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 toward accurate ballistic identifications and fast ballistics evidence searches. The 3D topographies are subdivided into arrays of correlation cells in order to identify the "valid correlation areas" and eliminate the "invalid correlation areas" from the matching and identification procedure. "Synchronous processing" is proposed for correlating multiple cell pairs at the same time to increase correlation speed. A "Congruent Matching Cells (CMC)" method using three identification parameters of the paired correlation cells (cross correlation function maximum CCF_{max}, spatial registration position in x-y and registration angle θ) is proposed for high accuracy ballistics identifications. 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 will be engineered to employ publicly available software and database file protocols, and provide published search algorithms and statistical models. 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 (NIBIN) in the United States.*

1. Introduction

Ballistics identifications are based on the uniqueness of the "ballistics signature" [1], which is a special kind of toolmarks left by the gun parts on the surface of the 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 which 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 area" and to eliminate the "invalid correlation area" from correlation [2].

In 2012, the NIST Ballistics Identification System (NBIS) was developed based on 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 correlations parameters and algorithms with system interoperability and error rate reports. The Congruent Matching Cells (CMC) method was proposed for ballistics identifications [4]. Initial tests have shown superior correlation accuracy by combining use of the 3D topography measurements on correlation cells and the CMC method [5]. In this paper, basic concepts for correlation cells are introduced in Section 2; the Congruent Matching Cells (CMC) method is discussed in Sections 3. The initial correlation results and error rate report are described in Sections 4 and 5.

2. Basic Concept

2.1 Valid and invalid correlation area

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] of the firearm's surface topography signature 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 surface signature, which should be eliminated from ballistics identification.

Figure 1 demonstrates a correlation of two surface topographies A and B originating from the same firearm. The valid correlation area is represented by the superscript (+), the invalid correlation area is represented by (–). In Fig. 1, the union symbol "∪" is used to represent the union of two sets of images; the intersection symbol "∩" is used to represent the intersection (or overlap) of two sets of images. For the individual topography A and B, each contains both the valid and invalid correlation areas (Fig. 1a):

$$A = A^{+} \cup A^{-},$$
$$B = B^{+} \cup B^{-}. \quad (1)$$

For a pair-correlated topography [A ∩ B] (Fig. 1b):

$$[A \cap B] = [A^{+} \cap B^{+}] \cup [(A^{+} \cap B^{-}) \cup (A^{-} \cap B^{+}) \cup (A^{-} \cap B^{-})] \quad (2)$$

where $[A^{+} \cap B^{+}]$ represents the combined valid correlation area, $[(A^{+} \cap B^{-}) \cup (A^{-} \cap B^{+}) \cup (A^{-} \cap B^{-})]$ represents the combined 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 from the invalid correlation area; and 2) a "sufficiently large" cell 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 the 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.

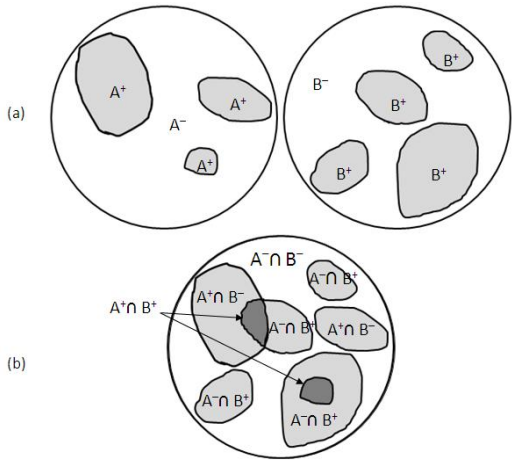


Fig. 1a shows the valid correlation areas (A^{+} and B^{+}) and invalid correlation areas (A^{-} and B^{-}) for individual topographies A and B. Fig. 1b shows the combined valid correlation areas $[A^{+} \cap B^{+}]$ and invalid correlation areas $[(A^{+} \cap B^{-}) \cup (A^{-} \cap B^{+}) \cup (A^{-} \cap B^{-})]$ for a unit with 1) a "sufficiently small" cell size so that a mosaic of cells can effectively represent the valid correlation area and separate it pair-correlated topography [A ∩ B].

