Validation Tests for the Congruent Matching Cells (CMC) Method Using Cartridge Cases Fired with Consecutively Manufactured Pistol Slides

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Keywords: Ballistics identification, cartridge case, congruent matching cells (CMC), correlation cell, identification criteria, topography measurements.

ABSTRACT

The National Institute of Standards and Technology (NIST) is developing the NIST Ballistics Identification System (NBIS) based on three-dimensional (3D) topography measurements and correlations of the paired correlation cells within the correlated topographies[1] to establish ballistics identifications. The Congruent Matching Cells (CMC) method [2] uses three criteria to determine a pair of matching cells. These consist of a threshold for the cross correlation function maximum CCF_{max}, and a consistent pattern for registration angle θ and x-y registration position among matching pairs of cells. The number of congruent matching cell pairs C is determined by the three identification parameters associated with their thresholds [2]. Presently the proposed numerical identification criterion for identification is $C \geq 6$. That is, two surfaces are identified as being fired by the same firearm if they contain at least six matching cell pairs [1, 2]. In order to test the CMC method and to verify the proposed numerical identification criterion, 40 cartridge cases fired from pistols with 10 consecutively manufactured slides are measured by a 3D confocal microscope and correlated by the CMC method. The breech face topographies are divided into cell arrays (7 × 7 or 6 × 6) for correlation. There are a total of 780 correlations comprising 63 known-matching (KM) and 717 known-non-matching (KNM). Initial tests support both the proposed CMC method and the numerical identification criterion $C \geq 6$ for ballistics identifications. Test results show a significant separation between the KM and KNM distributions without any false positive or false negative identification. This represents the highest objective 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 number of cells and the thresholds of the identification parameters, and registration algorithm.

1. Background

Since the late 1980s, different automated ballistics identification systems have been commercially developed. These systems typically include a digitized optical microscope, an analysis station and correlation software. These systems are based on comparisons of optical images acquired by microscopes with possibly 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. Current commercial systems are using proprietary correlation parameters and algorithms to quantify image similarity without objective open tests, which may make it difficult, if not impossible, for laboratory assessments and interoperability among different systems. The lack of error rate determination has been recognized as a shortcoming for the introduction of firearms evidence in some court proceedings of criminal cases [3]. In 2012, the NIST Ballistics Identification System (NBIS) was created based on 3D topography measurements on correlation cells [1, 2]. The concept of correlation cells was based on the observation that correlation accuracy could be improved by having the capability for correlation software to identify "valid correlation areas" and to eliminate "invalid correlation areas" from correlation and scoring. The NBIS aims to provide objective, high-accuracy and high-speed ballistics identifications and evidence searches using open correlation parameters and algorithms with system interoperability and error rate reporting. The Congruent Matching Cells (CMC) method using three identification parameters was proposed for identifying the congruent matching cell pairs *C*. A numerical identification criterion $C \geq 6$ has been suggested for identification of the matching topographies originating from the same firearm [1, 2].

In order to validate the NIST proposed CMC method and the numerical identification criterion *C*, 40 cartridge cases fired from handguns with 10 consecutively manufactured pistol slides are topographically measured and correlated by the CMC method. This sampling plan therefore includes a

Date Received: April 8, 2013
Peer Review Completed: September 3, 2013

total of 780 correlations with 63 known-matching (KM) and 717 known-non-matching (KNM). In this report, basic concepts for correlation cells and the CMC method are briefly introduced in Section 2 (detailed information can be found in Ref. 1 and 2). The test samples and instrument are described in Section 3. The experimental procedure and correlation results are discussed in Section 4, followed by a conclusion and future work in Section 5.

2. Basic Concept

2.1. Valid and invalid correlation area

Bullets and cartridge cases when fired or ejected from guns are marked by characteristic surface topographies from the gun parts, resulting in special toolmarks on their surfaces, called "ballistics signatures". The correlation surfaces of the bullets and cartridge cases include both "valid" and "invalid" correlation areas. A valid correlation area contains individual characteristics [4] of the ballistics signature that can be used effectively for identification. An invalid correlation area does not contain individual characteristics of the firearm's signature and should not be considered for ballistics identification.

