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PAPER

CRIMINALISTICS

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Striation Density for Predicting the Identifiability of Fired Bullets with Automated Inspection Systems*

ABSTRACT: Automated firearms identification systems will correlate a reference bullet with all evidence bullets without a selection procedure to exclude the bullets having insufficient bullet identifying signature. Correlations that include such bullets increase the workload and may affect the correlation accuracy. In this article, a parameter called *striation density* is proposed for determining and predicting bullet identifiability. After image preprocessing, edge detection and filtering techniques are used to extract the edges of striation marks, the resulting binary image distinctly shows the amount and distribution of striation marks. Then striation density is calculated for determining the quality of images. In the experiment, striation densities for six lands of 48 bullets fired from 12 gun barrels of six manufactures are calculated. Statistical results show strong relation between striation density and identification rate. It can provide firearms identification systems with a quantitative criterion to assess whether there are sufficient striae for reliable bullet identification.

KEYWORDS: edge detection, firearms identification, forensic science, identifiability, morphology, striation density

Traditionally, comparisons of striation marks on fired bullets have been accomplished manually by examiners using comparison microscopes. Since the early 1990s, computer-aided optical systems have been developed to aid firearms examiners by processing large volumes of firearms-related evidence more efficiently. Currently, the Integrated Ballistics Identification System (IBIS^{TM}) developed by Forensic Technology, Inc. (FTI, Cote-Saint-Luc, QC, Canada) (1) is widely used in U.S. forensic laboratories, and is the current standard technology in the National Integrated Ballistic Information Network (NIBIN). Developments of other commercial systems and studies in firearms identification have also been reported (2–7). IBIS and other systems adopt the procedure that ranks the bullets stored in the database in light of a certain similarity metric with a subject bullet. The ranking of the bullets in the database gives the firearms examiner an ordered list of the most promising potential matches for further manual comparison and to decide whether any compared bullets match the subject bullet.

The striation marks on the surface of the fired bullet are formed when the bullet is forced down the firearm barrel. Because the bullet signatures are topographic striations by nature, the quality of the bullet image depends on the quantity of clear striation marks contained in the image. Sometimes, there are only a few, if any, effective striation marks transferred from the barrel to the land impression (also called *land engraved area* or LEA) of the fired bullet. In this case, performing a correlation with this LEA will unnecessarily increase the processing time and may affect the accuracy of a correlation score. This correlation score is often calculated as the sum of correlation scores from each pair of LEAs when the two bullets are at their optimum phase orientation. Although a skillful examiner could judge the image quality based on his/her experience, it would still be difficult to decide whether or not to abandon any further correlation operation because of the lack of an accepted quantitative criterion.

In this article, a new parameter called striation density, d_s, is proposed as an objective criterion for quantifying the suitability of the bullet images for automatic bullet signature correlation. First, we introduce the image preprocessing. Then we describe the edge detection procedure and extraction of effective striation marks from the binary edge image. The evaluation criterion of the bullet image quality is proposed, and then we will discuss this new concept.

Image Preprocessing

The earlier version of IBIS (now known as IBIS Heritage) (8), acquires two-dimensional (2D) image data or photographs of bullet surfaces. The recent version of IBIS uses a three-dimensional (3D) topography imaging system (9) for acquisition of bullets. The National Institute of Standards and Technology (NIST) developed a correlation approach based on 3D topography measurements using commercial confocal microscopy. The approach was originally developed for signature measurements and inspection of the NIST Standard Reference Material (SRM) bullets and cartridge cases (2,10), but it has been adapted for the measurements and correlations of 2D and 3D bullet and cartridge case signatures.

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Theoretically, the extraction of binary edge image and establishment of an identifiability criterion do not rely on the data format acquired by the imaging system, but different image preprocessing may be required for 2D and 3D data. The preliminary image processing at NIST for data acquired by the 3D confocal topography measurement system consists of three steps.

Removal of Unreliable Data Points

The unreliable data points include dropouts and outliers. Some 3D imaging systems provide a value of "level of confidence" associated with each acquired data set. If the level of confidence is too low, the point is considered as a dropout. In contrast with dropouts, "outliers" are data points inaccurately measured by the 3D imaging system, which are not reported to the user as inaccurate by the acquisition hardware (11). In our algorithm, the outliers are detected by estimating the local slope between a point and its neighbors. If the slope is above a threshold of 50 degrees, generally related to the numerical aperture of the objective lens, the slope is regarded to be unphysical and the point is identified as an outlier. After all dropout and outlier points are identified, they are replaced by interpolated data.

