Proposed "NIST Ballistics Identification System (NBIS)" Based on 3D Topography Measurements on Correlation Cells*

By: John Song, Physical Measurement Laboratory, National Institute of Standards andTechnology (NIST), Gaithersburg, MD 20899, U.S.A.

Keywords: Ballistics identification, ballistics evidence search, CMC, correlation cells, contiguous matching cells, NBESE, NBIS, NIBIN, NIST, synchronous processing

ABSTRACT

The National Institute of Standards and Technology (NIST) has proposed a "NIST Ballistics Identification System (NBIS)" to facilitate accurate ballistics identifications and fast evidence searches [1]. The NBIS will use three-dimensional (3D) topography measurements for ballistics identification and evidence searches. The 3D topographies will be subdivided into arrays of correlation cells in order to help identify "valid correlation areas" and eliminate "invalid correlation areas" from the matching and identification procedure. "Synchronous processing" is proposed for correlating dozens or even hundreds of cell pairs at the same time. Based on the concept of correlation cells, a "Contiguous Matching Cells (CMC)" method using three identification parameters of the paired correlation cells (cross correlation function maximum CCFmax, spatial registration position in x-y and registration angle θ) is proposed for high accuracy ballistics identifications. Based on the proposed CMC method, a "National Ballistics Evidence Search Engine (NBESE)" is also proposed for fast and accurate ballistics evidence searches.

The proposed NBIS and NBESE can be used for correlations of both geometrical topographies and optical intensity images, and can be potentially applied for all case scenarios of fired bullets, cartridge cases and toolmarks. All the parameters and algorithms will be in the public domain and subject to open tests. An error rate reporting procedure will be 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. Both the NBIS and NBESE 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 using this invention can be more easily achieved. This interoperability will make the NBIS and NBESE suitable for ballistics identifications and evidence searches with large national databases, such as those of the National Integrated Ballistic Information Network (NIBIN) in the United States, as well as national databases in the European Network of Forensic Science Institutes (ENFSI).

**** This paper is based on a NIST provisional patent entitled "An Automated Ballistics Identification System Based on 3D Topography Measurements on Correlation Cells", Application No. 61610029, filled on March 13, 2012. This paper was presented on June 27, 2012 at the 2012 AFTE Annual Training Seminar in Buffalo, NY.***

1 Introduction

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" [2]. By analyzing these signatures, firearm examiners can potentially link questioned bullets and cartridge cases to the firearm used in a crime. Current automated ballistics identification systems are primarily based on image comparisons using optical microscopy. The correlation accuracy of these systems depends on image quality, which is largely affected by lighting conditions [3]. Because ballistics signatures are geometrical micro-topographies by nature, systems for direct measurement and correlation of surface topography have been researched and developed for ballistics identification [4-6].

NIST has developed Standard Reference Material (SRM) bullets and cartridge cases [7] which are being used in crime laboratories as reference standards in the United States and internationally. NIST has also developed a 2D/3D ballistics signature acquisition and correlation system [7] for the certification measurements of the SRM bullets and cartridge cases to ensure the similarity of their ballistics

Date Received: August 6, 2012
Peer Review Completed: February 21, 2013

topography signatures, as well as for designed experiments in ballistics identifications. This system has produced matching accuracies for cartridge cases and bullets higher than those of a commercial system in all experiments thus far [8, 9].

The NIST invention described here provides a further significant advancement that aims to do the following: (1) To develop an accurate and robust NIST Ballistics Identification System (NBIS) and a National Ballistic Evidence Search Engine (NBESE), both to be ultimately available to the firearm and toolmark examiner community, research interests, and commercialization; (2) To develop the "Contiguous Matching Cells" (CMC) method [1] as a common identification method for fast and accurate 3D ballistics and toolmark identifications; and (3) To use the proposed CMC method for accurate and fast ballistics evidence searches with large databases.

2 Basic Concepts

2.1 Valid and invalid correlation area

Figure 1 shows the striation signature on a bullet (left) and the breech face impression signature on a cartridge case (right). Both contain valid and invalid correlation areas. The valid correlation area is where the individual characteristics [2] of the ballistics signature are found that can be used effectively for ballistics identification. The invalid correlation area does not contain individual characteristics of the ballistics signatures and should be eliminated from consideration for ballistics identification purposes. In **Figure 1**, the outlined areas show possible invalid correlation areas. The outlined area on the left hand side shows a bullet surface that contains a poorly striated area, which results from poor contact between the bullet and the gun barrel during firing. The outlined area on the right hand side shows a breech face surface with striations dropping into the impression area of the firing pin. That clearly indicates the presence of original or "pre-firing" toolmarks on the breech face of the cartridge case, which are not caused by contact with the gun's breech face during firing.