Assuming two ballistics topographies A and B are originated from the same firearm; both contain valid and invalid correlation areas A^+, A^- and B^+, B^-, respectively. When A and B are correlated with each other, their combined valid correlation area is the overlapping part of the valid correlation areas A^+ and B^+. That means the combined valid correlation area is only part of the individual valid correlation areas A^+ and B^+ and may only be a very small part of A and B itself. If the correlation is performed on the whole area of A and B, the correlation accuracy must be relatively low; because the large invalid correlation areas are involved in correlation. If instead, the correlation area can be divided into correlation cells for correlation, the valid correlation cell pairs can be identified and the invalid correlation cell pairs can be eliminated from identifications. That will increase correlation accuracy.

2.2. Correlation cells and congruent matching cell pairs

The Correlation Cell is designed for accurate and fast ballistics identifications. A Correlation Cell is a sub-area of the surface topography that contains a sufficiently large amount of topography information for accurate ballistics identification [1, 2].

If topography A and B, originating from the same firearm, are registered at their maximum correlation position, the registered cell pairs located in their common valid correlation area characterized by:

1. High correlation values quantified by the cross correlation function maximum CCF_{max} [5];

2. The same registration angles θ for all 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 originating from the same firearm, 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.

2.3. Three identification parameters and thresholds

The congruent matching cell pairs are determined by three types of identification parameters, the correlation value CCF_{max}, registration angles θ, and translation distance (x, y), and their associated thresholds CCF_{low}, T_θ, and (T_x, T_y), respectively [1, 2]. 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.

2.4. 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 combined valid correlation area, all the three identification parameters CCF_{max}, θ and x, y will show positive results. 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 [6], the numerical identification criterion for the CMC method is suggested as $C \geq 6$ [1, 2], i.e., when the CMC number (C) of the correlated topographies A and B is equal to or more than 6, A and B are concluded as a match.

3. Test Samples and Instrument

As an initial validation test for the CMC method and the numerical identification criterion $C \geq 6$, correlation experiments were conducted with a set of breech face topographies originating from a study by the Miami Dade Crime Laboratory using consecutively manufactured pistol slides [7]. 40 cartridge cases fired from handguns with the 10

Figure 1: An acquired breech face raw data image (left), the trimmed surface (center), and the image after the Gaussian filter (right).

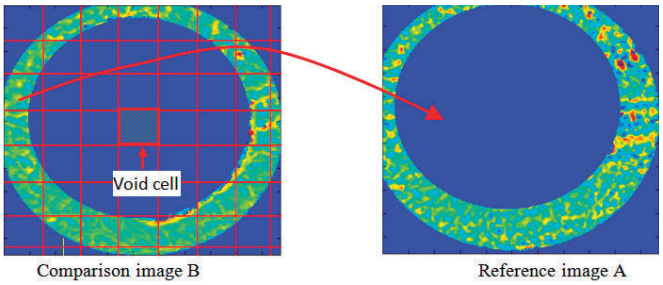

Figure 2: Correlation scheme using the CMC method.

consecutively manufactured slides were correlated with one another. That includes 20 known cartridge cases (2 per slide) for training and 20 unknown cartridge cases for tests [7]. 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.

The 3D topographies of these breech face samples were measured using a commercial disk scanning confocal microscope. Confocal microscopy allows the acquisition of 3D surface topography in a fast and nondestructive manner. All topography measurements were 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.

4. Ballistics Correlations Using the CMC Method

4.1. 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 were performed:

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

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 remove low frequency components including surface curvature, form error, waviness and high frequency components which is mainly the instrument noise. **Figure 1** shows schematically the processing of such a 3D casing topography.

