechanical, biomedical, and textile domains, as documented in some previous work by the authors (12,13), and thus may be useful for forensic applications as well.

Nevertheless, fundamental limitations intrinsic to how shape-based reasoning is implemented in current computer-based approaches to digital imaging are present in 3D surface topography analysis as well. With the main purpose of investigating such issues this work introduces a novel approach and prototype system to support firearm identification, based on 3D surface topography acquisition and analysis: advantages and disadvantages related to the availability of 3D surface shape information-pertaining evidence are discussed, analyzed, and compared with digital imaging techniques, with particular reference to cartridge cases.

Bearing in mind the fundamental limitations intrinsic to current algorithmic approaches for reasoning over shape-related information, the proposed approach does not aim to replace the firearm examiner in the identification process; instead, it proposes itself as a tool for supporting the firearm examiner in his/her decisional process. The *3D virtual comparison microscope* is introduced as a tool that the examiner can use to compare two specimens through their virtual 3D reconstructions, featuring several solutions for visual enhancement and quantitative measurement of surface shape data.

3D Surface Topography Acquisition, Analysis System Architecture, and Implementation

System Architecture Overview

The main functional components of the general purpose system introduced in this work for 3D surface topography acquisition and analysis are shown in Fig. 1, while being applied to an example firearm identification process based on cartridge case analysis. The same system architecture would be suitable for application to the analysis of other surfaces in forensic applications (bullet surfaces, toolmarks, etc.) and beyond.

In the proposed architecture, the *acquisition subsystem* encapsulates the actual measurement instrument: its role consists in acquiring 3D surface topography information through a set of measurements on the specimen surface and in providing the *acquired 3D surface topography* in a format that is compatible with the subsequent topography analysis processes.

The *analysis subsystem* is a general-purpose topography analysis application that is capable of performing a wide range of data manipulation and analysis operations in order to evaluate 3D surface topography properties; in the specific domain of firearm

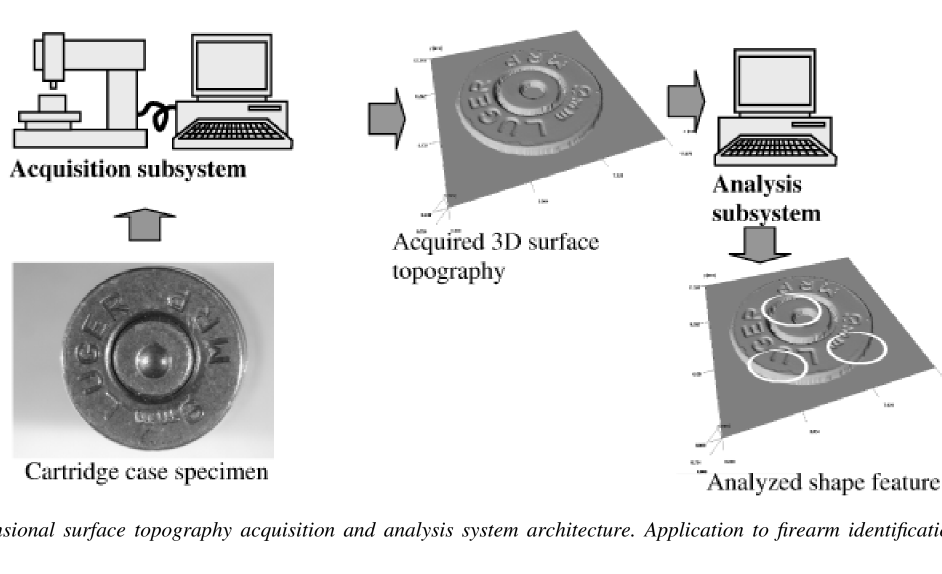

FIG. 1—*Three-dimensional surface topography acquisition and analysis system architecture. Application to firearm identification based on cartridge case topography analysis.*

identification through ballistic fingerprinting such a system would be oriented toward performing specialized analysis tasks that may be meaningful to the firearm identification process.

In the proposed architecture, the acquisition and analysis subsystems are purposedly kept physically separate: the architecture is designed to support acquisition subsystem interchangeability in order to overcome the measurement limitations that are intrinsic to any specific measurement instrument that may be embedded in the acquisition subsystem, as illustrated in the following section.

The Acquisition Subsystem

The topography acquisition capabilities for the proposed architecture are very much dependent on the measurement instrument adopted: instruments may differ in resolution, range of measurement, acquisition technique, size of the measurable specimens, allowed specimen material, and surface properties. In the specific domain of firearm identification, specimens generally constitute (but are not limited to) either bullets or cartridge cases. Most surface measurement instruments approach the surface from a predefined direction (e.g., from the top), and thus only have access to portions of the specimen (e.g., the above part); this may be suitable for roughly planar surfaces, such as the base of a cartridge case, while bullet-side surfaces and cartridge-side surfaces, being characterized by round shapes, may require special solutions to be properly acquired (typically, rotating fixtures). Cartridge base surfaces, on the other hand, are difficult to measure for other reasons: for example, they are often characterized by large height drops (e.g., firing pin impression) and almost vertical surfaces (e.g., the gap that separates the primer from the remaining part of the base, on the surface of the cartridge case). Additional issues arise from the fact that both large-scale shape features (e.g., primer, firing pin impression, ejector pin signature) and small-scale shape features (e.g., breech face marks, tiny scratches, and bumps inside the firing pin impression and so forth) need to be acquired at the same time for successful firearm identification. All the issues listed above give rise to demanding requirements for the measurement instrument to be adopted, in terms of resolution, range, and capability of measuring hardly accessible surfaces. Such requirements are typically difficult to fulfill at the same time and by a single measurement instrument. The problem becomes even more complex because two additional requirements for the measurement instrument must be considered as well: the surface of the specimen should be subjected to minimum alteration while being measured, which rules out most contact-based measurement solutions, and topography acquisition time should be kept to the minimum, which is a fundamental issue when a large number of specimens need to be acquired for direct firearm identification or for storage in a database.

All the issues listed above make the choice of a proper 3D topography acquisition measurement instrument a difficult task, and also explain why *digital imaging* is currently the preferred choice for 2D surface data acquisition in firearm identification. Digital imaging is a noncontact technique, it allows for a high horizontal resolution, mostly thanks to the magnification power of light, together with respectable measurement ranges, and most of the surface topography is acquired by a single shot (except the undercuts, of course), which leads to significant time saving. However, digital imaging acquisition processes have limitations that are intrinsic to their 2D nature, as mentioned briefly in the introduction, and as explained later in the text.

Going back to 3D surface topography, the selection of a proper measurement solution is currently an unresolved problem. In the next section, an example acquisition subsystem is introduced that does not represent a final solution to the problems illustrated above, but at least illustrates how some of the problems listed above can be dealt with. Once again, it is important to point out that the proposed architecture suggests an approach to topography data analysis and manipulation that is independent of the measurement instrument, and thus, the system illustrated in the following should be considered only as one of the many options available for acquiring topography data, and not necessarily the best one.

A Prototype Acquisition Subsystem

A prototype acquisition subsystem was developed at the Department of Industrial Engineering, University of Parma, with the cooperation of the SM s.r.l. company (Torino, Italy) (see Fig. 2). The acquisition subsystem is equipped with a commercial sensor based on laser conoscopic holography (14) for noncontact measurement. The sensor is capable of measuring the distance of a point located under the spot of the laser beam; in order to acquire a complete 3D topography, the specimen is translated under the sensor by means of a computer-controlled *x–y* table, so that a sequence of points can be acquired by scanning along the lines of a rectangular grid pattern (raster scanning). The system has been developed as a general-purpose surface topography measurement device, and it has already been applied to several surface characterization tasks, in various engineering domains. The current prototype can operate with different submicrometric vertical accuracies, in a millimetric vertical measurement range, depending on the lens assembly attached to the sensor; horizontal accuracy, which depends on the characteristics of the *x–y* table, is submicrometric as well. The system is currently capable of acquiring planar specimens only; however, the development of an additional rotating fixture to allow for the measurement of round surfaces is in progress.