Figure 2a shows a pair-correlated topography [A ∩ B] including both valid correlation areas [A ∩ 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 in the whole area, the correlation accuracy represented by the cross correlation function maximum CCF_{max} [6] must be low, because of the large invalid correlation area involved in correlation (see Fig. 2a). If the correlation area can be divided into correlation cells (see shadowed areas in Fig. 2b), the cell correlations can be used for identifying the valid correlation areas and eliminating the invalid correlation area; the correlation accuracy can thus be increased. If the cell size can be further reduced to a "sufficiently small" but still contains "sufficiently large" topography information for ballistics identification (see shadowed areas in Fig. 2c), the correlation accuracy can be further increased.

2.3 Cell size

As stated previously, a correlation cell must be "sufficiently small" for high correlation accuracy; but must be "sufficiently large" to contain enough topography features for accurate ballistics identification. In other words, the cell size must be experimentally optimized, not too small and not too large. Either may result in low correlation accuracy. As a starting point for tests, for the 9 mm caliber cartridge cases, it is suggested that the cell size for breech face correlations be in the range of (0.25 × 0.25) mm^2 to (0.5 × 0.5) mm^2; the cell size for firing pin and ejector mark correlations should be in the range of (0.08 × 0.08) mm^2 to (0.16 mm × 0.16) mm^2 [4].

3. Congruent Matching Cells (CMC) Method

3.1 Congruent matching cell pairs

If topography A and B originated from the same firearm are registered at their maximum correlation position, the registered cell pairs located in their common valid correlation area ($A^{+} \cap B^{+}$, see Fig. 3, solid cells) are characterized by:

(1) The high correlation values represented by the cross corre lation function maximum CCF_{max} [4];

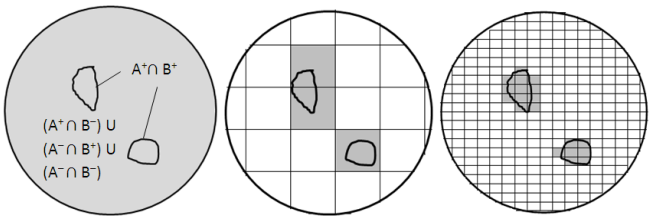


Fig. 2a shows a pair of topographies [A ∩ B] correlated over the whole area including both the valid and the invalid correlation areas. Fig. 2b shows that the use of correlation cells can eliminate part of the invalid correlation area and increase correlation accuracy. Fig. 3c shows the use of smaller correlation cells that can further reduce the invalid correlation area and increase correlation accuracy.

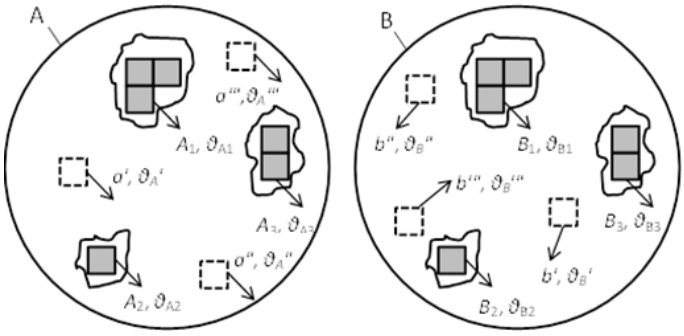


Fig. 3. Assuming A and B originating from the same firearm, there are three sets of correlation cells A_1, A_2, A_3 and B_1, B_2, B_3 located in three valid correlation areas $A^+ \cap B^+$ (as shown by three inside encircled areas). The other cell pairs a', a'', a'''… and b', b'', b'''… are located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

(2) The same registration angles θ for the correlated cell pairs in topography A and B;

(3) The same *x-y* spatial distribution pattern between cell arrays a_{ij} and b_{ij} which are characterized by the "congruent" *x-y* spatial registration positions between the cell arrays a_{ij} and b_{ij}.

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

3.2 Three identification parameters and thresholds

The congruent matching cell pairs are determined by three identification parameters including the correlation value CCF_{max}, registration angles θ, and translation distance *x, y* associated with their thresholds CCF_{low}, T_θ, and T_x, T_y, respectively [3, 4]. The correlated cell pairs are considered as CMCs when their correlation value $CCF_{max} \geq CCF_{low}$, 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 (CMC) method and the numerical identification criterion $C \geq 6$

If the correlated cell pairs a_{ij} and b_{ij} are located in the common valid correlation area ($A^+ \cap B^+$), all the three identification parameters CCF_{max}, θ and *x, y* will show positive results (see Fig. 3). These correlated cell pairs are considered as congruent matching cell pairs or CMCs. Based on the numerical identification criterion of the Consecutively Matching Striae (CMS) method developed by Biasotti and Murdock for identification of the bullet striation signatures [7], the numerical identification criterion for CMC method is suggested as $C \geq 6$ [3, 4], i.e., when the CMC number of the correlated topography A and B is equal to or more than 6, A and B are concluded as a "Match".