Gaussian Filter

After removal of unreliable data points, the topography data can be considered as a grayscale image. The grayscale image contains both low-frequency curvature and high-frequency noise. Both are not considered as *individual characteristics* and must be removed before correlation (11). In this project, the Gaussian filter (12,13) with 0.25-mm long wavelength cutoff λ_c and 0.0078-mm short wavelength cutoff λ_s is used to remove the low-frequency waviness and high-frequency noise. With Gaussian filter processing, topography components with a frequency range out of the specified bandwidth are strongly attenuated.

Top-Hat Transform

Some remnant of the bullet surface curvature may still exist even after Gaussian filtering. In the next step, a top-hat transform is applied to eliminate the remaining curvature. The top-hat transform is one of a large collection of techniques known as mathematical morphology (14), a branch of nonlinear image processing and analysis that concentrates on the geometric structure within an image. Mathematical morphology was initially developed for binary images and later extended to grayscale images. It includes a large number of operators and techniques for binary and/or grayscale image: dilation, erosion, opening, closing, thinning, skeletonization, hit-or-miss transform, and others. The labeling and area open operator will be used in the next section for edge element filtering.

The top-hat transform is a morphological operator to detect subtle structures. Puente León applied this technique in his research on bullet identification (7). Depending on whether bright or dark structures are to be detected, two different transforms, called the open top-hat transform and the close top-hat transform, may be applied. The open top-hat transform, $f \hat{\circ} g$, is given by:

$$f \hat{\circ} g = f - (f \circ g) \tag{1}$$

The close top-hat transform, $f \hat{\bullet} g$, is given by:

$$f \hat{\bullet} g = (f \bullet g) - f \tag{2}$$

where f and g are the image to be transformed and the structuring element, respectively; and the symbols "$\circ$" and "$\bullet$" denote the morphologic opening and closing operators, respectively. If the difference between them is calculated, a signal containing only fine peaks will be obtained, while the coarser structures are suppressed.

Figure 1 shows a 3D bullet topography image acquired by a confocal microscopy (*a*) and the consecutively processed results after removing unreliable data points and interpolation (*b*); Gaussian filter (*c*); and top-hat transform (*d*). During the top-hat transform procedure, a threshold is also set to remove the areas apparently higher or lower than other areas because they are not considered as striation marks.

Edge Detection and Extraction of Striation Information

An edge detection technique is used for extraction of striation information. Edge detection is a process that primarily measures, detects, and localizes changes of intensity (15). It has the desirable property of drastically reducing the amount of information to be processed subsequently while preserving information about the shapes of objects in a scene (16). Edges may or may not correspond to the boundary of an object. For images that do not contain concrete objects, the interpretation of the image depends on its texture properties. The edge detection procedure helps in the extraction of texture properties (17). In a bullet surface image, the textures are mainly comprised of striation marks. The properties of edge detection provide a possibility to quantitatively analyze the striation marks, or bullet signatures, which are of interest to effective bullet identification.

The edge detection is used to localize the striation edges. There are many methods to perform edge detection. We used the Canny edge detector, which is a multi-stage algorithm to detect a wide range of edges in images (18). Figure 2 shows a primary edge detection result using the Canny detector. The pixel points judged to be edges by the detector are evaluated "1" and shown as bright, while other pixel points judged to be background are evaluated "0" and drawn as dark. We define a parameter called edge density, d_e,

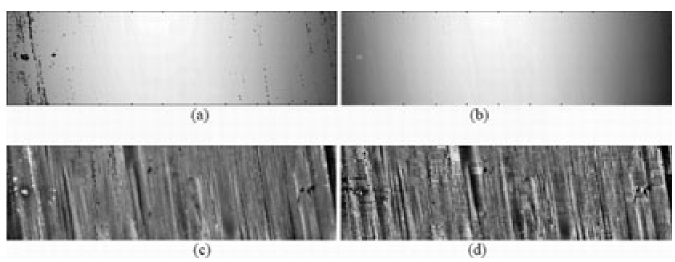

FIG. 1—*Preliminary processing result for a bullet LEA image: (a) raw data; (b) after removal of unreliable data points and interpolation; (c) after Gaussian filter; (d) after top-hat transform. The bullet nose is toward the top of the page.*

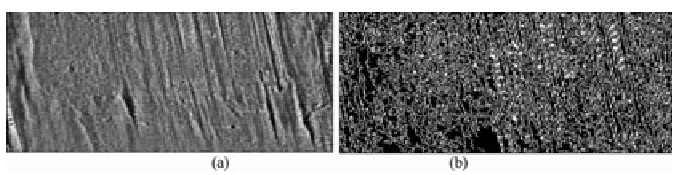

FIG. 2—*Edge detection: (a) grayscale image after preliminary processing; (b) detected result using the Canny detector. The edge density is* d_e = 18%.

to describe the ratio of the number of edge pixel points to the total pixel points of the area:

$$d_e = \text{number of pixels at the edges}/\text{total number of pixels in the area} \quad (3)$$

As indicated in Fig. 2*b*, the edge density is $d_e = 18.0\%$.