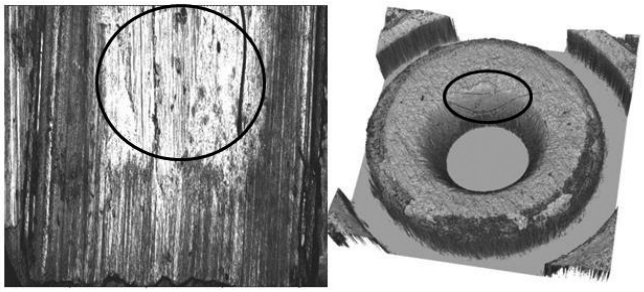

Figure 1: The striation signature on a bullet (left) and the breech face impression signature on a cartridge case (right).

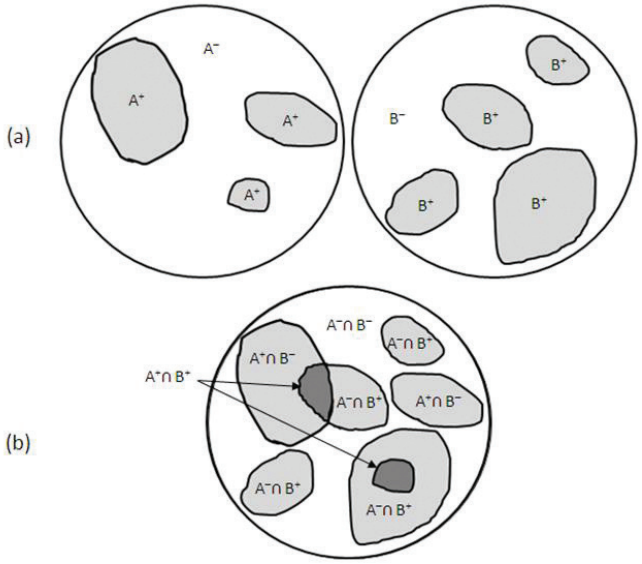

Figure 2: (a) The valid correlation areas ($^+$) and invalid correlation areas ($^-$) for individual topographies A and B. (b) The valid correlation areas $[A^+ \cap B^+]$ and the invalid correlation areas $[(A^+ \cap B^-) \cup (A^- \cap B^+) \cup (A^- \cap B^-)]$ for a pair of correlated topographies $[A \cap B]$.

Figure 2 schematically shows 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 the superscript ($^-$). In **Figure 2**, the union symbol "∪" [10] is used to represent the union of the two sets of images; the intersection symbol "∩" [10] is used to represent the intersection (or overlap) of the two sets of images. Both the individual topographies, A and B, contain valid and invalid correlation areas (**Figure 2a**); that is

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

For the pair-correlated topographies $[A \cap B]$(**Figure 2b**):

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

where $[A^+ \cap B^+]$ represents the valid correlation areas, and $[(A^+ \cap B^-) \cup (A^- \cap B^+) \cup (A^- \cap B^-)]$ represents correlations where at least one of the paired areas is invalid.

2.2 Correlation cells

The correlation cell Method is designed for accurate ballistics identifications of 3D ballistics signatures. A correlation cell is a basic correlation unit having a square or rectangular shape with (1) a sufficiently small cell size so that a mosaic of cells

can effectively separate the invalid correlation areas from the valid areas; but (2) a sufficiently large cell size so as to contain a significant number of peaks and valleys for accurate correlation. Both are important for effective and accurate ballistics identifications. By using the correlation cells, the valid correlation areas can be identified, and the invalid correlation areas can be eliminated from correlation, with the purpose of increasing the correlation accuracy.

Figure 3a shows a pair of correlated topographies [A ∩ B] containing 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, the correlation accuracy represented by the cross correlation function maximum CCF_{max} [11] must be low, because of the large invalid correlation area involved that must be analyzed in the correlation process (**Figure 3a**). If the correlation area can be divided into correlation cells (see shaded areas in **Figure 3b**), the individual cell correlations can be used to identify the valid correlation areas and to eliminate the invalid correlation areas, thus increasing the correlation accuracy. If the cell size can be further reduced to a sufficiently small area that still contains a sufficiently large amount of topography information for ballistics identification (see shaded areas in **Figure 3c**), the correlation accuracy can be further increased.