4.2. Ballistics correlation using CMC method

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

4.3. Determination of the CMC numbers

The ten pairs of known matching cartridge cases were correlated first and statistically analyzed. Excluding those cell pairs that do not contain sufficient data points (see Fig 2, left), the correlations were implemented for 279 cell pairs of 10 KM correlations and 4737 cell pairs of 180 KNM correlations (20 × 18/2). The frequency distribution histograms for the 279 KM and 4737 KNM cell pairs are shown in **Figure 3**. **Figure 3a** shows the CCF_{max} distribution for the KM and KNM cell pairs; **Figure 3b** shows the registration angle θ distribution; and **Figure 3c and 3d** show the x-y registration pattern distributions. The data in **Figures 3b, 3c, and 3d**

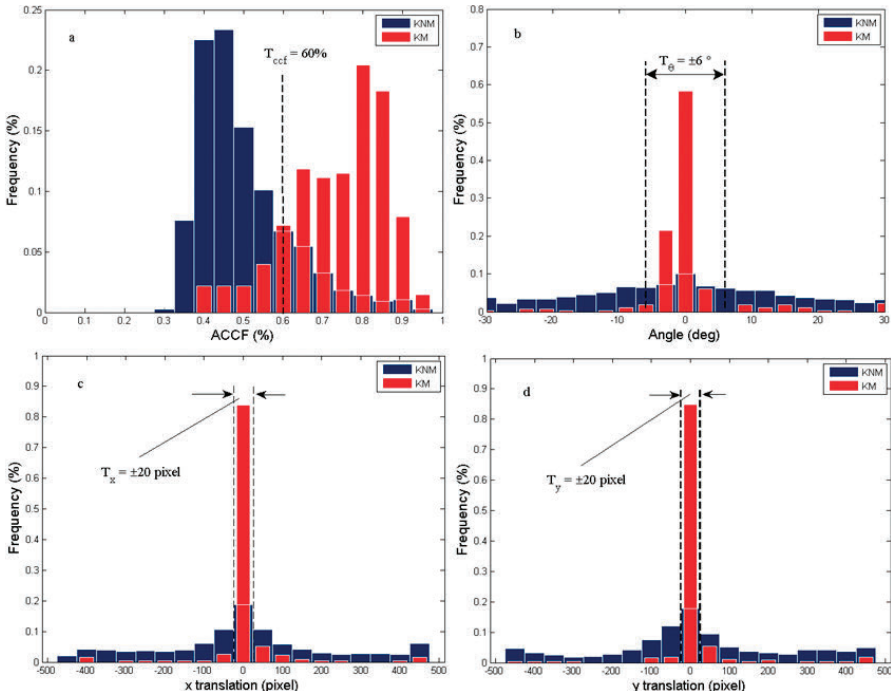

Figure 3: Distribution histogram of KM and KNM cell pairs for CCF_{max} (a), θ (b) and x, y (c and d).

were normalized, that is, the abscissas indicate differences of the individual cell rotation angles and *x*-*y* translations with respect to median registration angles and translations obtained for each pair of compared images.

It can be seen that there are large areas of overlap between the distributions of KM and KNM cell pairs for all the three identification parameters (CCF_{max}, θ and x, y), especially for the CCF_{max} distributions (see **Figure 3a**). That indicates that if a single parameter, such as CCF_{max}, is used for cell correlations and ballistics identifications, it will involve a large error rate for both the false positive (or misidentifications) and the false negative errors (or missed identifications).

However, when the three identification parameters (CCF_{max}, θ and x, y) are combined together to determine the CMC numbers for ballistics identification, the procedure can yield a very high correlation accuracy with very low error rates.

Before arriving at a ballistics identification using the CMC method, it is necessary to specify the values of the thresholds CCF_{low}, T_θ, and T_x, T_y for the determination of the CMC numbers. The correlated cell pairs are considered as CMCs when their correlation values $CCF_{max} \geq CCF_{low}$, and their registration angles θ and translations *x*-*y* are within the thresholds T_θ, and T_x, T_y (see **Figure 3**). In this experiment, CCF_{low} = 60% is set near the intersection of the KM and KNM cell pair distributions (see **Figure 3a**). The thresholds of T_θ, T_x, and T_y are approximately three times the standard deviation (3σ) from the θ- and *x*-, *y*-distribution data after successively removing the gross error values that lie outside of the 3σ range. As a result, the thresholds of T_θ, T_x, and T_y are set as T_θ = 6°, T_x = 20 pixels and T_y = 20 pixels, respectively.

Since the qualification of CMCs requires 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), a single congruent matching cell pair or CMC = 1 is not possible. At least two CMC cell pairs are required to form a pattern. . Without another cell pair as reference, one cell pair cannot be considered as a CMC. As a result, besides CMC = 0, the minimum CMC number must be CMC = 2.