The primary edge image depicts the contour of all detected features on the bullet surface, including useful features associated with the striation marks impressed by the barrel, and useless features located within the image areas not engraved by the barrel rifling. In this article, we define a pixel point evaluated "1" by the edge detector as an edge element. An edge element belonging to a striation mark is called a striation element, and the edge elements belonging to all other features are called disturbance elements. In order to extract the striation elements from the disturbance elements, an additional filtering process has been designed.

First, we need to analyze the connection relationship of all the pixel points. Two pixels are said to be 4-neighbors if they are vertically or horizontally adjacent. They are said to be 8-neighbors if they are 4-neighbors or diagonally adjacent. In Fig. 3, all pixels labeled with "+" are 4-neighbors of the center pixel labeled with "•". All 4-neighbors of the center pixel and the remaining pixels labeled with "*" are its 8-neighbors. A collection of edge elements is considered 8-connected if for any two pixels *p* and *q* in the collection there exists a sequence of pixels also in the collection such that the first pixel is *p*, the last is *q*, and each pixel in the sequence is an 8-neighbor of the next. We define such an 8-connected collection separated from other collections as a connection unit. A morphological labeling operation (14) is then used to identify all connection units and mark them with sequence numbers.

Figure 4 shows three connection units with typical shapes. Fig. 4(*a*) is an edge detection result from a striation mark. It has the property of an approximately straight and continuous long span in the vertical direction. Contrarily, the edge detection results originating from other features irrelevant to striations may have various shapes, straight or tortuous, simple or complicated, fragmentary or extensive, but few of them have a long vertical span, like Fig. 4(*a*) representing a striation mark, or bullet signature. Figure 4(*b,c*) show two examples of edge patterns other than striation marks. In term of this difference, they can be filtered out from the primary edge image.

First, a threshold, denoted as *l*, is used to distinguish them. The vertical span of each connection unit is checked and compared with *l*. All the units, whose vertical pixel position difference between their top elements and their bottom elements is greater than *l*, are reserved. Otherwise, they are removed by re-evaluating the pixels as "0". Prior to this processing, a morphological area open operator is used to reduce the processing time. This operator can automatically omit the connection units that have a total number of elements less than *l*, as Fig. 4(*b*) shows. For more complicated cases, where contours of different features connect together, a tracing process is developed to filter out the disturbance elements connected with the striation edges. At first, a rule for tracing is built and shown as Fig. 5(*a*). Assuming that the dot point is the current point being traced, the rule prescribes that the next possible traced point can only be one of three adjacent points labeled by 1, 2 and 3. The numerical sequence is their priority. The priority sequence of 2 and 3 depends on the direction of twist of the barrel. Figure 5(*b*) shows an example of tracing. The tracing starts from the top pixel point of this connection unit. The tracing path is determined in terms of the established rule until the last pixel point is reached. The pixels along this path will be reserved if the vertical span is more than *l*. The path in Fig. 5(*b*) is marked in bright, while the edge elements that have not been traced are marked in gray. The same process is repeated until all the edge elements have been considered. Figure 6 shows the filtered edge image from Fig. 2(*b*) in which only the contours of striation marks are highlighted.

Note that the tracing process can complete the filtering alone, but the application of the morphological operator can significantly reduce the processing time.

Evaluation of Bullet Identifiability

By analogy with Eq. 3, we define a parameter called striation density, d_s, to describe the percentage of pixel points on striations within the total area of pixel points:

$$d_s = \text{number of pixels on the striations} \quad \text{total number of pixels in the area} \quad (4)$$

