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3D topography measurements on correlation cells—a new approach to forensic ballistics identifications

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Abstract

Based on three-dimensional (3D) topography measurements on correlation cells, the National Institute of Standards and Technology (NIST) has developed the 'NIST Ballistics Identification System (NBIS)' aimed at accurate ballistics identifications and fast ballistics evidence searches. The 3D topographies are divided into arrays of correlation cells to identify 'valid correlation areas' and eliminate 'invalid correlation areas' from the matching and identification procedure. A 'congruent matching cells' (CMC)' method using three types of identification parameters of the paired correlation cells (cross correlation function maximum CCF_{max}, spatial registration position in x–y and registration angle θ) is used for high accuracy ballistics identifications. 'Synchronous processing' is proposed for correlating multiple cell pairs at the same time to increase the correlation speed. The proposed NBIS can be used for correlations of both geometrical topographies and optical intensity images. All the correlation parameters and algorithms are in the public domain and subject to open tests. An error rate reporting procedure has been developed that can greatly add to the scientific support for the firearm and toolmark identification specialty, and give confidence to the trier of fact in court proceedings. The NBIS is engineered to employ transparent identification parameters and criteria, statistical models and correlation algorithms. In this way, interoperability between different ballistics identification systems can be more easily achieved. This interoperability will make the NBIS suitable for ballistics identifications and evidence searches with large national databases, such as the National Integrated Ballistic Information Network in the United States.

Keywords: forensics, ballistic identification, topography measurement, correlation cells, congruent matching cells

(Some figures may appear in colour only in the online journal)

1. Introduction

Ballistics identifications are based on the uniqueness of the 'ballistics signature' [1], which is a special kind of toolmark left by gun parts on the surfaces of fired bullets or ejected cartridge cases during the firing process. Striation signatures on a bullet are caused by its passage through the gun barrel. Impression signatures on a cartridge case are caused by impact with the firing pin, breech face and ejector. Both the striation and impression signatures are unique to the firearm. By analyzing these ballistics signatures, firearm examiners can connect a firearm to criminal acts [1].

Side-by-side image comparisons using optical microscopes for ballistic identifications have more than a hundred year history [1]. Since the late 1980s, different automated ballistics identification systems have been developed. These systems typically include a digitized optical microscope, a signature analysis station and correlation

software. Most of these systems are primarily based on comparisons of optical images acquired by microscopes under different lighting conditions. The correlation accuracy depends on image quality, which is largely affected by lighting conditions such as the type of light source, lighting direction, intensity, material color and reflectivity, and image contrast [2]. Accurate identification also depends on the capability of the correlation software to identify the 'valid correlation areas' and to eliminate 'invalid correlation areas' from correlation. Currently, the final determination of a match (identification) or non-match (exclusion) is based on visual comparisons made by an examiner having the experience required to exclude invalid correlation areas.

In 2012, the NIST Ballistics Identification System (NBIS) was developed based on three-dimensional (3D) topography measurements on correlation cells [3]. The NBIS aims to provide objective, high-accuracy and high-speed ballistics identifications and evidence searches using open correlation metrics and algorithms with system interoperability and error rate reports. The congruent matching cells' (CMC) method was proposed for ballistics identifications [3, 4]. Initial tests have shown superior correlation accuracy by combining use of 3D topography measurements of the surfaces and the CMC method [5]. In this paper, basic concepts for correlation cells are introduced in section 2; the CMC method is discussed in section 3. Initial correlation results and error rate estimation are described in sections 4 and 5.

2. Basic concept

2.1. Valid and invalid correlation areas

When bullets and cartridge cases are fired or ejected from a firearm, the parts of the firearm that make forcible contact with them create characteristic topographies (toolmarks) on their surfaces called 'ballistics signatures' [1]. The 'valid' correlation area on the bullet or cartridge case has good contact with the gun-parts, and contains 'individual characteristics' [1] left by firearm's microsurface topography that can be used effectively for ballistics identification. The 'invalid' correlation area has poor contact with the gun-parts, and does not contain individual characteristics of the firearm's ballistics signature. The invalid area should be eliminated from any analysis leading to ballistics identification.