2.3 Initial registration phase and initial registration phase angle Θ_0

If the two correlated topographies A and B are registered by translations in the *x*- and *y*-directions and a rotation θ around the z-axis, so that their correlation value CCF_{max} achieves maximum, this registration position is called the "initial registration phase" for topography A and B, which is represented by initial registration position X_0, Y_0 and phase angle Θ_0. The initial registration phase (X_0, Y_0, Θ_0) can be determined by direct correlation of topographies A and B after Gaussian filtering (see Section 2.4.1). The initial registration phase angle Θ_0 can also be determined by cell correlations without Gaussian filtering (see Section 2.4.2).

2.4 Determining the initial registration phase angle Θ_0

2.4.1 Correlation of the entire topography A and B

The initial registration phase angle Θ_0 of the paired correlated topographies A and B can be determined by correlation of the entire topography A and B. It is important to apply a standardized high pass Gaussian filter [12] to both topographies to remove or attenuate the form and waviness of the overall topographies and emphasize the small scale identifying characteristics. Disadvantages of using a Gaussian filter are:

(1) The boundary effect of the standard Gaussian filter will trim the length of the correlated topography by half the long wavelength cutoff λc [12] in both the *x*- and *y*-directions; this will reduce the useful correlation information. The use of Gaussian regression filters can prevent the correlation area from being trimmed [13].

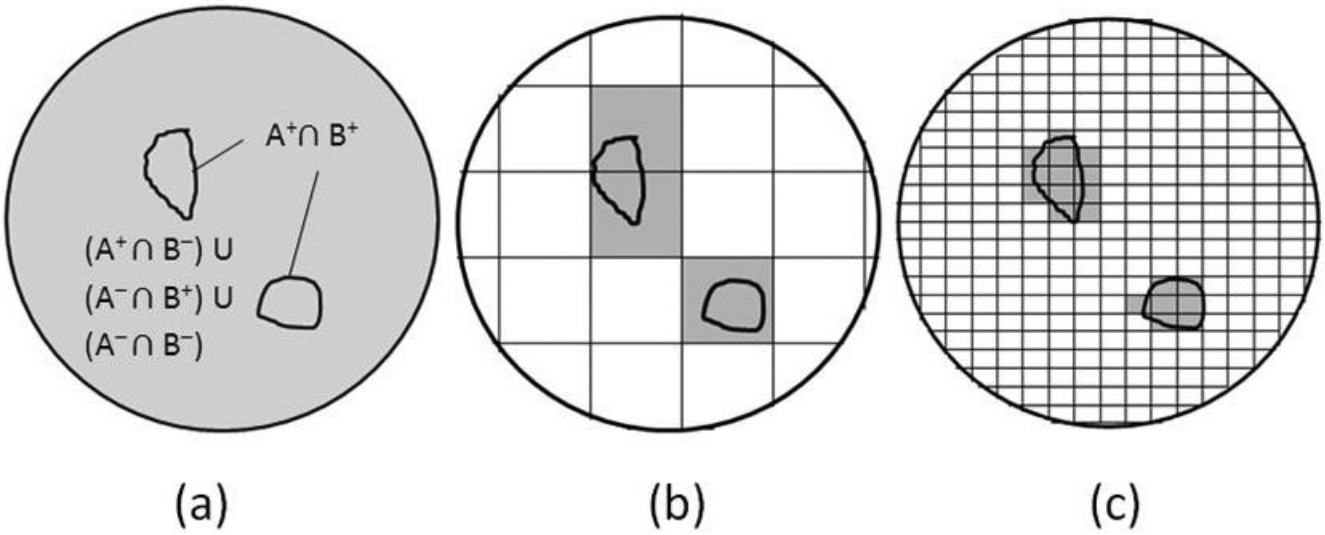

Figure 3: (a) Schematic diagram showing a pair of topographies [A ∩ B] correlated over the whole area including both the valid and the invalid correlation areas. (b) Diagram showing how the use of correlation cells can crop part of the invalid correlation area and increase correlation accuracy. (c) Diagram showing how smaller correlation cells can further crop the invalid correlation area and increase correlation accuracy.