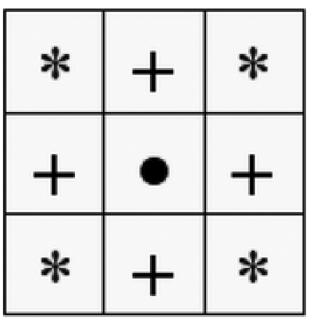

FIG. 3—*Connection relationship.*

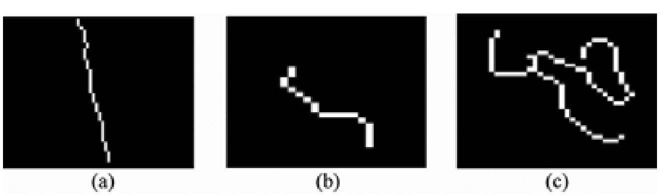

FIG. 4—*Three entity examples existing in the primary edge image. (a) represents a striation mark, or bullet signature; (b) and (c) do not.*

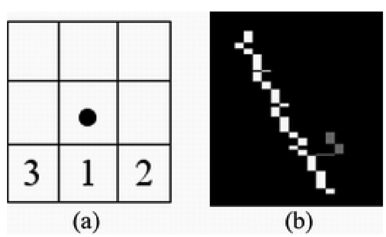

FIG. 5—*Element tracing: (a) rule and priority; (b) a tracing example.*

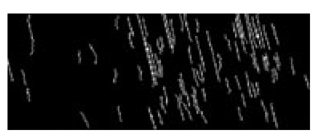

FIG. 6—*Filtered edge image result with a striation density* $d_s = 2.90\%$.

As indicated in Fig. 6, the striation density is $d_s = 2.90\%$. It is obvious that d_s must be less than d_e.

Two more bullet images with edge detection and filtering processing are shown in Fig. 7. Although the edge density d_e for these two sets of images is about the same, 16.9% for (b) and 17.8% for (e), the striation density d_s shows a large difference, 5.70% for (c) and 0.16% for (f). Apparently, the striation density d_s appropriately captures the amount of striations in the bullet image. The more and clearer striation marks a bullet image has, the higher the striation density will be. Striation marks are the foundation for bullet signature correlation, and they determine the reliability of bullet identification. The striation density parameter d_s can provide examiners with a means to estimate the quality of bullet images and predict the potential for identification.

Data from our previous study on correlations among 48 bullets provides us evidence to support the aforementioned point (19). In that study, 48 topographic images (4 bullets × 2 barrels × 6 firearm brands) were selected from a collection of sample bullets fired by a variety of firearms (11,20) and were correlated with each other. An overlap metric P was calculated in order to characterize the quality of the separation (or the degree of overlap) between the matching and nonmatching distributions of correlation values. The parameter P describes the probability that the CCF value of a randomly chosen member from the nonmatching distribution is larger than the CCF value of a randomly chosen member from the matching distribution (20). The parameter P quantifies the potential for making accurate matches. The smaller the value of P the better the separation between matching and nonmatching distributions. A value of zero for the overlap metric P implies ideal identification without error. The data of Figs. 2(*d*), 7(*a*), and 7(*d*) are processed from bullets fired through Taurus, Beretta, and Bryco barrels, respectively. Their image qualities are representative of other bullets fired from same brand barrel as well. Table 1 lists the averaged striation densities of bullets fired from these barrel brands along with the values of P.

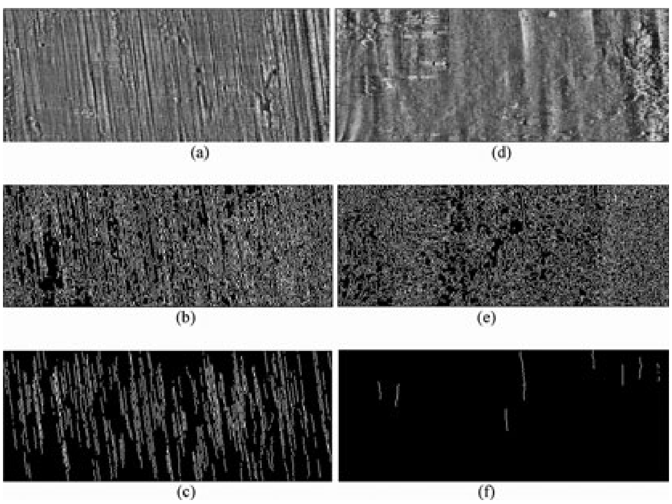

FIG. 7—*Two examples of edge detection: (a) and (d) are two grayscale images after preliminary processing, (b) and (e) are primary edge detection images, and (c) and (f) are filtered edge images. The edge density* d_e *is 16.9% for (b) and 17.8% for (e), two values which are very close, but the striation density* d_s *is 5.70% for (c) and 0.16% for (f), indicating a large difference in the image quality for firearms identification.*

TABLE 1—*Averaged striation densities,* d_s*, of 48 land images of 8 bullets for each of three different barrels.*

No.	Brand	Overlap Metric P	Average Edge Density d_e (%)	Average Striation Density d_s (%)
1	Beretta	0.026	16.5	4.07
2	Taurus	0.277	17.8	1.73
3	Bryco	0.554	16.9	0.84

For bullets fired through the Beretta barrel, the separation is high. Conversely, the overlap metric P of bullets fired through Bryco barrels shows a more random condition. This suggests that the associated striation density at this level is not sufficient for a bullet to be identified. Although a precise relationship between the striation density and the identification rate has not been developed, higher striation densities of compared bullets might lead to higher confidence in correlation results.