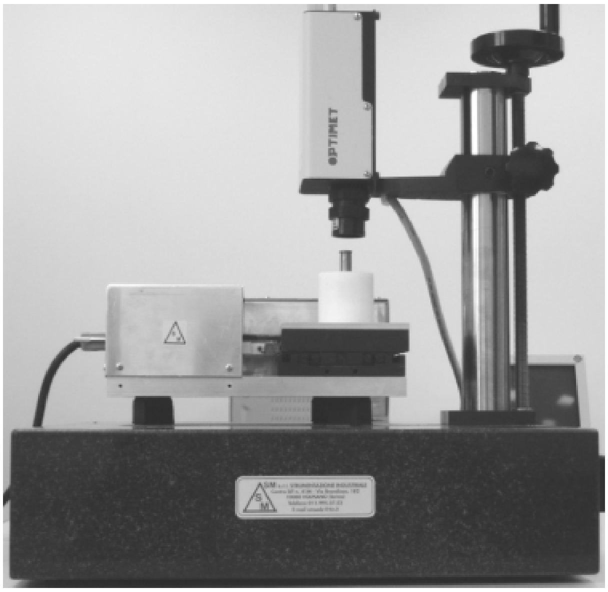

FIG. 2—*Prototype three-dimensional surface topography acquisition system equipped with a laser conoscopic holographic sensor and computer-controlled x–y table for precise positioning of the specimen.*

Formal Encoding of 3D Surface Topography

As stated previously, the main strength of the proposed architecture is the capability of supporting acquisition subsystem interchangeability. In order to enforce this, a common format to represent 3D surface topography data provided by the measurement instrument must be adopted. The proposed format is illustrated in Fig. 3, where 3D surface topography is represented by a set of points defined by three scalar coordinates in a Cartesian reference system.

With reference to Fig. 3, surface topography data are stored as a set of $N_x \times N_y$ points arranged in an x–y grid with uniform Δ_x, Δ_y spacing. Given this assumption, the x, y and z coordinates of the ijth sample can be defined as follows:

$$x_i = \Delta_x \cdot i, \quad y_j = \Delta_y \cdot j, \quad z_{ij} = z(x_i, y_j) = z[i,j] \qquad (1)$$

with $i = \{0, 1, 2, \ldots, N_x - 1\}$ and $j = \{0, 1, 2, \ldots, N_y - 1\}$

Uniform spacing is the strongest assumption adopted by the proposed representation as it gives rise to an array of important consequences: first, surface topography data encoded as such can be conveniently stored in a 2D matrix of z coordinates, the x and y coordinates being retrievable by knowing matrix indices and uniform sample spacing (see equation (1)); second, uniform x–y spacing makes the proposed representation formally equivalent to the representation of a digital image (where the RGB value of each pixel is stored in a cell of a 2D matrix, which can be retrieved through proper indices); and the formal equivalence with digital images opens up a wide array of possibilities for data analysis and processing, as will be illustrated in a later section.

The assumption of uniform x–y spacing also has some drawbacks, starting from the fact that geometric undercuts or vertical surfaces (i.e., aligned with the z coordinate) cannot be represented, as no more than a single z value can be stored for a given pair of x–y coordinates: this may not be a serious problem in firearm identification, given that most of the current measurement solutions are not capable of detecting such cases anyway, and also given that most signatures on cartridge cases and bullets are either the product of the bullet/cartridge manufacturing process, or the product of mechanical interaction between the bullet/cartridge and firearm parts during the firing of the firearm, or the product of subsequent damage of the specimen, all phenomena that are not likely to produce such geometric entities.

The most critical issues related to uniform spacing arise when planning the sampling strategy, as illustrated in the next section.

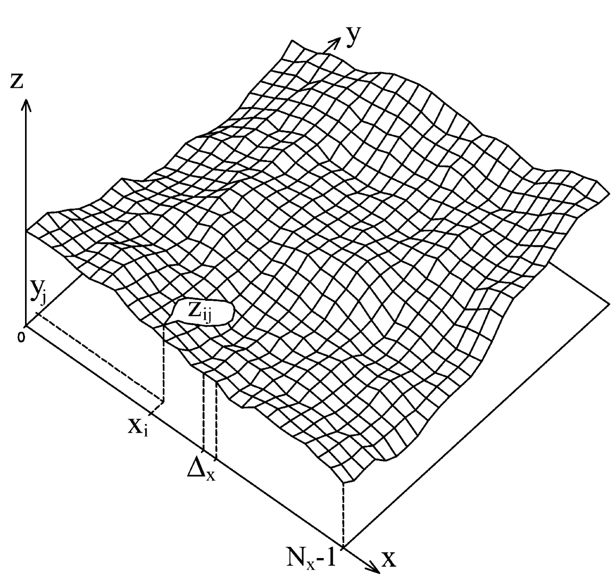

FIG. 3—*Formal representation of three-dimensional surface topography: rectangular region of* $N_x \times N_y$ *samples, with uniform* Δ_x, Δ_y *sample spacing.*

Sampling Issues in Acquisition

Horizontal sampling resolution is dependent on the requirements for the shape to be acquired. For the proposed formalism, the Nyquist criterion could be rephrased to state that sample spacing should be smaller than half the minimum size of the smallest shape feature to be acquired. However, as the horizontal spacing between samples decreases, the amount of samples needed to cover the same surface area increases, which may have repercussions on acquisition time span, on the memory required to store the acquisition data and on the mathematical tractability of the acquired set of samples. As an alternative, the region to be acquired could be reduced in order to keep the overall number of acquired samples constant; however, the potential loss of meaningfulness and representativeness of the acquired region should be considered as well.

The problem of identifying the proper horizontal resolution and range for topography acquisition is fundamentally a process planning problem, which should be dealt with in terms of goals (acquire meaningful information concerning specific relevant shape features) and constraints (limitations intrinsic to the measurement system of choice, time requirements, memory requirements, etc.).

The sampling problem in firearm identification is conceptually summarized in Fig. 4 for a cartridge case bottom surface: different regions (e.g., as shown in Fig. 4*a*, firing pin impression, extractor signature, ejector pin signature, breech face marks on the primer, etc.) may need to be sampled at different resolutions (see Fig. 4*b*) in general or as a consequence of other analysis results. Nonuniform sampling would solve this problem; however, the resulting nonuniform grid of sample points would be significantly more difficult to manipulate and to analyze with most of the known algorithms (see also "The Analysis Subsystem"). On the other hand, with uniformly spaced sampling, either an optimal horizontal resolution is identified, which allows for the acquisition of all the significant surface shape features in a reasonable time span, or multiple passes at different resolutions need to be performed. In case the approach of performing multiple acquisitions is chosen, the planning problem becomes the problem of identifying the optimal number of passes, and the localization and resolution for each one of them (see Fig. 4*b*).

Similar considerations can be made for vertical resolution and range as well. Sensors characterized by high resolution usually have a limited range, and vice versa; this is often a limitation for firearm identification where some of the signatures that one may be looking for may be barely denting the surface (and thus requiring high vertical resolution to be measured properly) while laying at the same time on surface regions characterized by significant height drops (and thus requiring a high vertical range to be reached and acquired completely). A typical example of this situation can be found in cartridge case analysis, when looking at the tiny signature marks that may be left by a firing pin at the bottom of a deep firing pin impression. Again, the planning problem can be dealt with in different ways: the z axis could be motorized in order to follow the main surface shape (but then the overall vertical resolution would be a combination of the sensor resolution and of the z axis resolution), or as an alternative, different sensors (or sensor setups) could be used for preliminary

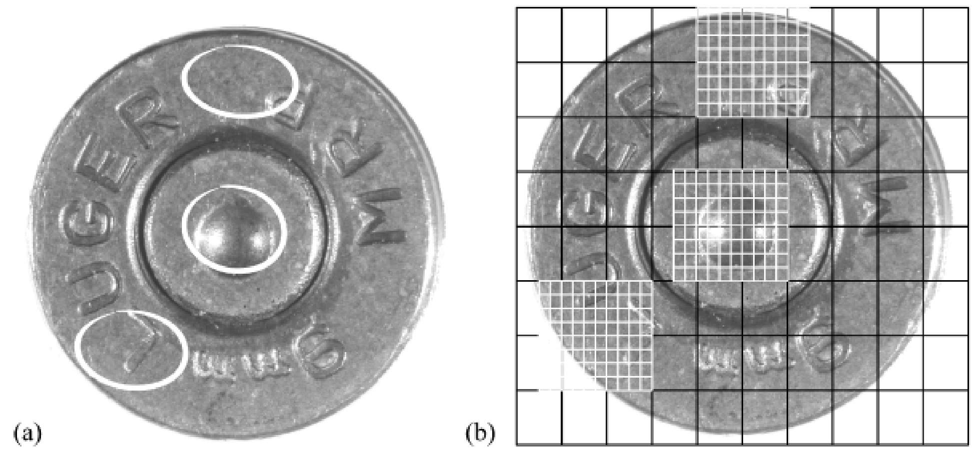

FIG. 4—*Multiresolution sampling of cartridge case bottom surface with uniform scanning constraints: (a) localization of some relevant shape features to be acquired at higher resolution; (b) definition of multiple scanning patterns.*

coarse scans and subsequent finer scans in limited regions, which is the preferred mode of operation for the prototype measurement system illustrated above.