Figure 1 demonstrates a correlation of two surface topography samples A and B originating from the same firearm. The valid correlation area of each sample is represented by the superscript (+) and the invalid correlation area is represented by (−). In figure 1, the union symbol '∪' is used to represent the union of two surface areas and the intersection symbol '∩' is used to represent the overlapped areas of the two surfaces. Each of the surface topographies, A and B, contains both valid and invalid correlation areas (figure 1(*a*)):

$$\begin{aligned} \mathrm{A} &= \mathrm{A}^{+} \cup \mathrm{A}^{-}, \\ \mathrm{B} &= \mathrm{B}^{+} \cup \mathrm{B}^{-}. \end{aligned} \tag{1}$$

For a pair-correlated topography [A ∩ B] (figure 1(*b*)),

$$[\mathrm{A} \cap \mathrm{B}] = [\mathrm{A}^{+} \cap \mathrm{B}^{+}] \cup [(\mathrm{A}^{+} \cap \mathrm{B}^{-}) \cup (\mathrm{A}^{-} \cap \mathrm{B}^{+}) \times \cup (\mathrm{A}^{-} \cap \mathrm{B}^{-})], \tag{2}$$

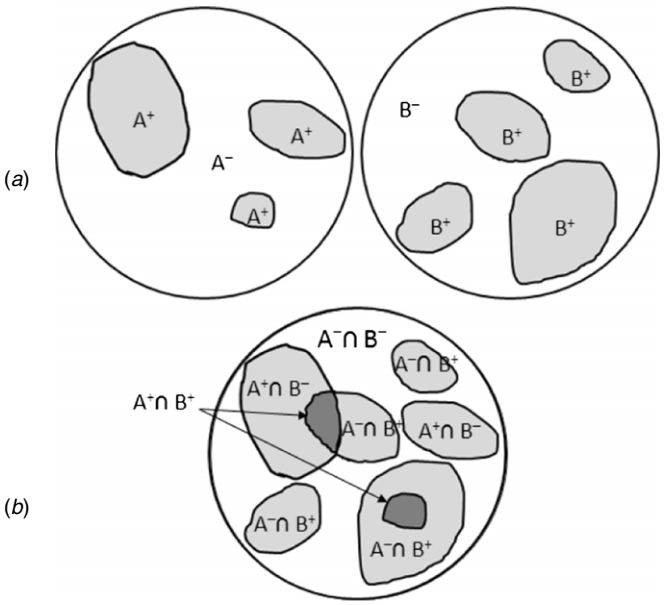

Figure 1. (*a*) The valid correlation areas (A^+ and B^+) and invalid correlation areas (A^- and B^-) for individual topographies A and B are shown. (*b*) The common valid correlation areas $[A^+ \cap B^+]$ and invalid correlation areas $[(A^+ \cap B^-) \cup (A^- \cap B^+) \cup (A^- \cap B^-)]$ for a pair-correlated topography [A ∩ B] are shown.

where $[A^+ \cap B^+]$ represents the common valid correlation area and $[(A^+ \cap B^-) \cup (A^- \cap B^+) \cup (A^- \cap B^-)]$ represents the common invalid correlation area.

2.2. Correlation cells

The correlation cell is designed for accurate ballistic identifications of 3D topography signatures. A correlation cell is a basic correlation unit with (1) a 'sufficiently small' size so that a mosaic of cells can effectively represent the valid correlation area and can separate it from the invalid correlation area; and (2) a 'sufficiently large' size so as to contain a significant number of peaks and valleys for accurate topography correlations. Both are important for effective and accurate ballistic identifications. By using correlation cells, the valid correlation area can be identified and the invalid correlation area can be eliminated from correlation. Thus, the correlation accuracy can be increased.

Figure 2(*a*) shows a pair-correlated topography [A ∩ B] including both valid correlation areas $[A^+ \cap B^+]$ (as shown by two inside encircled areas) and an invalid correlation area $[(A^+ \cap B^-) \cup (A^- \cap B^+) \cup (A^- \cap B^-)]$ (as shown by the remaining area). If the correlation is conducted over the whole area, then a topography correlation metric, such as the cross correlation function maximum CCF_{max} [6], has a relatively low value, because of the large invalid correlation area involved in correlation (see figure 2(*a*)). If the correlation area is divided into correlation cells, then the cell correlations can be used for identifying the valid correlation areas (see shadowed areas in figure 2(*b*)) and eliminating the invalid correlation area, thus increasing correlation accuracy. If the cell size can be further reduced to a small area that still contains sufficient topography information for ballistics identification (see shadowed areas