3.4 Define the thresholds CCF_{low}, T_θ, and T_x, T_y for ballistics identifications using the CMC method

Before ballistics identifications using CMC method, it is necessary to define the values of the thresholds CCF_{low}, T_θ, and T_x, T_y. These threshold values are experimentally determined [5]. In the validation tests described in Section 4, CCF_{low} = 60% is set near the intersection of the cell pair distributions for the known-matching (KM) and known-non-matching (KNM) topographies [5]. The thresholds of T_θ and T_x, T_y are calculated by approximate three times of the standard deviation (3σ) from the θ- and *x*-, *y*-distribution data of the correlation cell pairs, after successively removing the gross error values that outside of the 3σ range [5]. As a result, the thresholds of T_θ and T_x, T_y used for identifications shown in Section 4 are T_θ = 6°, $T_x = T_y$ = 20 pixels (or 0.125 mm).

3.5 Ballistics identifications and evidence searches using the CMC method

After topography measurements and data pre-processing, ballistics identification and evidence search using the CMC method are conducted by three steps:

(1) ***CCF_{max}* - search:** If both topography A and B are divided into *N* cells for correlations, there are N^2 cell pairs for correlations. For the thousands correlated cell pairs, most of them will show $CCF_{max} < CCF_{low}$, which must be eliminated from continuous analysis.

(2) ***θ* - search:** For the correlated cell pairs with $CCF_{max} \geq CCF_{low}$, if their correlation angles θ are out of range of the threshold T_θ, they will be eliminated.

(3) ***xy* - search:** For the correlated cell pairs with $CCF_{max} \geq CCF_{low}$ and $\theta \leq T_\theta$, if their *x-y* distribution pattern are within the range of the thresholds T_x and T_y, these correlation cell pairs are considered as congruent matching cells (CMCs). If CMC ≥ 6, the correlated topography A and B are considered as "Match" [3, 4].

4. Validation Tests

4.1 Test samples and instrument

As an initial validation test for the CMC method and the numerical identification criterion $C \geq 6$, correlation experiments are conducted by a set of breech face topographies which comes from a study initiated by Miami Dade Crime Laboratory using consecutively manufactured slides [8]. 40 cartridge cases fired from handguns with 10 consecutively manufactured pistol slides are correlated. That includes 20 known cartridge cases (2 per slide) for training and 20 unknown cartridge cases for tests. As a result, a total of 780 correlations are performed without repetition, i.e., B vs. A will not be correlated if A vs. B has already been correlated. That consists of 63 matching and 717 nonmatching correlations. (Note: The correlations for the group of 20 test cartridge cases conducted at NIST are blind to validate the NIST proposed CMC method. The terms "known matchings" and "known non-matchings" are used for statistical analysis after the correlations.)

The 3D topographies of these breech face samples are measured using a commercial confocal microscope. Confocal microscopy allows the acquisition of 3D surface topography in a fast and nondestructive manner. All topography measurements are performed in a temperature controlled laboratory of 20° ± 0.1°C. Owing to the dimensions of the breech face 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 total combined correlation area is about (3.8 × 3.8) mm^2.

4.2 Image pre-preprocessing

Besides individual characteristics which can be effectively used for ballistics identifications, the topography raw data of the breech face also includes components of curvature, form error, waviness, noise, outliers or other unreliable components. Image pre-processing must be performed to remove or attenuate these components. In this study, the following processing procedures are performed:

(1) Trim off the inside firing pin surface and other areas outside of the breech face mark, so that only breech face impression remains for correlation (see Fig. 4).

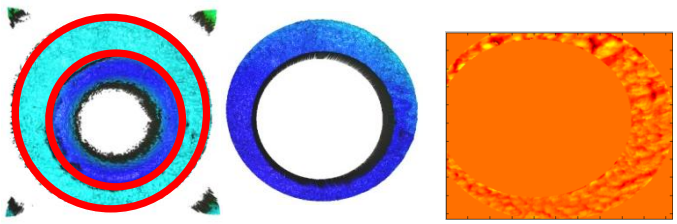
(2) Decimate the image data to speed up the correlation process.

(3) Identify and remove dropouts and outliers, and replace these points with interpolated data.