Finally, some considerations should be made on the selection of a proper *scanning strategy*, that is planning the order the samples should be acquired. Acquisition systems like the prototype illustrated above are based on *raster scanning*, that is sequential acquisition of samples along the lines of a rectangular grid; raster scanning is the most straightforward strategy to implement, and the most widely adopted for point-based measurement instruments. Other strategies that may prove to be useful in ballistic fingerprinting may include radial scanning, adaptive scanning, and other types of nonsequential scanning: in particular, the multiresolution sampling strategy introduced above seems particularly suitable to be paired with an adaptive scanning strategy. However, this issue needs further investigation.

The Analysis Subsystem

By enforcing a standard encoding formalism for 3D surface topography data such as the one illustrated above, it is possible to focus on the development of instrument-independent 3D surface topography analysis techniques. From the proposed formal representation, two additional advantages arise: first, as the proposed formalism completely encapsulates scale information in the sample spacing coefficients, it is possible to develop scale-independent techniques for topography data analysis and manipulation; second, as mentioned earlier, as a 2D matrix of sample heights is formally equivalent in terms of data structure to a digital image, analysis systems can be developed that work almost indifferently on 3D surface topography data and on image data, thus widening the range of possibilities that such tools can provide to the end user; and also a great deal of algorithms originally developed for image analysis and manipulation can be transferred with substantially no effort to 3D surface topography data, thus widening the available options in terms of data analysis and manipulation algorithms.

For this reason, the literature on 3D surface topography analysis for engineered surfaces (7–10) and the literature on digital image analysis and processing (15) can be merged into a single powerful approach, aimed toward firearm identification.

A Prototype Analysis Subsystem

Figure 5 shows a prototype analysis subsystem that has been developed as a general-purpose software framework for 3D surface topography data analysis and processing (12,13). Topography data can come from different measurement instruments as long as they are provided in a format that is compatible with the proposed formalism; the system is capable of handling 3D topography data or 2D images indifferently, and all the algorithms are scale independent. Given the broad range of applications the system has been designed for, it is provided with a modular architecture that allows for the integration of additional data analysis and processing modules, often custom tailored according to the specific needs of each different application domain.

Visual Analysis with 3D Surface Topography

Firearm Identification as a Visual Shape Comparison Process

Firearm identification is a decisional process based on shape information. By identifying and comparing relevant shape features, a human operator with the proper expertise is capable of assessing with a certain degree of reliability whether or not two bullets or cartridges case have been fired by the same weapon. Human operators perform shape identification primarily through vision: 3D shape is reconstructed through interpretation of light patterns on different slopes, filtered by commonsense knowledge. The human vision–brain system is the most versatile shape analysis engine available for any application, and firearm identification is no exception; however, the result is very qualitative and subjective.

Direct observation of a physically available specimen is the most powerful approach available for acquiring shape information; when supported by proper tools, it allows for dynamic change of viewpoint, lighting, focus and resolution, essentially providing the highest quality shape information for a given specimen, on demand and in real time. In this sense, comparison microscopes can be seen as visual enhancement tools that do nothing more than allowing for the best performance of the direct observation process. The main drawback of direct observation is that the information acquired in this way cannot be permanently recorded, which is needed when shape information needs to be stored for later use (e.g., cartridge case/bullet databases) or when documentation must be generated to support and explain the

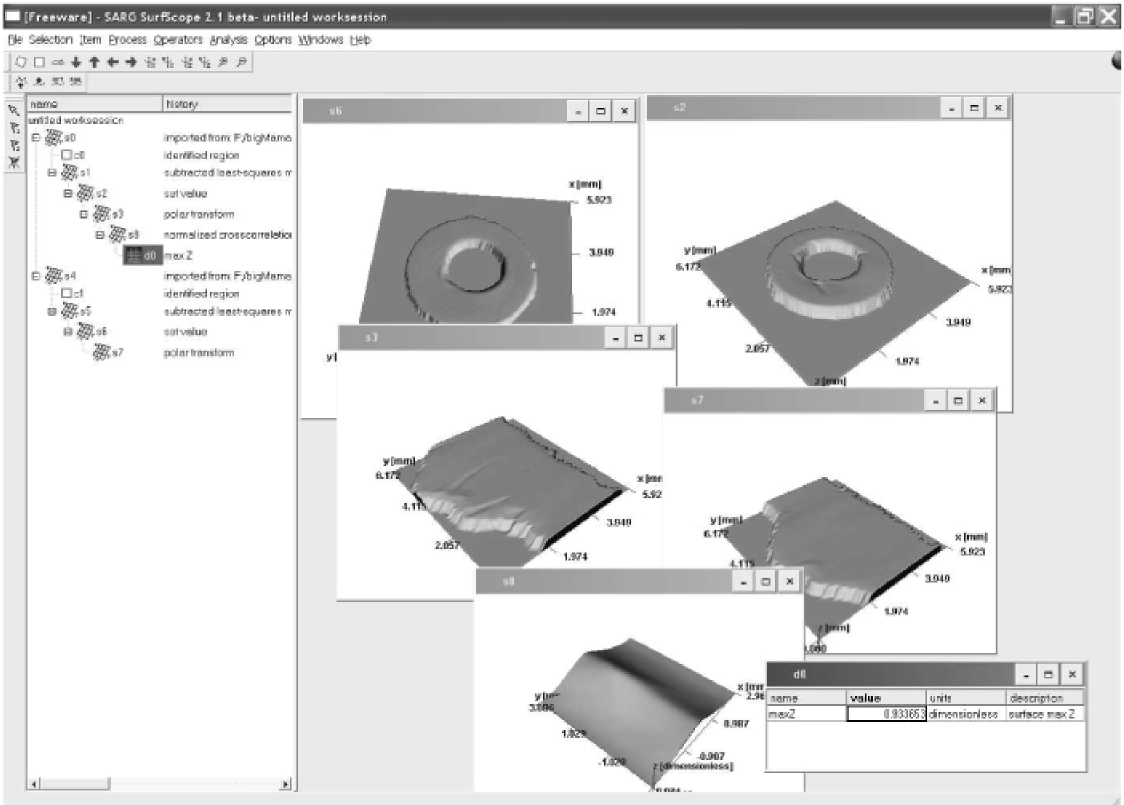

FIG. 5—*Surface topography analysis subsystem: interactive analysis session for the comparison of two primer surfaces.*

decisional process that leads to a positive or negative identification assessment. Thus, direct observation is usually supported by the generation of *still images* (i.e., analog or digital pictures), as they are the most common solution to record shape information so that the sensorial experience from direct observation is somewhat replicated. However, still images have their own limitations: the immutable choice of viewpoint, lighting, focus, and resolution reduces the amount of shape information that the single image can capture and deliver. Such limitations are sometimes very penalizing: it is not a rare event that, in case a firearm identification process has to be repeated, the original specimens are retrieved and direct observation is performed all over again. However, still images are currently the main data format used to store shape information for firearm identification, as for example in databases of cartridge cases or bullets, for later retrieval and comparison. In order to reduce the problem of information reliability in still images, digital pictures are taken in standard and repeatable viewpoint, lightning and focus conditions, as for example in the IBIS system (1).

3D Surface Topography and Shape Visualization

In order to be able to provide support to visual analysis, a system that handles 3D surface topography needs to be able to generate output that is suitable to stimulate the vision–brain system: such output may be still images, or "streaming" data to emulate direct observation of a physically available specimen (which will be referred to as *dynamic images*).

Under the premise that surface topography data are stored according to the formal representation introduced earlier, still or dynamic images can be generated by means of many known rendering algorithms. Figure 6 shows the application of a sequence of rendering techniques for generating a photo-realistic image from a set of data points acquired from the surface of a cartridge case.