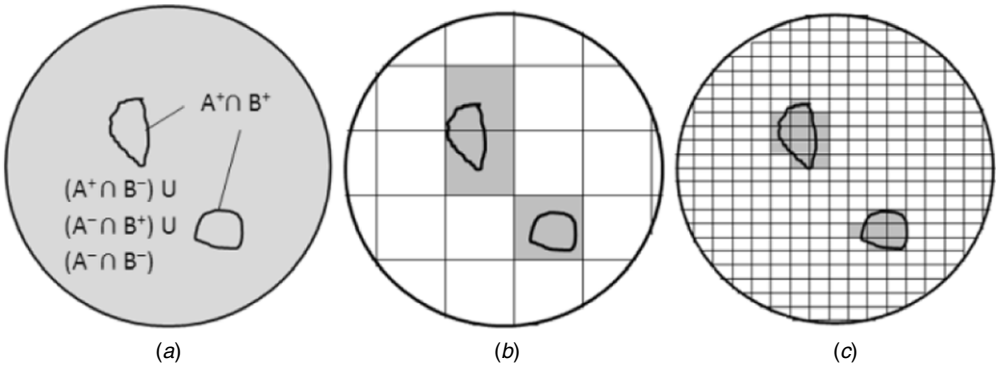

Figure 2. (*a*) A pair of topographies [A ∩ B] correlated over the whole area including both the valid and the invalid correlation areas is shown. (*b*) It is shown that the use of correlation cells can eliminate part of the invalid correlation area and increase correlation accuracy. (*c*) It is shown that the use of smaller correlation cells can further reduce the invalid correlation area and increase correlation accuracy.

in figure 2(*c*)), then the correlation accuracy can be further increased.

2.3. Cell size

The cell size must be experimentally optimized, not too small and not too large. Either condition may result in low correlation accuracy. For the initial tests of 9 mm caliber cartridge cases, good correlation results for breech face correlations were obtained using the cell sizes ranging from (0.25 × 0.25) to (0.5 × 0.5) mm^2 [5].

3. Congruent matching cells' method

3.1. Congruent matching cell pairs

If cell pairs from topographies A and B, originating from the same firearm, are registered at their maximum correlation position, then the cell pairs located in the common valid correlation area ($A^+ \cap B^+$, see figure 3, solid cells) are characterized by the following.

(1) High correlation values represented by the cross correlation function maximum CCF_{max}.
(2) Similar registration angles θ for the correlated cell pairs in topographies A and B.
(3) Similar *x*–*y* spatial distribution pattern between cell arrays a_{ij} and b_{ij}, which are characterized by the 'congruent' *x*–*y* spatial registration positions of a_{ij} and b_{ij}.

On the other hand, if the registered cell pairs come from invalid correlation areas of A and B originating from the same firearm (see figure 3, dotted cells), or if they come from different firearms, then their correlation value CCF_{max} will be relatively low, and their cell arrays a_{ij} and b_{ij} will show significant difference in *x*–*y* distribution patterns and registration angles θ.

3.2. Three identification parameters and thresholds

CMC pairs are identified by three types of identification parameters: the correlation value CCF_{max}, registration angle θ and translation distances *x*, *y* with thresholds T_{CCF}, T_θ and T_x, T_y, respectively. The correlated cell pairs are considered as CMCs when their correlation value $CCF_{max} \geqslant T_{CCF}$, and their registration angle θ and *x*–*y* registration pattern are within the thresholds T_θ, and T_x, T_y.

3.3. The contiguous matching cells' method and the numerical identification criterion CMC ⩾6

If the correlated cell pairs a_{ij} and b_{ij} are located in the common valid correlation area $\left(A^+ \cap B^+\right)$, then all the identification parameters CCF_{max}, θ and *x*, *y* will typically show 'positive' results (see figure 3). These correlated cell pairs are considered as CMC pairs or CMCs. Based on the numerical identification criterion of the consecutively matching striae (CMS) method developed by Biasotti and Murdock for the identification of the bullet striation signatures [7], the numerical identification criterion for the CMC method is suggested as CMC ⩾ 6, i.e., when the number of CMCs of the correlated topographies A and B is equal to or more than 6, A and B are concluded as a 'Match' or 'identification'.