(2) Attenuation of the amplitude information of the roughness components (50% at the wavelength of the long wavelength cutoff λc [12]) may reduce the correlation accuracy.

(3) The Gaussian filter may not be used for correlation of rectangular-shaped firing pin signatures as shown in **Figure 4**, left, because the significant curvature difference in the *x*- and *y*- directions that will cause a large form deviations after the Gaussian filter. For the same reason, the Gaussian filter cannot be used for some complex-shaped ejector marks (see **Figure 4** right).

Generally speaking, Gaussian filtering may be suitable for correlation of large and flat surfaces, such as breech face impression topographies. It may not be suitable for topographies with small curvatures and complex shapes, such as damaged bullets or certain firing pin and ejector mark signatures as shown in **Figure 4**.

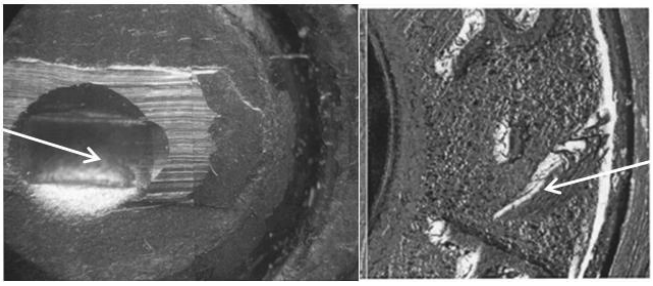

Figure 4: Gaussian filtering is not suitable for the rectangular-shaped firing pin signature (left) and for the complex shaped ejector mark signature (right).

2.4.2 3D topography correlation on correlation cells

The disadvantages of using a Gaussian filter for determination of the initial phase angle Θ_0 can be avoided by dividing the measured 3D topographies into paired correlation cells. The dividing process itself functions as a type of high pass filter. The initial cell size should be fairly large. If the initial correlation results using the relatively large cells clearly show a "Match" condition or a "Non-match" condition (to be discussed in Section 3), the identification results are accepted. If the initial results using the relatively large cells show "No-conclusion" (to be discussed in Section 3), topographies A and B are aligned at their common initial registration phase angle Θ_0 and divided into smaller cells for accurate identification (see Section 5).

2.5 Registration reproducibility

If the two correlated topographies A and B are repeatedly measured and correlated under different measurement setups, the variation range of their initial phase position (X_0, Y_0, Θ_0) represents the registration reproducibility *Rep* (X_0, Y_0, Θ_0):

$$Rep\ (X_0,\ Y_0,\ \Theta_0) = (2\sigma_{x0},\ 2\sigma_{y0},2\sigma_{\theta 0}), \quad (3)$$

where σ_{x0}, σ_{y0}, and $\sigma_{\theta 0}$ represent the standard deviations resulting from the reproducibility tests for the initial phase position (X_0, Y_0, Θ_0).

2.6 Cell size

As stated before, 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.

The minimum cell size also depends on the registration reproducibility. It is suggested that the minimum choice of cell dimensions, represented by the pixel numbers n_x and n_y, must be at least three to ten times larger than the registration reproducibility in the *x*-*y* directions:

$$n_x \geq (3 \text{ to } 10)\ Rep(X_0),$$
$$ny \geq (3 \text{ to } 10)\ Rep(Y_0). \quad (4)$$

In most cases, square-shaped cells (i.e. $n_x = n_y = n$) are likely to be used for correlation. The cell size may also depend on the size and shape of the correlated topographies. If the correlation area is large and flat, such as the breech face impression of a cartridge case, the cell size may be relatively larger. If the correlation area is relatively small and contains curvatures, such as a firing pin impression, or contains complex shapes, such as some ejector mark signatures and damaged bullets, the cell size may necessarily be smaller.

As a starting point for tests, it is estimated that for 9 mm caliber cartridge cases, the cell size for breech face correlations is in the range of (0.25 mm × 0.25 mm) to (0.5 mm × 0.5 mm); and the cell size for firing pin and ejector mark correlations is in the range of (0.08 mm × 0.08 mm) to (0.16 mm × 0.16 mm). Those estimates imply that an optimum number of cells are in the range of 50 to 200 for the correlations of breech face, firing pin and ejector mark signatures. A relatively larger cell size might be useful for tests of the possible subclass characteristics [2] of the ballistics signatures.