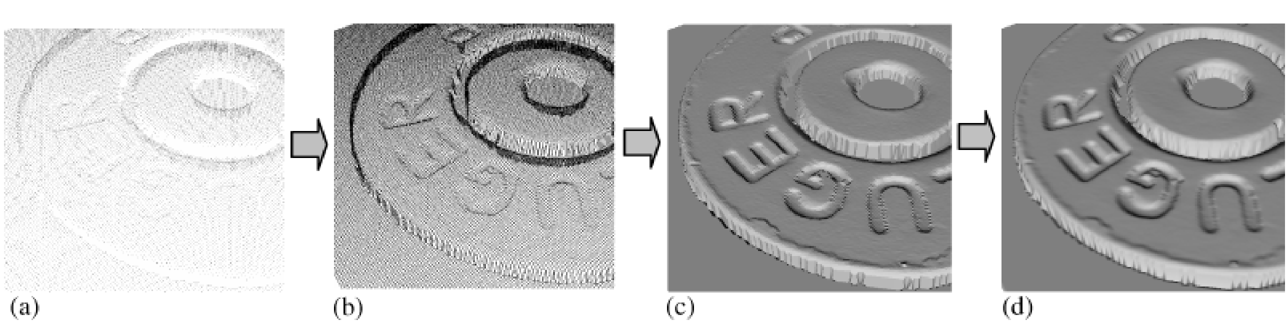

FIG. 6—*Photo-realistic image generation through rendering: (a) perspective projection of sample data points; (b) reconstruction of quadrilateral facets; (c) flat shading with fixed-position light source; (d) smooth shading (Gouraud shading) with fixed-position light source.*

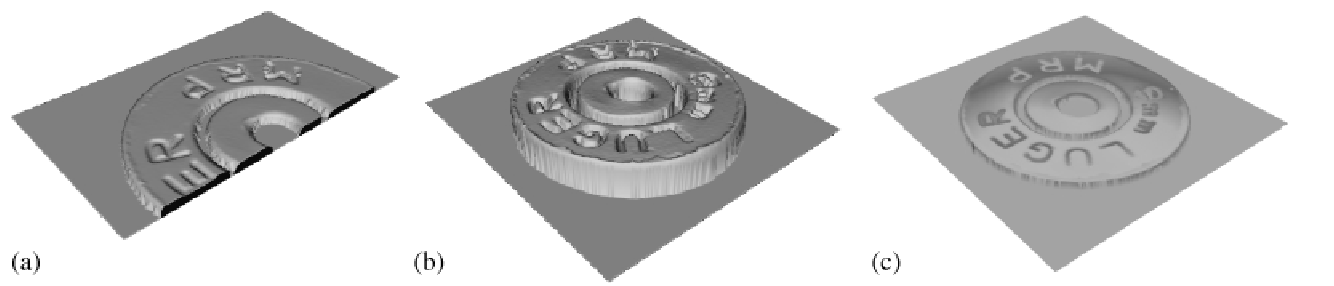

FIG. 7—*Generation of virtual, nonrealistic, images for selective enhancement of surface properties: (a) virtual sectioning; (b) z magnification; (c) height-based coloring (gray scaled).*

By means of rendering it is possible to exert control on many aspects that are relevant to visual observation: viewpoint, lighting, magnification, and other factors can be changed by simply acting on the parameters of the rendering algorithms, and an image reflecting the new viewing conditions can be generated in real time. Thus, most of the aspects of direct observation of a physically available specimen can be replicated, as long as the amount of information provided by the surface topography data points is sufficient.

Moreover, the combined availability of a virtual model and of a wide array of rendering techniques allows for the generation of virtual images to enhance a specific aspect of a surface topography, images that could never be obtained by direct observation of the real specimens. Figure 7 shows some examples of this technique.

In detail, with *virtual sectioning* (see Fig. 7*a*), it is possible to analyze the specimen shape cross-section without actually damaging, or even touching, the real specimen, with *proportion magnification* (see Fig. 7*b*), it is possible to enhance artificially one of the three Cartesian coordinates of the samples (in this case the *z* coordinate); and with *artificial coloring* (7c—gray scaled), it is possible to assign an artificially chosen colorset to a surface depending on the surface local properties (e.g., local slope, local height, local curvature, etc.).

Along the same lines, Fig. 8 shows examples of *reference geometry superimposition*, where virtual geometrical entities such as planes, lines, axes, etc., are overimposed to the original surface topography in order to highlight specific shape properties; for example in Fig. 8*a* a rectangular mesh is superimposed to highlight the position of the original samples; in Fig. 8*b* a contour plot is superimposed with lines at constant height to enhance the perception of *z* levels on the surface.

Introducing the 3D Virtual Comparison Microscope

Techniques like those described so far allow for a human operator to perform the same visual comparisons that he/she would perform with a comparison microscope on the real specimens, but operating on virtual, reconstructed surfaces. Thus, the concept of a *3D virtual comparison microscope* can be introduced, where virtual images of the specimens can be placed side by side and compared, essentially replicating the same mode of operation that would be adopted on a comparison microscope, including the change of the viewpoint and lighting conditions; with the additional advantage of the availability of a wide range of visual enhancement tools that extend the comparison well beyond what could be accomplished with a traditional comparison microscope. Figure 9 shows the reconstructed views of two ejector pin signatures on the rim of two different cartridge cases, placed side by side to emulate operation on a comparison microscope: in Fig. 9*a* the ejector pin signature regions are placed close by and highlighted, and in Fig. 9*b* the ejector pin regions are matched emulating the traditional visual comparison process.

Finally, Fig. 10 shows three primer surfaces being compared with contour plots for visual enhancement. In this case, contour plots are used to highlight the overall morphology of the surface of the primers for a better comparison.

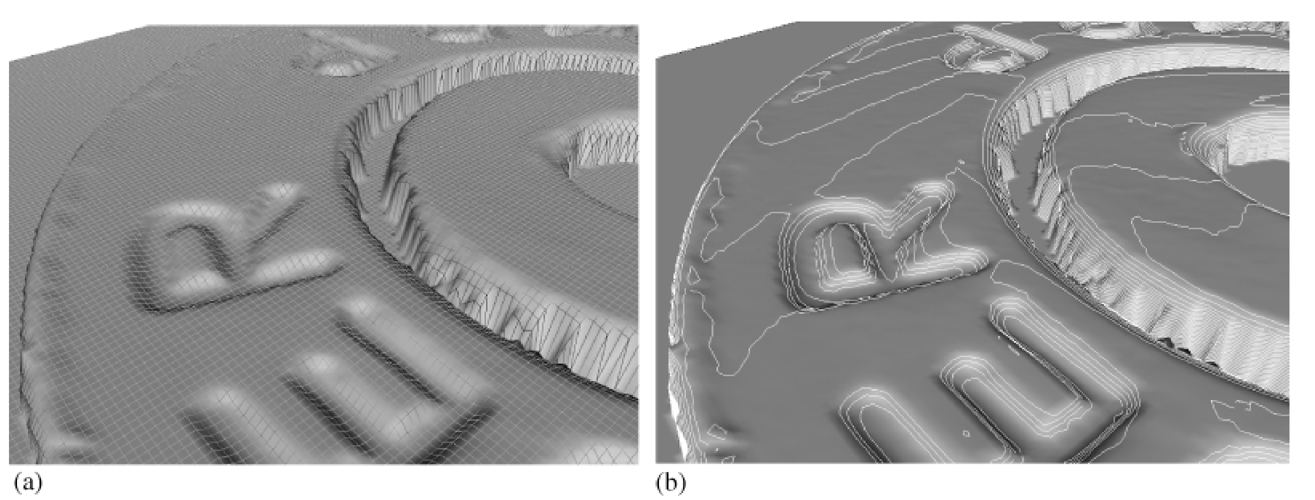

FIG. 8—*Generation of artificially enhanced images by overimposing reference geometry: (a) quadrilateral mesh on sample points; (b) z-level contour plot.*