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, the distributions of all the 63 KM and the 717 KNM topography pairs are still widely separated and strongly indicate that the KM pairs

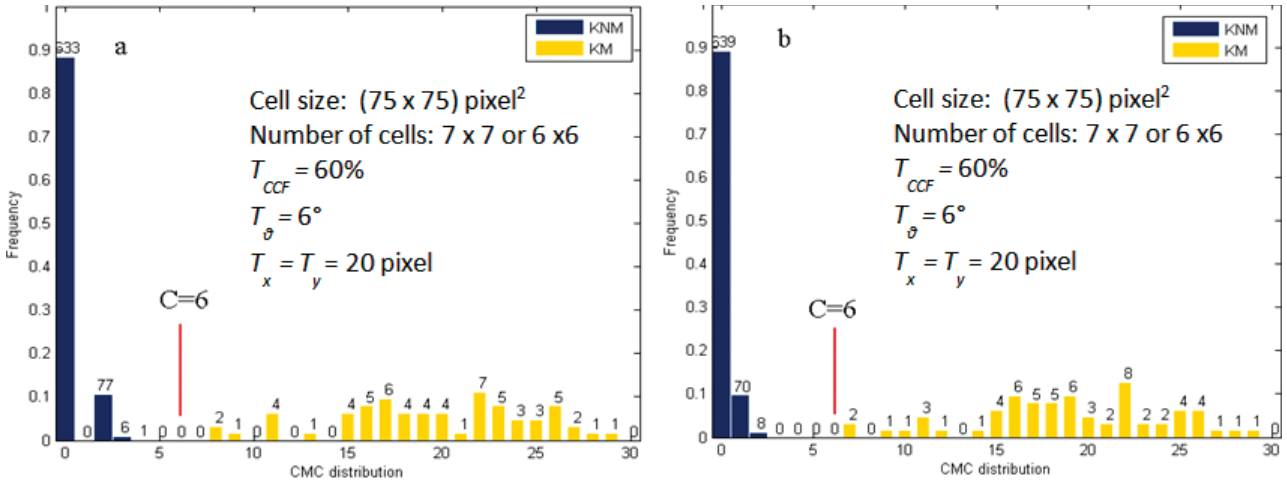

Figure 4: CMC distributions: a) calculated based on CMC definition; b) calculated using the virtual reference.

are identifiable. Although the correlations for the group of 20 test cartridge cases conducted at NIST were blind tests to validate the NIST proposed CMC method, the terms "known matching" and "known non-matching" are used in the subsequent statistical analysis of the results after the correlations were performed. 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, leaving a gap of 4 CMCs between the KMs and KNMs (see **Figure 4a**). The remaining gap still indicates no misidentification or missed identification. These correlation results support the proposed numerical identification criterion $C \geq 6$ for ballistics identifications.

As previously mentioned, there is no correlation result of CMC = 1 shown in the KNM distribution scheme based on the CMC definition (see **Figure 4a**). 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}, which are calculated as the median values of the collective θ, x- and y-translation values of all cell pairs in each correlation sequence. When the pair of full images is correlated, these median values are used as the virtual reference. All the individual θ, x- and y-translation values are compared with the parameters of the virtual reference to see if they are in the thresholds range. As a result, CMC = 1 for KNM distributions can be included in the distribution scheme (see **Figure 4b**). The maximum 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 the CMC method depend on the selection of the cell size (or the number of cell N) and the parameter thresholds CCF_{low}, T_{θ}, and T_x, T_y. Correlation results also