Table 1 shows some statistical characteristics of bullets fired from different barrel brands. It does not necessarily mean that bullets fired from certain brand barrels are identifiable or bullets fired from other brand barrels are not identifiable. The result relies on the striation analysis of *individual* bullets and suggests a relationship between the striation density, the image quality and the possible correlation results.

Discussion

In the previous examples, the edge density d_e by itself is not an important factor for bullet identification. Very similar values are calculated from different images. From the numerical experiment, we preliminarily conclude that d_e is not sensitive to image quality when an edge detector is selected. Conversely, the striation density d_s has a strong sensitivity to different image qualities as described in the foregoing sections. More detailed studies for d_e itself and for its relation to d_s are in process to try to reveal more characteristics of bullet signatures.

Sometimes, the striations are not evenly distributed over an entire image. Calculation of the striation density of an entire image might mistakenly cause the exclusion of an LEA image of sufficient quality. For example, for an image with low striation density d_s, a partial area of it may contain strong striation marks and an effective compressed profile can be extracted from it. Manual selection of the area of interest is a straightforward way to solve this problem, but automatic selection by the software would be a better choice for increased objectivity. Figure 8 shows such an example. Figure 8(*a*) is a grayscale image after preliminary image processing. Figure 8(*b*) represents its corresponding striation edge image. The striation density d_s calculated directly from the edge image is 4.08%. If the bottom rectangular area, which does not contain any striation element, is excluded, this value increases slightly to $d_s = 4.18\%$. Further, the useful area can be more strictly selected. Figure 8(*c*) plots the accumulative sum of edge elements of each horizontal section, with the abscissa indicating the accumulative sum of edge elements versus the ordinate indicating the y-direction pixel index. It can be clearly seen that the striation

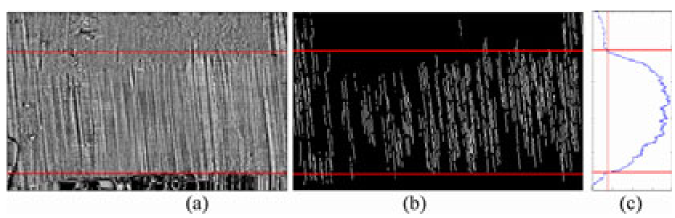

FIG. 8—*Select dense area of striation to recalculate the striation density* d_s*.*

elements are concentrated at the central part of the edge image. A vertical line further partitions the curve at abscissa values equal to 20% of the maximum sum. Calculating the striation density only from the area lying between the two horizontal lines yields an increased value for $d_s = 5.59\%$.

Distinguishing connection units through a morphological operation makes the analysis of the statistical and individual characteristics of these units possible. All such units after filtering are assumed to be the contours of striation marks in the foregoing section. But we might go beyond this assumption and develop a stricter set of striation selection criteria. Through first-order least-squares fitting, the tilt angle and straightness degree of each striation can be obtained by calculating the slope and the residuals of the fitting line. Thus, we can further decide whether every single striation candidate is reasonable and acceptable by checking whether the tilt angle or straightness degree is within our expectation. However, this is accompanied by an increase in the processing time, and an overly strict selection of striations may also cause a loss of useful information and lead to inaccurate compression of 2D profile data.

Summary and Future Work

Based on edge detection, an objective criterion, known as the striation density d_s, is proposed for determining the bullet identifiability. The relationship between the striation density and the identifiability of fired bullets is verified using identification results obtained with an automated system. However, we believe that the concept can be extended to assess identifiability as well for experts using manual microscope systems. In addition, other derived parameters, such as depth, average length, straightness, or distribution of striations, may also be considered for quantifying the quality of striations.

The concept of striation density is described in this article, but the determination of the threshold for considering striation data to be identifiable will require further research on issues, such as standardization of processing steps and experimental statistical analysis, which in turn will require considerable observation, experimentation and participation by experts.

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