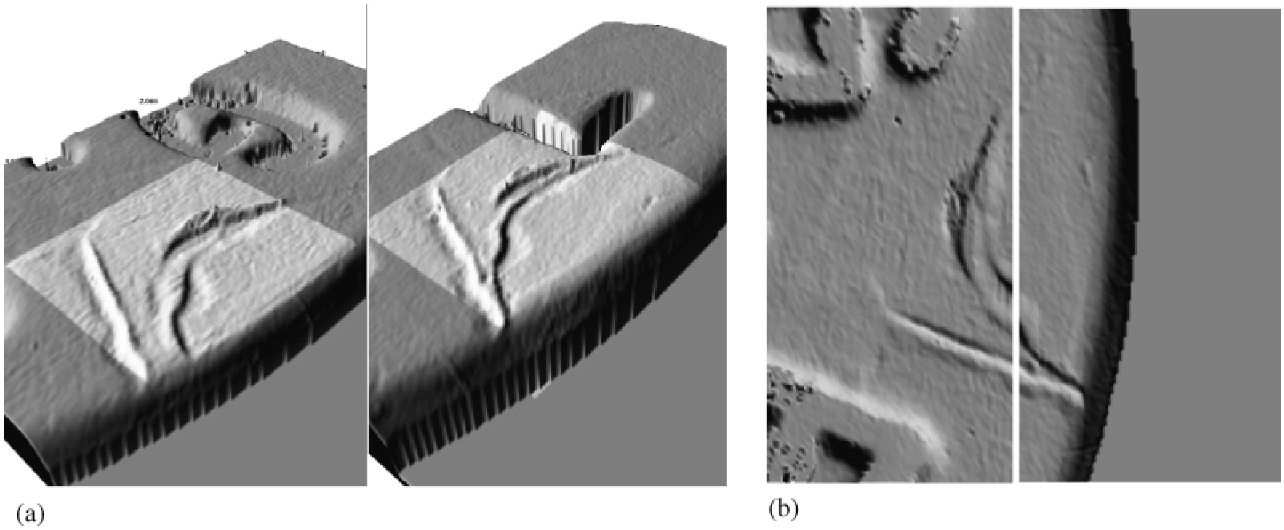

FIG. 9—*Ejector pin signature comparison: (a) region highlighting; (b) feature-based manual matching.*

Even though the 3D virtual comparison microscope provides almost as much freedom as the real comparison microscope for observing the specimens and also provides additional functionality through artificial enhancing techniques, some important limitations should be taken into account as well. First, the magnification power of light should not be underestimated: visual observation of light reflection patterns on the shiny surface of a real specimen may allow for the identification of tiny shape features that may not be visible otherwise; this performance may be difficult to be matched by the available solutions for 3D surface topography acquisition. Second, while direct observation of the real specimen benefits from the constant availability of the specimen itself, which means that topography information can be truly acquired on demand and in real time to fulfil the emergent needs of the ongoing analysis process, in 3D surface topography analysis architectures such as the one described in this work, surface topography data are made available through an off-line acquisition process and thus it can fulfill in real time only the analysis requests that do not seek a resolution that is higher than the original resolution that the topography was acquired with. This limitation is because of the performance of current 3D surface topography data acquisition systems in terms of acquisition time, and may not be overcome until new techniques are developed.

Quantitative Measurement to Support Firearm Identification

Quantitative Measurement to Enforce Comparison Assessments

Shape comparison through visual perception is an extremely complex phenomenon to be captured and replicated. It is well known that the human brain is more capable of perceiving regularity in some types of shape features than in others: for example, it is fairly easy to spot planarity errors on a flat surface, or straightness errors on a segment, while it is more difficult, for example, to see curvature errors on a surface that has a nominal curvature already. The same uneven performance can be observed in how size is perceived: our qualitative assessment works better for sizes that are within our common sensorial experience, while it becomes increasingly less accurate for significantly smaller or larger sizes; size perception is also affected by specific bright and dark color patterns, so that a bright feature on a darker background seems larger than the same dark feature on a brighter background. Finally, size perception is more accurate if a reference for comparison is placed nearby in the field of view: it is much easier to detect small size differences for close-by entities than for entities that are far away from each other. These are just some examples of how uneven the performance of the human perception actually is when assessing and comparing shape and size; good practice when

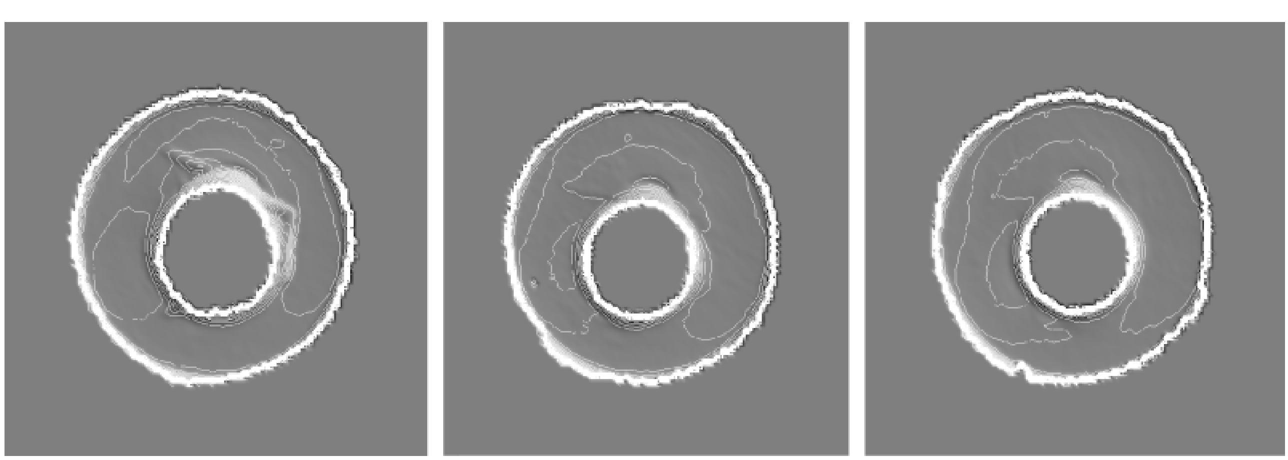

FIG. 10—*Comparison by means of contour plots of three primer surfaces placed side by side.*

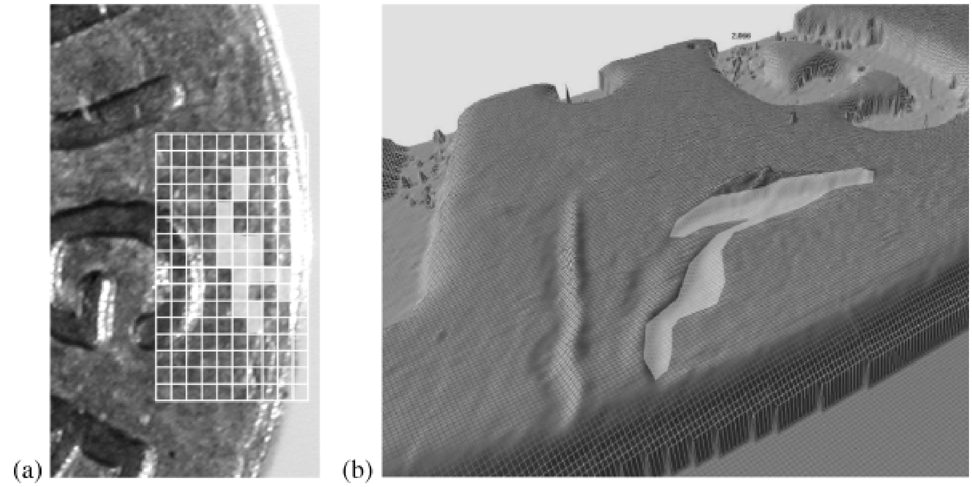

FIG. 11—*Main issues in performing quantitative geometric measurements over sampled surface topography: (a) discretization error; (b) reference identification error.*

performing visual comparison of shapes for firearm identification consists in creating the conditions that maximize the performance of the sensorial experience, which is why, for example, comparison microscopes are designed to place shape features side by side, in some cases even partially overlapped.

In order to compensate at least partially for the lack of uniformity in the performance of visual perception, means for obtaining quantitative measures of 3D surface topography shape features can be introduced; measurement helps reasoning with sizes and supports shape comparison providing partial compensation to the pitfalls of visual perception, adding quantitative content to an otherwise predominantly qualitative and subjective process.

Simple Types of Measurement and Related Issues

Within the domain of 3D surface topography analysis, measurement is to be intended as *geometric measurement*. The simplest types of geometric measurement for surface topography data involve concepts that are easy to understand and well accepted for describing continuous geometry, such as *distance*, *area*, and *volume*. However, in the discrete realm introduced with the formalism for 3D surface topography defined above, the accuracy of such measurements strongly depends on sampling resolution. An example of this dependency is shown in Fig. 11, where measurements must be performed on the impression left by an ejector pin: in Fig. 11*a*, the projected area enclosed by the marks left by an ejector pin is evaluated by adding up the unit areas defined by adjacent samples belonging to the ejector pin signature region: the discretization error originates both from the discrete size of the unit areas that are added up and from the error in selecting which unit areas do belong to the ejector pin impression.