(4) Apply a band-pass Gaussian filter with 0.25 μm short cutoff length and 250 μm long cutoff length to remove low frequency components including surface curvature, form error, waviness and high frequency components which is mainly the instrument noise. Figure 4 shows a schematic processing of such a 3D casing topography.

4.3 Ballistics correlation using CMC method

A scheme for dividing the topography data into correlation cells is shown in Fig. 5. For a pair of correlated topographies A and B, A (right) is used as the reference and B (left) is the correlated topography which is divided into a cell array for correlations. In this experiment, the cell size is set as 75 pixels by 75 pixels or (0.47 × 0.47) mm^2. The resulted cell numbers may be either (7 × 7) or (6 × 6) depending on the actual size of different correlation areas. The actual cell number involved in the correlation is less than the nominal cell number, because some cells contain only very limited data or even no data points (see Fig. 2, left). The reference topography A is rotated in a range of ±30° with 3° increment. At each rotated position (see Fig. 2, right), each correlation cell in topography B scans the whole area of the reference topography A to find the maximum correlation position. Once the procedure is completed, the similarity metric including the CCF_{max} value, the rotated registration angle θ and the translation distances in x and y are recorded.



(a) (b) (c)

Fig.4a shows an acquired breech face raw data. Fig. 4b shows the trimmed surface and Fig. 4c shows the image after the Gaussian filter.

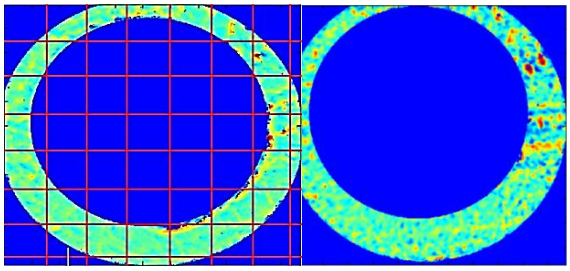


Fig.5 Correlation scheme using the CMC method.

4.4 Correlation results

Correlation tests show that, for the 20 known cartridge cases fired from the 10 slides (two per slide), the KM and KNM distributions are well separated. The maximum CMC number for the 180 KNM correlations is 2, while the minimum CMC number for the 10 KM correlations is 11. There is a gap of 9 CMCs, which indicates no misidentification or missed identification.

By using the same cell size and thresholds for correlation of the entire set of 40 cartridge cases, all the 63 KM and the 717 KNM topography pairs can still be completely identified and show separation. The maximum CMC number for KNM correlations increases from 2 to 4 and the minimum CMC number for KM correlations decreases from 11 to 8, with a gap of 4 CMCs (see Fig. 6). It also indicates no misidentification or missed identification. These correlation results support both the CMC method and the proposed numerical identification criterion $C \geq 6$ for ballistics identifications.

The qualification of CMCs requests not only the high correlation values $CCF_{max} \geq CCF_{low}$, but also the same registration angles θ (within the threshold T_θ) and the same x-y registration pattern (within the thresholds T_x, T_y), As a result, single congruent matching cell pair or 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 CMC. From Fig. 6, it can be seen that besides CMC = 0, the minimum CMC number is CMC = 2 (see Fig. 6).

In order to fit in a smooth distribution without a gap at CMC = 1 for KNM distributions, 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 scheme (see Fig. 7). The maximum

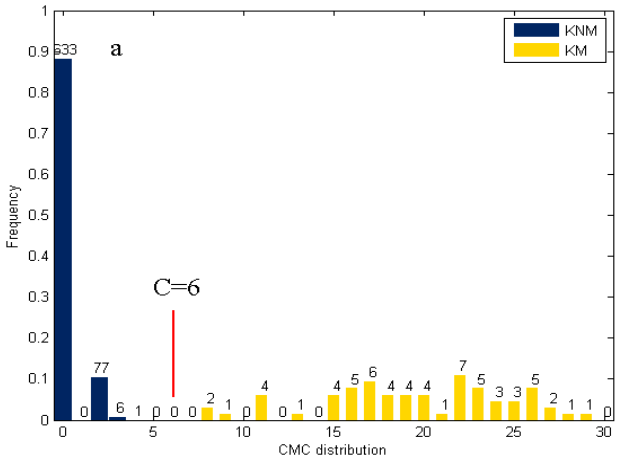


Fig.6. CMC distributions calculated based on CMC definition.