3.4. Specifying the thresholds T_{CCF}, T_θ and T_x, T_y for ballistics identifications using the CMC method

Before using the CMC method for ballistics identifications, it is necessary to specify the values of the thresholds T_{CCF}, T_θ and T_x, T_y. These threshold values are experimentally determined [5]. In the validation tests described in section 4, $T_{CCF} = 60\%$ is set near the intersection of the cell pair CCF_{max} distributions for the known-matching (KM) and known-non-matching (KNM) topographies. The thresholds of T_θ and T_x, T_y are each approximately three times the standard deviation (3σ) of the θ- and *x*-, *y*-distribution data of the correlation cell pairs for KM topographies, after successively removing highly erroneous values that lie outside the 3σ range. As a result, the thresholds of T_θ and T_x, T_y used for identifications shown in section 4 are $T_\theta = 6^\circ$ and $T_x = T_y = 0.125$ mm (equal to 20 pixels or about 27% of the cell dimension).

4. Validation tests

4.1. Test samples and instrument

As an initial validation test for the CMC method and the numerical identification criterion CMC ⩾ 6, correlation

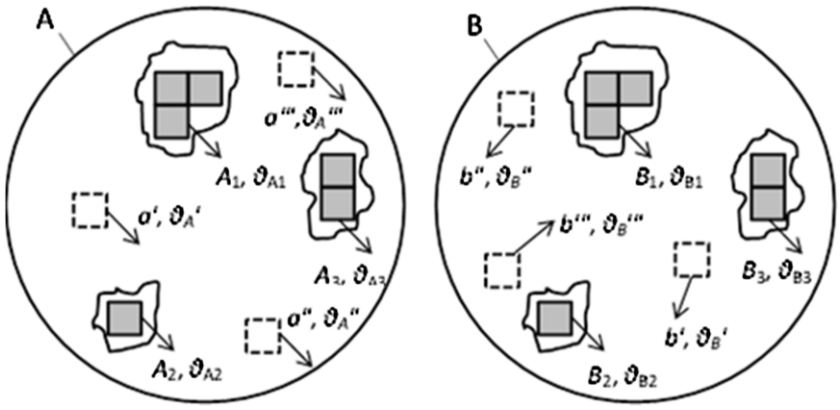

Figure 3. Topographies A and B originating from the same firearm show three sets of correlation cells A_1, A_2, A_3 and B_1, B_2, B_3 located in three valid correlation areas $[A^+ \cap B^+]$ (three inside encircled areas). The other cell pairs a', a'', a''' ... and b', b'', b''' ... are located in the invalid correlation area $[(A^+ \cap B^-) \cup (A^- \cap B^+) \cup (A^- \cap B^-)]$ (the remaining area). Correlation cells in topography A are used as reference cells for correlation with topography B.

experiments were conducted on a set of breech face impressions originating from a study initiated by the Miami Dade Crime Laboratory using consecutively manufactured pistol slides [8]. Ballistics correlations using consecutively manufactured gun parts represent the most challenging scenario for testing the capability to identify cartridge cases or bullets fired from the same firearm. Forty cartridge cases fired from handguns with ten consecutively manufactured pistol slides were correlated. As a result, a total of 780 correlations were performed without repetition, consisting of 63 KM and 717 KNM correlations.

The 3D topographies of the breech face impressions were measured using a commercial confocal microscope. All topography measurements were performed in a temperature controlled laboratory of 20° ± 0.1 °C. Owing to the dimensions of the breech face impression area and the selected 10 × magnification, one field of view was unable to cover the entire breech face impression. Instead, a 3 × 3 matrix of images was captured and mathematically stitched together. The resulting correlation area is about (3.8 × 3.8) mm^2 with a decimated pixel spacing of 6.25 μm.

We studied whether the image stitching could cause significant image distortion, which in turn could affect the correlation accuracy. From our previous measurements and correlations of the breech face images of 137 units of NIST Standard Reference Material (SRM) 2461 Standard Cartridge Cases using the same instrument, stitching pattern and method of analysis, we found that their CCF_{max} values were higher than 94.3% with a confidence of 95%, when correlated with a breech face image of the master sample. We concluded that stitching does not cause significant degradation or variation in the correlation accuracy of the Miami Dade breech face surfaces. Detailed measurement and correlation results can be found in [9].

4.2. Image pre-processing

Besides individual characteristics that can be effectively used for ballistics identifications, the topography measurement data of the breech face images also include components of surface form, waviness, noise, outliers or other unreliable components for ballistics identification. Image pre-processing must be performed to remove or attenuate these components. In this study, the following image processing procedures are performed.