The latter issue, that is, what samples do belong to a specific shape feature, can be generalized into the problem of identifying the geometric entities that act as references for the measurement. For example, in evaluating the length of a scratch as a distance between two points, two extreme points bounding the feature should be located; similarly, in evaluating the area covered by a depression, the exact depression boundary should be identified first. The problem of identifying the boundary of a shape feature is a complex one, both for continuous and discrete geometry, and is often dealt with by using slope- or height-related information, filtered by specific-domain knowledge. Figure 11*b* shows the sample points belonging to the same ejector pin impression marked with a bright color; the boundary identification was performed manually: a careful observation of the rendered image shows how determining the correct boundary may not be an easy task, and the decision of including/excluding some samples may be considered quite arbitrary.

A Generalized Take on Measurement

In a general sense, geometric measurement can be seen as the act of associating one or more scalar quantities to a set of geometric entities with the intent of capturing some properties of such entities. Under this generalized viewpoint, many mathematical transforms applied to surface topography samples and resulting in one or more scalar quantities can be seen as measurement types.

Measurement Through Roughness Parameters

A considerable amount of literature work is available for surface roughness analysis. Roughness has been characterized over the years, in two dimensions on profiles and in three dimensions on surfaces, by many quantitative parameters, each one meant to highlight specific surface properties (7–11).

A large number of parameters can be identified in the current literature: while those evaluated over profiles (2D parameters) are almost completely standardized and well known (the most well-known one being R_a, the *arithmetic mean deviation of the profile*), 3D parameters are still in the process of being completely defined and standardized. For the most part, 3D parameters are defined to be general purpose, suitable to be applied to any surface in any application scenario in order to assess some generic topographical property of the surface; however, an undefined but growing number of other parameters is being custom built to address the requirements of specific application domains.

For general-purpose 3D surface topography analysis, the most widely adopted parameter sets include *amplitude parameters*, aimed at describing properties related to the probability distribution of surface heights (e.g., S_a: the *arithmetic mean deviation of surface heights*, which is the 3D counterpart of Ra); *spatial parameters*, which address properties that are measurable over the spatial extension of the surface (e.g., S_{ds}, the *density of summits of the surface*, a measure of the density of summits per unit surface projected area); *hybrid parameters*, which combine the amplitude and the spatial properties of a surface (e.g., $S_{\Delta q}$, the

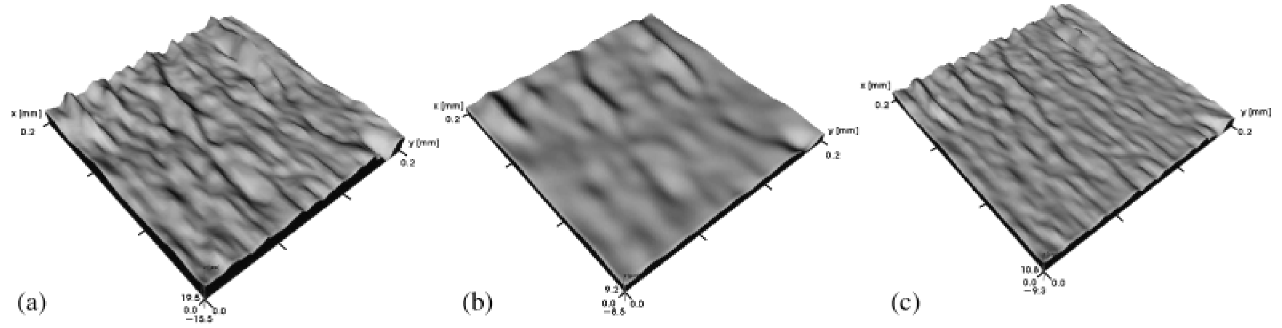

FIG. 12—*Filtering in the spatial frequency domain by means of the FFT: (a) original topography—portion of the surface of a primer region; (b) low-pass filtering result; (c) high-pass filtering result.*

root-mean-square slope of the surface); and *functional parameters,* which are meant to be representative of surface properties that affect its functional interaction with other surfaces (e.g., related to wear, friction, lubrication, etc.), parameters that often rely on the concept of *bearing area*, the area of a virtual cross-section that may be obtained by truncating the original surface topography at a given height (e.g., the parameter S_{bi}, *surface bearing index*, the ratio of the RMS deviation over the surface height at 5% bearing area).

However, such a wide choice of parameters does not necessarily make it easier to identify measurement types that are meaningful and at the same time applicable to the problem of firearm identification. The use of roughness parameters to support firearm identification gives rise to two main criticisms: first, parameters to be used in surface topography comparison should have enough *discrimination power*, meaning that they should be capable of conveying the differences between two surfaces through their own values; second, they should be able to provide measurements that are suitable to characterize overall surface properties as well as singular, localized, surface shape features, which are often even more relevant in firearm identification. Unfortunately, known parameters tend to perform poorly with respect to both these issues: *discrimination power* is generally low, as most parameters produce results that *summarize* the properties of a surface into a single value, and thus they tend to average out local shape differences in the process, ending up with the same parameter value even for different surfaces; also, parameters tend to seldom be suitable for characterizing localized, singular shape features, as for the most part they are designed to be representative of properties involving the surface as a whole and lose significance on smaller entities.

In summary, the concept of using a generic mathematical transform on surface topography data in order to obtain a scalar quantity that can be used as a measurement for surface comparison purposes seems promising for firearm identification through ballistic fingerprinting. However, the application of known transforms, such as the parameters introduced by the literature on roughness analysis, should be performed with caution: existing parameters should be chosen, or *ad hoc* parameters should be created, by looking carefully at their representational and discrimination power for the surface features they are meant to be applied to.

Data Preprocessing for Measurement

As stated earlier, any transform or sequence of transforms producing a single scalar quantity when applied to surface topography data can be potentially adopted as a measurement. Other transforms, although not generating a single scalar directly, could be used as topography data preprocessing tools to improve the subsequent applicability of other measurement techniques: filtering techniques are a typical example of this approach. Figure 12 shows FFT-based filtering in the spatial frequency domain for the surface of a primer: low-pass filtering (Fig. 12*b*) can be used to highlight the underlying overall shape of a surface; high-pass filtering (Fig. 12*c*) can be used to highlight roughness components such as scratches, breech face marks, etc.

Another use of data preprocessing techniques is to generate transforms of the original surface topography that, even if they do not resemble the actual surface shape any longer, still may be more suitable to highlight specific properties of the original surfaces, and act as a better base for measuring such properties. Figure 13 shows an example of such a transform: in order to evaluate the predominant orientation of the breech face marks, the areal autocorrelation function (AACF) has been evaluated over the

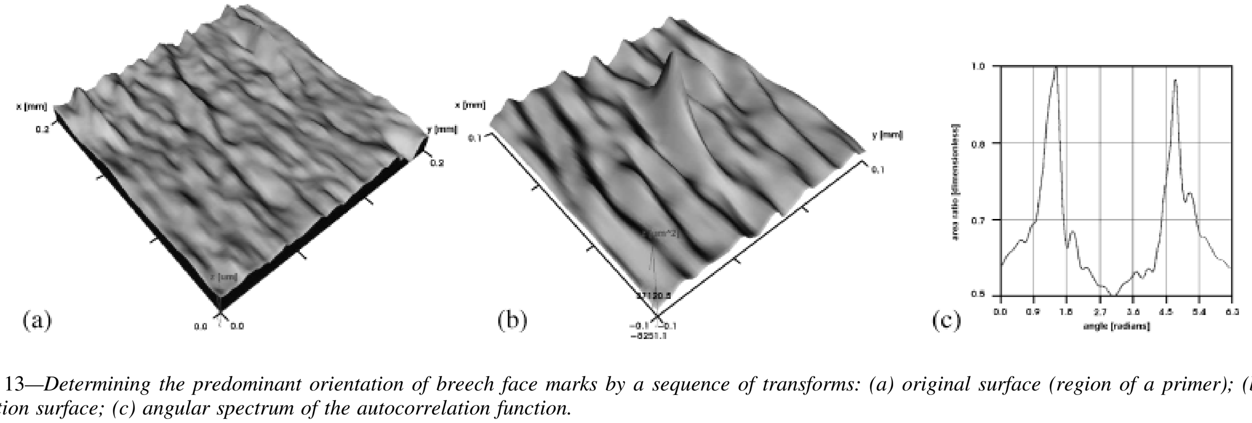

FIG. 13—*Determining the predominant orientation of breech face marks by a sequence of transforms: (a) original surface (region of a primer); (b) autocorrelation surface; (c) angular spectrum of the autocorrelation function.*