Controlled experiments and statistical analysis on paired known-match (KM) and known-non-match (KNM) cartridge cases and bullets will enable the determination

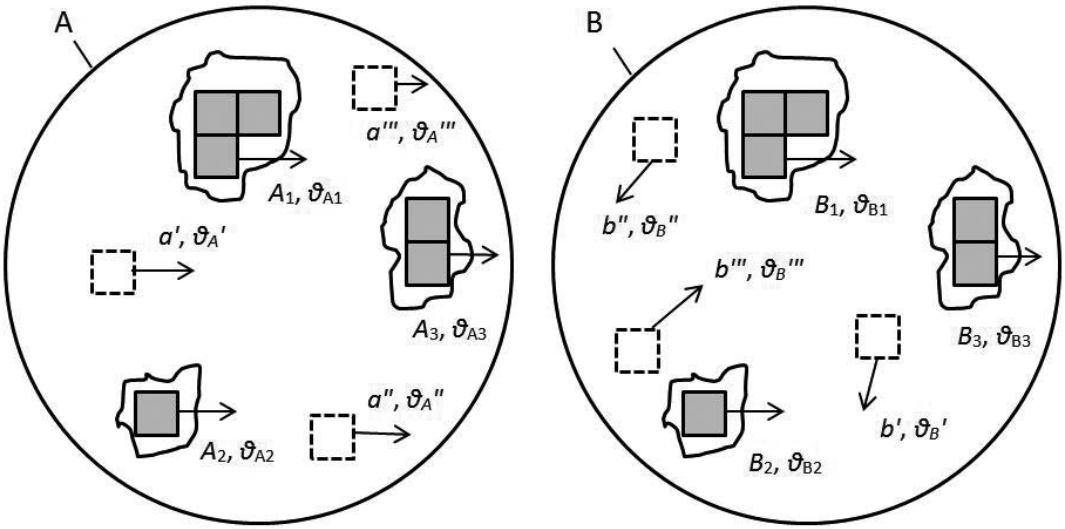

Figure 5. Assuming A and B originating from the same firearm, there are three sets of correlation cells A_1, A_2, A_3… and B_1, B_2, B_3… located in three valid correlation areas [$A^+ \cap B^+$] (as shown by three inside encircled areas). The other cell pairs a', a", a'"… and b', b", b'"… are located 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. The arrows and θ symbols provide a general illustration of rotational orientation.

and optimization, and maybe the standardization and normalization, of the cell sizes.

2.7 Identifying valid and invalid correlation areas using correlation cells

Assume that topographies A and B are divided into correlation cells for correlations. In order to identify the valid and invalid correlation areas using correlation cells, it is necessary to develop *identification parameters* for quantifying the different characteristics of the registered cell pairs when:

(1) they are located in the valid correlation areas [$A^+ \cap B^+$] of A and B originating from the same firearm;

(2) the correlated cell pairs are located in the invalid correlation area [$(A^+ \cap B^-) \cup (A^- \cap B^+) \cup (A^- \cap B^-)$] of A and B originating from the same firearm; and

(3) the correlated cell pairs are located in any areas of A and B originating from different firearms.

We consider these three cases below:

2.7.1 Valid correlation areas:

Figure 5 shows two registered topographies A and B originating from the same firearm, assuming their initial registration phase angle is $\Theta_0 = 0^o$. Both topographies A and B are divided into cell arrays for correlation. The correlation cells in topography A (see **Figure 5** left) are used as reference cells with their reference *x-y* positions and reference phase angle θ (as shown by the arrows in **Figure 5** left, which are equal to the initial registration angleel $\Theta_0 = 0^o$) to be used as references for correlations with cell arrays in topography B (see **Figure 5**, right). The entire registration area contains both valid correlation areas[$A^+ \cap B^+$] (as shown by three 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). There are three pairs of correlation cells A_1, A_2, A_3… and B_1, B_2, B_3…, located in three valid correlation areas [$A^+ \cap B^+$], containing three, one, and two cell pairs, respectively. When correlation cells $B_1B_2B_3$… located in the valid correlation areas of topography B (**Figure 5** right) are correlated with the reference cells $A_1A_2A_3$… located in the valid correlation areas of topography A (**Figure 5** left), these cell pairs should show a strong correlation represented by three characteristic parameters:

1) High correlation values represented by CCF_{max}:

$$CCF_{max} \geq CCF_{low}, \tag{5}$$

where CCF_{low} represents the lower control limit to be determined (see Section 4);

2) The same spatial distribution pattern which is characterized by the "congruent" *x-y* spatial registration positions of cell

arrays $B_1B_2B_3\ldots$ and $A_1A_2A_3\ldots$

$$B_1B_2B_3\ldots \cong A_1A_2A_3\ldots \quad (6)$$

and 3) The equal phase angles θ_{B1}, θ_{B2},$\theta_{B3}\ldots$ of correlation cells in topography B after registration with the reference cells in topography A with the phase angles $\theta_{A1} = \theta_{A2} = \theta_{A3}\ldots$ All are equal to the initial registration angle $\Theta_0 = 0^o$

$$\theta_{B1} = \theta_{B2} = \theta_{B3}... = \theta_{A1} = \theta_{A2} = \theta_{A3}... = \Theta_0 = 0^o. \quad (7)$$

It must be noted that, in **Figure 5** and Eq. 7, $\Theta_0 = 0^o$ is used for illustrating the relationship of the phase angles of θ_A and θ_B located in the valid correlation areas after registration. Similar equations would apply to any initial phase angles Θ_0. For practical ballistics identifications using correlation cells, if the *x*-*y* spatial positions of the correlated cell pairs are closely aligned within a pre-determined spatial threshold in both the *x*- and *y*-directions,; and if their registration angles θ are all the same within a pre-determined angular threshold of θ, these cell pairs are considered to have the same distribution pattern.

2.7.2 Invalid correlation area:

If A and B originate from the same firearm but the correlated 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 in Fig. 5, or if the paired topographies A and B originate from different firearms (not shown in **Figure 5**), these cell pairs may have only a weak correlation represented by low CCF_{max} values, and their spatial distribution patterns of *x*-*y* position and phase angles θ may not have the relationships as shown in Equations. 5, 6, and 7.

3. The "Contiguous Matching Cells (CMC)" Method

The "Consecutively Matching Striae" (CMS)" method, first proposed by A. Biasotti [14,15], and then described by Biasotti and J. Murdock in 1984 has been used internationally for bullet signature identifications since 1984 [16], was developed into a quantitative criteria for both 2D and 3D striated toolmarks by these authors in 1997 [17]. However, the CMS method can only be used for bullet identifications with striation signatures. This CMS criterion has been used by some firearm and toolmark examiners since 1997. Based on the proposed 3D topography measurement on correlation cells, the "Contiguous Matching Cells" (CMC)" criterion is proposed with a potential use for identification of both 2D and 3D signatures of bullets, toolmarks and cartridge cases [1].

The CMC method is based on distinguishing mathematical characteristics of the correlated cell pairs when they are similar vs. when they are dissimilar. The cell pairs should be similar when they are located in the valid correlation areas of topographies A and B originating from the same firearm. Otherwise, the cell pairs should be dissimilar if they are located in the invalid correlation areas of topographies A and B originating from the same firearm; or in topographies A and B originating from different firearms. These distinguishing characteristics are used as *identification parameters* for ballistics identification (see Section 5) and for ballistics evidence searches (see Section 6). These parameters are:

- High (vs. low) cross correlation function maximum (CCF_{max}),
- The same (vs. different) *x*-*y* spatial registration position, and
- The same (vs. different) registration angle θ for the paired correlation cells.

If the registered cell pairs are located in the valid correlation areas $[A^+\cap B^+]$ of the topographies A and B originating from the same firearm (see **Figure 5**), all three *identification parameters* must show positive results, i.e. high CCF_{max}, same *x*-*y* spatial registration positions and phase angles θ (see Eqs. 5-7). On the other hand, if the registered cell pairs are located in the invalid correlation area $[(A^+\cap B^-)\cup(A^-\cap B^+)\cup(A^-\cap B^-)]$ of the topographies A and B from the same firearm (also see **Figure 5**), or if they are from different firearms, all three *identification parameters* must show negative results.

Based on the three-component *identification parameters* of the paired correlation cells, it is proposed to develop a *numerical identification criterion* for the proposed CMC method by experimental tests and statistical analyses on KM and KNM cartridge cases and bullets (see Section 4).