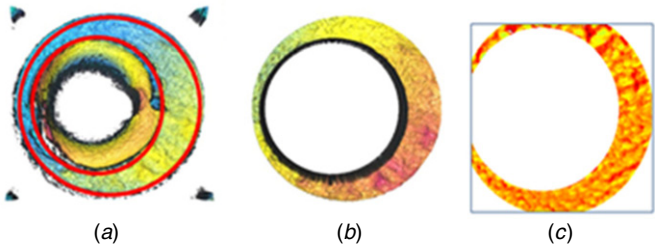

Figure 4. (*a*) Raw measurement data for a breech face impression are demonstrated. (*b*) and (*c*) The trimmed surface and image after the Gaussian filter are demonstrated.

(1) Trim off the inside firing pin surface and other areas outside the breech face mark, so that only breech face impression data remain for correlation (figures 4(*a*) and (*b*)).
(2) Identify and remove dropouts and outliers.
(3) Apply a band-pass Gaussian regression filter with 40 μm short cutoff length and 400 μm long cutoff length to remove low frequency components, including surface curvature, form error, waviness and high frequency components which mainly arise from the instrument noise. Figure 4 demonstrates a schematic for image processing of such a 3D casing topography.
(4) If desired, decimate the image data to speed up the correlation process.

4.3. Ballistics correlation using the CMC method

A scheme for dividing the topography data into correlation cells is shown in figure 5. For a pair of correlated topographies A and B, A (left) is the reference and B (right) is the correlated topography. Sample A is divided into a cell array for correlations. In this experiment, the cell size is set at (0.47 × 0.47) mm^2. The resulting number of cells may be

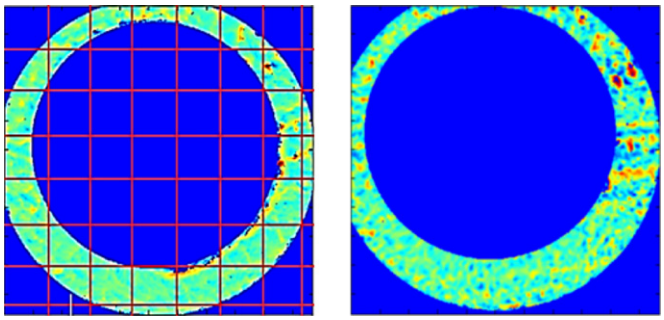

Figure 5. The reference image A (left) and the correlated image B (right) are correlated using the CMC method.

either (7 × 7) or (6 × 6) depending on the actual size of the correlation areas. The actual number of cells N in correlation is less than the nominal cell number, because some cells contain insufficient or no data (see figure 5, left). The correlated topography B is rotated in a range of $\pm 30^\circ$ with 3° increment. At each rotated position, each correlation cell in the reference topography A scans the whole area of the correlated topography B to find the position with the maximum correlation value CCF_{max} and the corresponding registration angle and translation distances. Once the procedure is completed, the similarity metric including the CCF_{max} value, the registration angle θ and the translation distances in x and y are recorded.

The qualifications of CMCs require not only high correlation values $CCF_{max} \geqslant T_{CCF}$, but also similar registration angles θ (within the threshold T_θ) and similar x–y registration pattern (within the thresholds T_x, T_y). As a result, a single CMC pair, i.e., CMC = 1 is not possible. Because the CMCs are defined as cell pairs with similar registration pattern, without another cell pair as reference, one cell pair cannot be considered as a CMC. In order to fit in a smooth distribution curve without a gap at CMC = 1, an alternative CMC computation approach is developed. It uses a virtual reference with three reference registration parameters θ_{ref}, x_{ref} and y_{ref} generated by the median values of the collective θ, and x-, y-translation values of all cell pairs in each correlation sequence. As a result, CMC = 1 for KNM distributions can be included in the distribution.

4.4. Correlation results

One of the correlation results obtained for the studied samples is shown in figure 6. All the 63 KM and the 717 KNM topography pairs are correctly classified as matching or non-matching with a wide separation between the groups. The CMC number for 717 KNM correlations ranges from 0 to 2. The CMC number for 63 KM correlations ranges from 7 to 29. The results indicate no false identification (false positive error) or false exclusion (false negative error) for an identification criterion CMC $\geqslant$ 6. These correlation results support both the CMC method and the proposed numerical identification criterion CMC $\geqslant$ 6 for ballistics identifications.