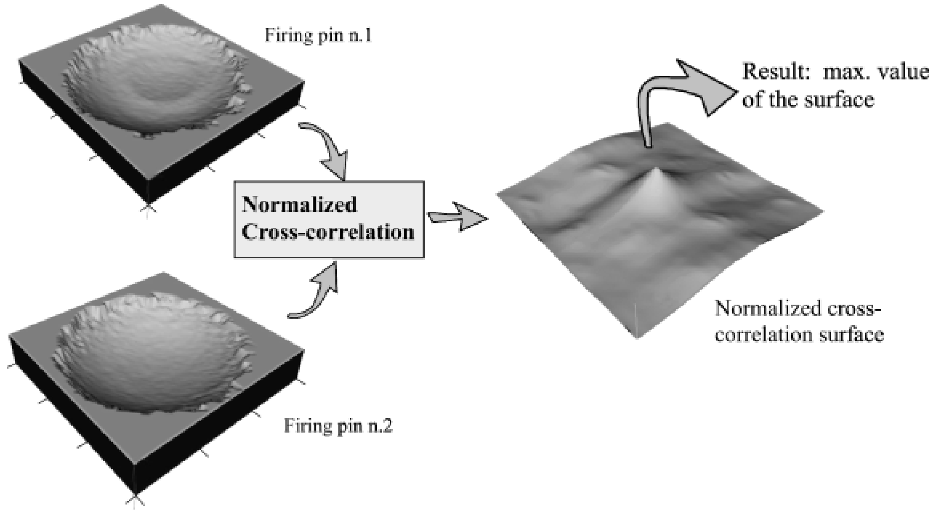

FIG. 14—*Normalized cross-correlation applied to the comparison of the central regions of two firing pins impressions.*

original surface topography of the primer, and the angular spectrum of the AACF has been computed, its maximum values corresponding to the predominant orientation of the surface texture.

Cross-Correlation as a Similarity Metric

Cross-correlation is a data-processing technique that can be applied on two surface topographies in order to provide a quantitative measure of their similarity. Given the equivalency of the formal representations for image data and surface topography data, the technique applied to surface topography is very similar to the one applied to digital images: shapes are seen as summations of spatial frequency components and similarity is evaluated in terms of the amount of overlapping of such components; in *normalized cross-correlation* the result can be normalized so that similarity is always expressed by a value between 0 and 1. The result of cross-correlation between two surfaces is a surface as well, whose maximum can be taken as a measure of similarity; the process of applying normalized cross-correlation to compare the central regions of two firing pin impressions is illustrated in Fig. 14.

Data Preprocessing for Cross-Correlation

The result of cross-correlation, although invariant with respect to the relative translation of the two surface topographies being compared, is sensitive to rotational misalignments, which can be typically found when acquiring rounded shapes such as cartridge cases: in this situation, in fact, even though proper fixturing can minimize the problem, it is reasonable to assume that a slight rotational misalignment will be present notwithstanding. One way to solve the rotational misalignment problem consists in preprocessing the surfaces in order to obtain invariants to rotation, for example, by applying a *polar transform* on the surface, as shown in Fig. 15 for an example comparison of two primer surfaces.

Unfortunately, data preprocessing activities such as the polar transform introduce additional issues to be taken care of: in the example shown in Fig. 15, a slight misplacement of the pivot point of the polar transform from the ideal center of the primer surface may generate errors in the transformed surface that may affect the results of the comparison. Moreover, the polar transform causes nonuniform resampling of surface topography data, since regions that are closer to the pivot point are scanned at much higher an-

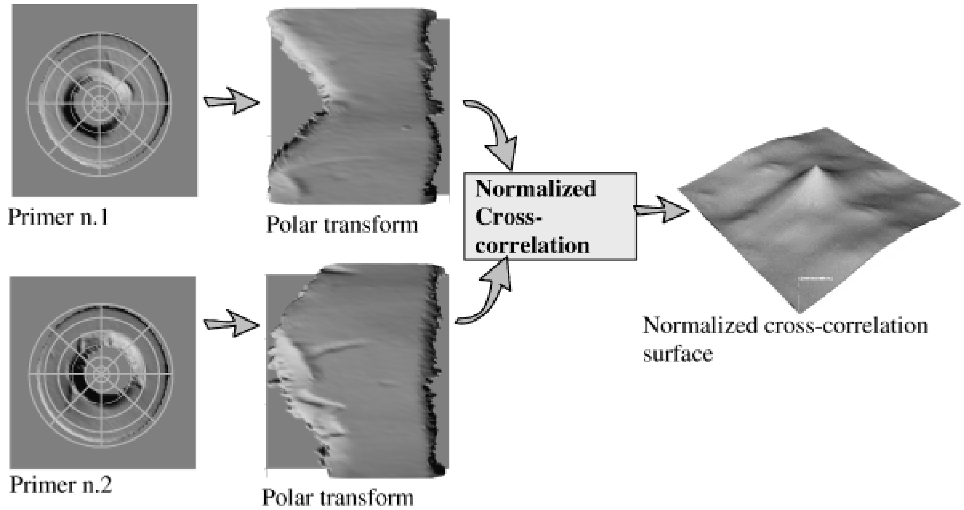

FIG. 15—*Surface preprocessing by means of the polar transform: example comparison of primer surfaces by means of normalized cross-correlation.*

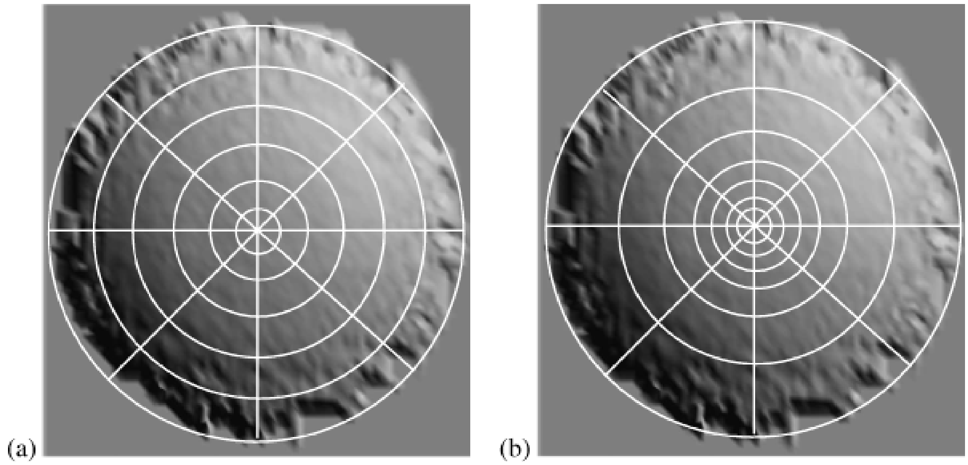

FIG. 16—*Sampling grids applied to the central region of a firing pin impression: (a) grid of a polar transform; (b) grid of a log-polar transform.*

gular resolution than regions that are far from it, as shown in Fig. 16*a* where the sampling grid of a polar transform is overimposed to the topography of the central region of a firing pin impression. The polar transform acts as a nonuniform filter for the angular coordinate in the spatial frequency domain, preserving the high-resolution features that lie in proximity to the pivot point, while acting as an increasingly low-pass filter (on the angular coordinate) moving away from it.

As there is no way to eliminate this effect, which is intrinsic to the polar transform, at least a similar resolution loss can also be applied in the radial direction so that resolution loss is uniform on both coordinates: this can be achieved by the *log-polar transform* (16) where radial spacing increases together with angular spacing, moving away from the pivot point (see Fig. 16*b*). By keeping the resolution high in proximity to the central region of the viewing field, while increasingly losing resolution moving away from it, the log-polar transform is believed to emulate the human vision system, where maximum resolution is achieved in the *fovea* region, while peripheral regions are less important and their content is filtered out for the most part, for efficient image processing.

In firearm identification, the successful application of such transform implies some *a priori* knowledge of the location of the relevant features, so that the pivot point can be conveniently centered with respect to them: in the already mentioned example shown in Fig. 16, it is assumed that the most interesting high-resolution shape features are located in the central region of the firing pin impression.