As a starting point for discussion, the numerical criterion for the "Consecutively Matching Striae" (CMS)"method for striated toolmark identification [14] is adapted as the CMC identification criterion for initial trials of the CMC method. That is:

- At least six pairs of contiguous cells must show *matching* characteristics; these are termed "Contiguous Matching Cells"; or
- At least two sets of cells each having three pairs of contiguous cells must show *matching* characteristics.

The terms *matching* and *non-matching* are specified defined below.

3.1 Matching (Figure 6a and 6b):

Based on the three *identification parameters*, the matching cell pairs can be determined by:

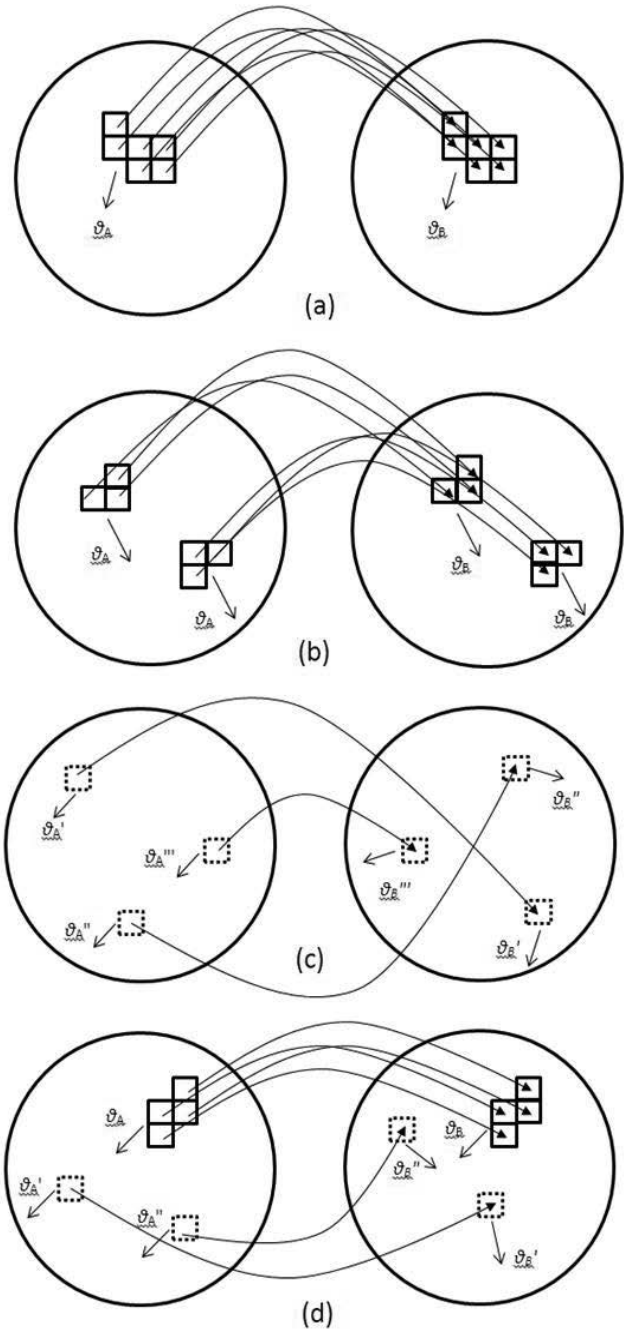

Figure 6: Match (Fig. 6a and 6b), Non-match (Fig. 6c) and No-conclusion (Fig. 6d) results using the Contiguous Matching Cells (CMC) method, assuming the numerical identification criterion for CMC is the same as CMS (one set of six, or two sets of three CMCs).

(1) High CCF_{max} value (higher than a lower control limit CCF_{low}, to be developed, see Section 4; at this point, it is assumed $CCF_{max} > CCF_{low} = 60$ %),

(2) Same *x-y* spatial registration positions, and
(3) Same registration angle θ for the paired correlation cells.
For example, Figure 6a shows a correlation of topography A and B where six cell pairs show high correlation ($CCF_{max} > CCF_{low} = 60$ %). All six cell pairs also show the same distribution pattern represented by the same *x-y* spatial registration positions and the same phase angle θ. Accordingly, it is concluded that A and B are a match. **Figure 6b** shows two sets each containing three cell pairs. All six cell pairs show high correlation ($CCF_{max} \geq CCF_{low} = 60$ %) and the same distribution pattern. Accordingly, this is also concluded considered to be a match.