More experimental correlations have shown that the correlation results using the CMC method depend on the selection of the cell size (or the number of cells N),

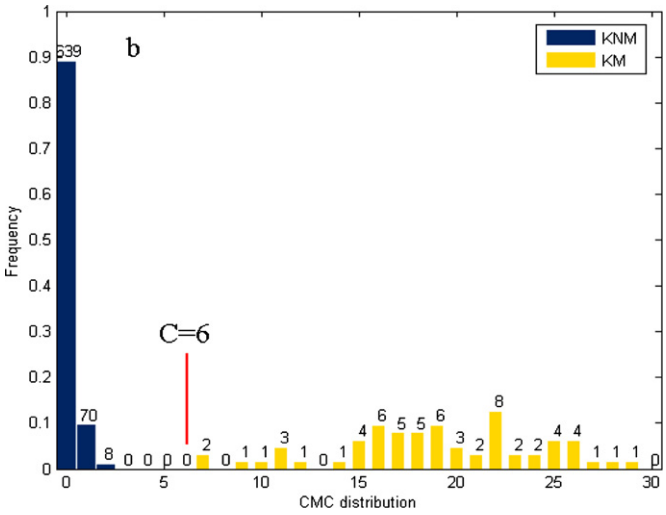

Figure 6. CMC distributions calculated using the virtual reference. The CMC number for 717 KNM correlations ranges from 0 to 2. The CMC number for 63 KM correlations ranges from 7 to 29.

and the thresholds T_{CCF}, T_θ and T_x, T_y. Correlation results also show that there are wide ranges for these parameters that do not cause an overlap between the KM and KNM distributions. By selecting a smaller cell size and optimizing the correlation parameters, the correlation accuracy could be further increased.

5. Error rate report

Based on the 3D topography measurements on correlation cells and the proposed CMC method, a procedure to estimate and report identification error rates was developed [4] that can greatly add to the scientific support for the firearm and toolmark identification specialty, and give confidence to the trier of fact in court proceedings.

For ballistic identifications using the CMC method, false positive errors (false identifications) would occur when topographies originating from different firearms (KNM) are mistakenly classified as match, i.e., have at least six CMC pairs (or CMC $\geqslant C = 6$). On the other hand, false negative errors (false exclusions) would occur when topographies originating from the same firearm (KM) are mistakenly classified as a non-match, i.e. do not have enough CMCs showing positive results (or CMC $< C = 6$).

The proposed CMC method provides an approach to estimate and report the respective error rates. Theoretically, both the false positive and false negative error rates, E_1 and E_2, can be calculated from the actual number of cells N in a correlation, the threshold value for the required number of CMCs and the combined false positive and false negative identification probabilities, P_1 and P_2, of a correlated cell pair to be classified as a CMC. The probabilities P_1 and P_2 are a combination of the individual false positive and false negative identification probabilities caused by the three types of identification parameters CCF_{max}, θ and x–y. Detailed information on this approach to error rate calculation can be found in [4].

6. Conclusion and future work

Based on 3D topography measurements and correlation cells, the 'NIST Ballistics Identification System' is developed for accurate ballistics identifications and fast ballistics evidence searches. A 'congruent matching cells' (CMC)' method using three types of cell identification parameters (cross correlation function maximum CCF_{max}, spatial registration position in x–y and registration angle θ) is proposed for high-accuracy ballistics identifications.

Correlation tests using 40 cartridge cases fired with 10 consecutively manufactured pistol slides strongly support the CMC method and the proposed numerical identification criterion (CMC $\geqslant 6$) for ballistics identifications. Test results using different cell sizes and thresholds also show a significant separation between the KM and KNM distributions without any false positive or false negative error. The identification accuracy can be further improved by optimization of the cell size, cell registration and threshold values.

We are currently working on optimizing the various parameters and algorithms for the CMC method. We are also evaluating the method for a wider range of ballistics samples, including optical intensity images for the same set of cartridge cases. We plan to conduct validation tests using different sample sets, and conduct correlations on firing pin and ejector mark signatures using the CMC method. We plan to develop a correlation program using the 'synchronous processing' for the multiple correlation cell pairs to increase the correlation speed. A key research area is the development of reliable error rate estimates or confidence intervals for correlation results obtained using the CMC method.

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