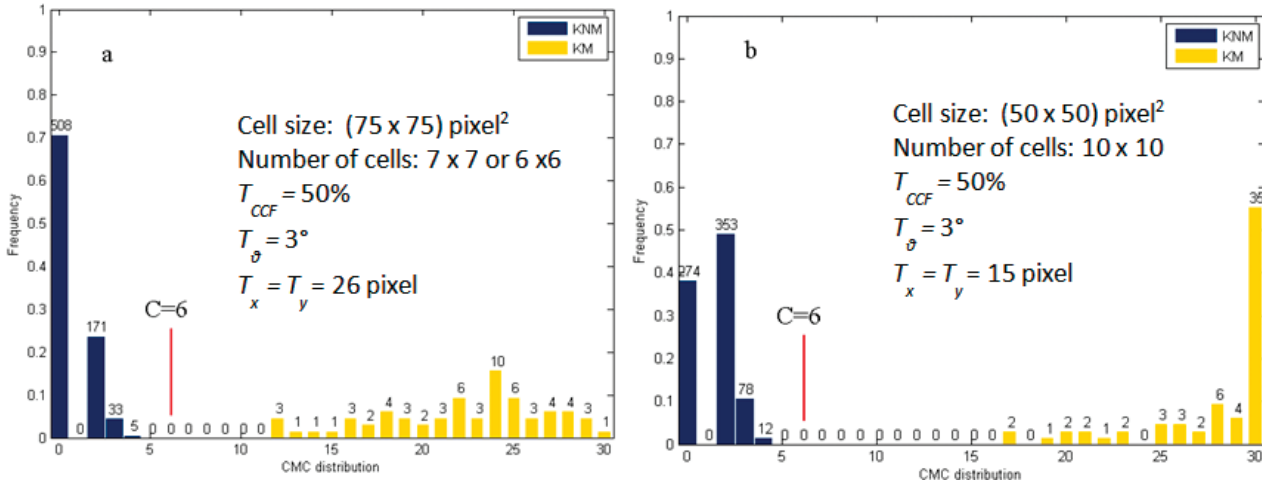

Figure 5: CMC distribution using optimized thresholds.

show that wide ranges of choices of cell number N and the parameter thresholds CCF_{low}, T_θ, and T_x, T_y may be made without generating an overlap between the KM and KNM distributions, i.e., without causing any false positive and false negative identifications. **Figure 5** shows two KM and KNM distributions using the same set of data as **Figure 4** but correlated by different cell sizes and/or thresholds. In **Figure 5a**, the cell size is not changed but the selected thresholds are CCF_{low} = 50% T_θ = 3° and $T_x = T_y$ = 26 pixels. The maximum CMC for the KNM distribution is 4, the minimum CMC for the KM distribution is 12 with a CMC gap of 8, larger than before. In **Figure 5b**, the cell size is changed to (50 × 50) pixels (10 × 10 cells in each single image) and thresholds are selected as CCF_{low} = 50%, T_θ = 3° and $T_x = T_y$ = 15 pixels. The maximum CMC for the KNM distribution is 4, but the minimum CMC for the KM increases to 17 so the CMC gap increases further to 13.

5. Preliminary Conclusions and Future Work

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. These results have higher identification accuracy than we obtained before at NIST for the set of Miami Dade Crime Laboratory cartridge cases [8]. The identification accuracy can be further improved by optimization of the number of cells and the thresholds of the correlation parameters.

The proposed numerical identification criterion, C ≥ 6, for the CMC method is based on the identification criterion of the Consecutively Matching Striae (CMS) method developed by Biasotti and Murdock [6]. The CMC method using the same numerical identification criterion of the CMS method, C ≥ 6, represents an extrapolation from the subjectively-determined CMS criteria for correlation of striated toolmarks to a CMC method for correlation of both the striated signatures of bullets and the impressed signatures of cartridge cases.

The validation tests have demonstrated that by combining the use of the three types of identification parameters (CCF_{max}, θ and x, y) of the correlation cells, the identification accuracy can be significantly improved over our previous correlations that only utilize the overall topography similarity indicator CCF_{max} [8]. We are currently working on the optimization of the identification parameters for the CMC method. We are also applying the CMC method to optical intensity images of the same set of cartridge cases. We plan to conduct validation tests using different sample sets as well, and conduct correlations on firing pin and ejector mark signatures using the CMC method. We plan to develop a correlation program using synchronous processing for the correlation cells to increase the correlation speed. We are also working on an error rate report for ballistics identification based on the CMC method.

Acknowledgement

The funding for this work is provided by NIST's Forensic Measurement Challenge Project (FMC2012). The authors are grateful to A. Zheng for providing experiment data, and to T. Vorburger, R. Thompson, and J. Soons of NIST for their discussion, review and comments.

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