While the polar and log-polar transforms are essentially used to make cross-correlation invariant to rotational misalignments, the result may still be influenced by scaling problems, meaning that two shape features, even though morphologically similar, may receive a low correlation score only because their size is different. This problem is relevant to firearm identification, where the size of some types of impression is characterized by a degree of variability, even when the specimens have been fired by the same firearm: for example, a firing pin may leave a more or less pronounced signature on the primer surface depending on slight variations of the mechanical interactions between the cartridge case and the firing pin itself, during the firing of the firearm.

One way to solve this problem consists in preprocessing the surfaces with the *Fourier–Mellin transform* (17) a sequence of transform operations that is illustrated in Fig. 17, as it is applied to the surface topography of a primer. The result of the Fourier–Mellin transform is a surface that is insensitive to translation, rotation and scale, and thus can be conveniently used for comparison purposes; the price to pay is that each transform introduces data loss and error in different forms. Once again, in order for such a methodology to be really useful to firearm identification, it needs to be carefully tuned for operation on the specific shape feature it is meant to be used with.

Selective Comparison Issues

The most important and still unsolved problem in the application of cross-correlation to evaluate the degree of similarity of surface topographies is that in cross-correlation all the samples belonging to the two surfaces are accounted for, when determining the final similarity judgment. As each and every sample counts in the final decision, each shape feature affects the final similarity result depending on the amount of samples it is made of; thus,

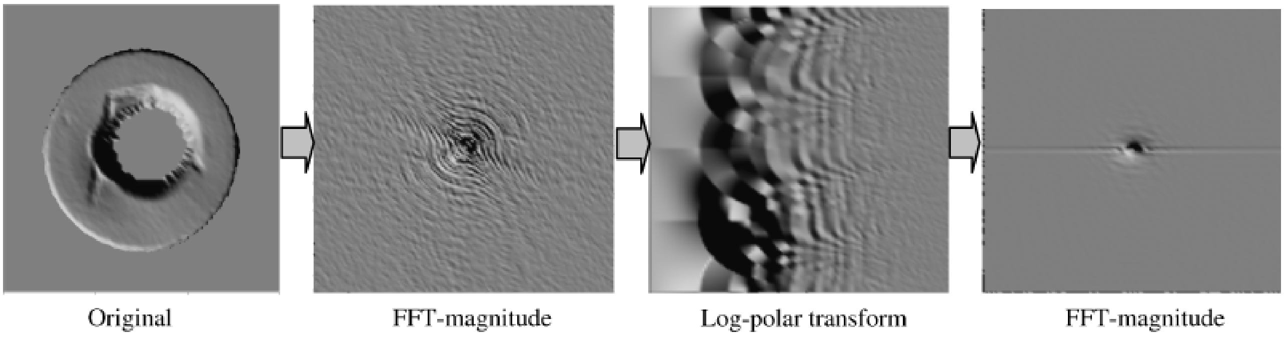

FIG. 17—*Surface preprocessing for cross-correlation by means of the Fourier–Mellin transform.*

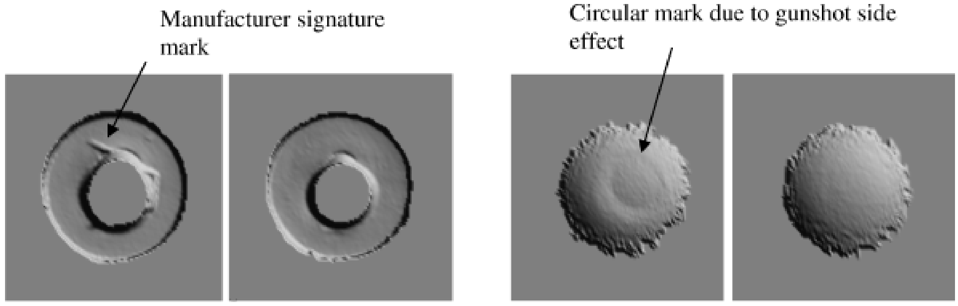

FIG. 18—*Shape features affecting cross-correlation results. Left: manufacturer signature imprinted on one of the two primer surfaces being compared; right: circular shape feature generated by a gunshot on one of the two firing pin impressions being compared.*

larger shape features tend to drive the similarity measurement. Firearm identification practice shows that this may not necessarily be a good thing: key features that determine a positive identification are often tiny signature marks, while large shape features are often almost completely irrelevant. Examples of this are illustrated in Fig. 18: Fig. 18*a* shows two primer surfaces placed side by side: a very large "v"-shaped impression, highlighted in Fig. 18*a*, is the result of a signature mark left by the manufacturer on that particular cartridge model, and it is completely irrelevant to the firearm identification process; thus, even though the two primer surfaces reported in Fig. 18*a* belong to cartridges that were shot from the same firearm, cross-correlation would return a low score, being affected by the manufacturer signature mark. Similarly, Fig. 18*b* shows two firing pin impressions side by side: one is characterized by a large, circular shape feature (highlighted in Fig. 18*b*) that has a strong influence on the result of cross-correlation; however, expert knowledge finds justification for such a feature in the variability of the mechanical interactions that the cartridge is subjected to during the firing of the firearm; thus, once again, it is irrelevant to firearm identification. Also, in this case, the two specimens reported in Fig. 18*b* where shot by the same firearm.

It follows that, at least for the examples shown, a successful application of cross-correlation for evaluating similarity in firearm identification cannot be performed without having first eliminated nonrelevant features that may drive the similarity measurement to wrong conclusions. Unfortunately, this cannot be done without an in-depth knowledge of the application domain. The problem can be dealt with in two ways: either the nonrelevant features are identified and somehow subtracted from the original surface prior to cross-correlation, or the relevant features are identified and extracted, and cross-correlation is performed on them. Unfortunately, both approaches have significant drawbacks: assuming for a moment that the problem of extracting the relevant (or nonrelevant) shape features may be solved, as cross-correlation algorithms usually need regular sets of contiguous samples to operate, the problem for both approaches would be how to handle the voids created by the feature extraction process.

Conclusions

3D surface topography can play many relevant roles in firearm identification through ballistic fingerprinting. Systems based on 3D surface topography can be developed for supporting the visual comparison process, for example by providing means to generate virtual still images of the specimens, up to the point of replicating the entire direct observation process, emulating the operation with traditional optical comparison microscopes. Furthermore, as images are generated through simulation, algorithms can also be adopted for generating artificially enhanced images that go beyond the capabilities of optical observation of the real specimen. Proper combinations of these techniques may provide a valid contribution to the shape comparison processes that are at the basis of firearm identification.

In addition to this, systems based on 3D surface topography can support the firearm identification process by providing means to make quantitative measurement over shape data: such measurements range from simple and well-established concepts, such as distance, area and volume, to more generalized approaches, such as the evaluation of custom-tailored parameters that may act as discriminators when comparing shapes under the viewpoint of some particular shape property.

All the concepts introduced and illustrated in this work need further investigation, especially when considered as an alternative, or a complement, to ballistic imaging: it is clear that the acquisition of 3D surface topography takes longer than the acquisition of a digital picture; it is also understood that current technology for acquiring 3D surface topography has limitations, especially related to acquisition time, range, and resolution of measurement. However, the advantages in terms of shape information representation and storage, and related to the availability of a wide range of flexible analysis techniques, may eventually compensate such shortcomings.

Additional considerations should be made on the downsides related to the introduction of 3D topography in firearm identification; as it always happens with novel approaches, potential advantages come together with additional issues to be solved, and those issues discussed in this work, related for example to the applicability of parameters, the meaningfulness of some data processing and analysis techniques, and so forth, are just the tip of the iceberg with respect to the whole set of issues that are there to be analyzed.

The final and most important consideration is related to the biggest and still unsolved problem concerning automated identification and comparison of characteristic signature markings, which holds for both digital imaging and 3D surface-topography-based approaches: the capability of capturing the intrinsic variations of shape, orientation and localization of the signature markings, which are due to the natural variability of the firearm/ammunition interaction, even for the same combination of firearm/ammunition types, while still producing consistent identifications. At the moment, no computer-based solution seems to constitute a better alternative to a skilled and experienced firearm examiner.

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Additional information and reprint requests:
Nicola Senin, M.S.
Professor
Dipartimento di Ingegneria Industriale
Università di Parma
Parco Area delle Scienze 181/A
I-43100 Parma (PR)
Italy
E-mail: nsenin@unipr.it