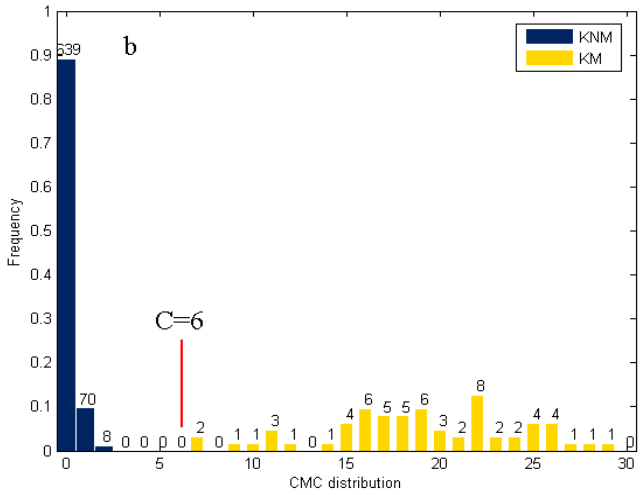


Fig.7. CMC distributions calculated using the virtual reference.

CMC number for the 717 KNM correlations is 2, while the minimum CMC number for the KM correlations is 7.

Experimental correlations have shown that the correlation results using CMC method depend on the selection of the cell size (or the cell number N) and the parameter thresholds CCF_{low}, T_θ, and T_x, T_y. Correlation results also show that there are wide ranges for the selections of cell number N and parameter thresholds CCF_{low}, T_θ, and T_x, T_y without causing an overlap between the KM and KNM distributions, i.e., without causing any false positive and false negative identifications [5].

5. Error Rate Report

Based on the 3D topography measurements on correlation cells and the proposed CMC method, an error rate reporting procedure is 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 the ballistic identifications using the CMC method with three identification parameters CCF_{max}, θ and x-y, the false positive error, or the misidentifications E_1, will happen when the KNM topographies are mistakenly identified as Match by at least six cell pairs showing positive results for all the three identification parameters, or CMC $\geq C = 6$. On the other hand, the false negative error, or the missed identifications E_2, will happen when the KM topographies are mistakenly identified as Non-match because of not enough CMCs showing positive results (CMC $< C - 1 = 5$) [4].

The proposed CMC method using correlation cells provides an approach to developing error rate procedures through theoretical calculations and experimental verifications. Theoretically, both the false positive and false negative error rate E_1 and E_2 can be calculated by the total cell number N, the numerical identification criterion C, and the combined false positive and false negative identification probability, P_1 and P_2, of the CMC method, which is a combination of the individual false positive and false negative identification probabilities caused by the three identification parameters CCF_{max}, θ and x-y. Detailed information for error rate calculation can be found in Ref. [4].

6. Conclusion and Future Work

Based on three dimensional (3D) topography measurements on correlation cells, the "NIST Ballistics Identification System (NBIS)" is developed aimed to accurate ballistic identifications and fast ballistics evidence searches [3]. A "Congruent Matching Cells (CMC)" method using three identification parameters of the paired correlation cells (cross correlation function maximum CCF_{max}, spatial registration position in x-y and registration angle θ) is proposed for high accuracy ballistics identifications [4].

Correlation tests using 40 cartridge cases fired with 10 consecutively manufactured slides strongly support the Congruent Matching Cells (CMC) method and the proposed numerical identification criterion (C $\geq$ 6) for ballistics identifications. Test results using different cell sizes and thresholds show a significant separation between the KM and KNM distributions without any false positive or false negative identification. That represents the highest identification accuracy for the same set of cartridge cases that have been tested at NIST thus far. The identification accuracy can be further improved by optimization of the cell numbers and the thresholds of the correlation parameters [5].

The proposed numerical identification criterion (C $\geq$ 6) for the CMC method is based on the identification criterion for the Consecutively Matching Striae (CMS) method developed by Biasotti and Murdock [7], which has been widely accepted by firearm examination community for bullet signature identifications. The CMC method using the same numerical identification criterion C $\geq$ 6 has expanded the CMS method from 2D bullet signature correlations to 3D casing signature correlations.

The validation tests have demonstrated that by combining use of the three identification parameters (CCF_{max}, θ and x-y) of the correlation cells, the identification accuracy can be significantly improved comparing with the previous correlations that only utilize the topography similarity indicator CCF_{max} [8].

We are currently working on the optimization of the identification parameters for the CMC method. We are continuing the validation tests using 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 correlation cells to increase the correlation speed. We are also working on the error rate report procedure for ballistics identification based on the CMC method.

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