Based on the above Contiguous Matching Cells (CMC) criterion, the correlation shown in **Figure 5** is not a match, because the six CMCs are distributed in *three* areas, not *two*. We are considering expanding the Contiguous Matching Cells criterion to be *no limitation* for the correlation areas of the cell pairs. For example, if a correlation of topography A and B showing six CMCs distributed over three areas (see **Figure 5**), or even distributed over six areas with each area containing only one cell pair, it could still be concluded as a match.

3.2 Non-matching (Figure 6c):

If no paired correlation cells show positive results for the above three *identification parameters*, or if there are only a limited number of cell pairs showing $CCF_{max} \geq CCF_{low}$ (**Figure 6c** shows three), but their distribution pattern is different (i.e., their *x-y* registration positions and phase angles θ do not match), the result is a non-match.

3.3 No-conclusion (Figure 6d):

If the paired correlation cells show:

(1) $CCF_{max} \geq CCF_{low}$ but the number of the paired cells is less than the required number specified by the *numerical identification criterion* for CMC, and

(2) At least some of the paired correlations cells show strong correlations in their *x-y* special registration positions, and the same phase angle θ, the correlated topographies A and B result in no-conclusion.

In **Figure 6d**, three sets for a total of six paired correlation cells (containing one, one and four cell pairs, respectively,) show $CCF_{max} \geq CCF_{low}$. Four pairs show the same *x-y* distribution positions and the same phase angle θ, but two other pairs show different distribution patterns and registration angles. As a result, there are four cell pairs qualified as CMCs, less than the required number six. It is concluded as no-conclusion. It

is then necessary to use smaller cells to determine if a more definitive conclusion can be obtained (see Section 5).

4. How to Determine the Numerical Identification Criterion and the Control Limit CCF_{low} for the Proposed CMC Method

Two key factors must be developed for the proposed CMC method: The numerical identification criterion *C* and the lower control limit CCF_{low}. Both can be developed by experimental tests and statistical analyses on KM and KNM cartridge cases and bullets. We plan to select four groups of samples for tests:

- A selection of KM and KNM topographies of cartridge cases from the National Ballistics Imaging Database Evaluation (NBIDE) project [8] using three types of new handguns. Four guns of each type were used; each gun was fired four times with ammunition having three types of cartridge cases. Each fired cartridge case has three correlation regions for analyses: breech face, firing pin, and ejector mark.

- A selection of topography signatures from the De Kinder tests (used guns) [18].

- A selection of topography signatures of cartridge cases ejected from guns with consecutively manufactured breech slides [19].

- A selection of topography signatures of bullets fired from guns with consecutively manufactured barrels.

As a starting point for tests, we assume that the lower control limit of CCF_{low} is 60 %, and the numerical identification criterion *C* is six: the same as the numerical identification criterion for the CMS method [14-17]. Both must be verified and may be revised after the experimental tests and statistical analyses.

5 Establishing a NIST Ballistics Identification System (NBIS) Based on 3D Topography Measurements on Correlation Cells

The proposed "NIST Ballistics Identification System" (NBIS) will use a state-of-the-art optical instrument capable of accurate 3D topography measurements and image acquisitions, with high resolution, low image distortion, large *x*-*y*-*z* measurement range and state-of-the-art analytical software (including data smoothing and image stitching capabilities) for accurate and fast acquisitions and analyses. The measurement range in *x*-*y*-*z* must be large enough to cover different types of measurements and correlations, such as acquisitions of both the breech face and firing pin topographies of cartridge cases with a single measurement setup.

A correlation procedure for the proposed NBIS includes:

- Acquire 3D topographies of A and B and pre-process the raw data;
- Separate A and B into cell arrays ($a_{11}\ a_{12}..a_{ij}$) and ($b_{11}\ b_{12}..\ b_{ij}$) using a relatively large cell size;

- Conduct cell correlations by scanning the paired correlation cells in *x*-*y* using a proposed "synchronous processing" program:

$$\begin{bmatrix} a_{11}a_{12}\dots a_{1j} \\ a_{21}a_{22}\dots a_{2j} \\ \vdots \\ a_{i1}a_{i2}\dots a_{ij} \end{bmatrix} \quad vs. \quad \begin{bmatrix} b_{11}b_{12}\dots b_{1j} \\ b_{21}b_{22}\dots b_{2j} \\ \vdots \\ b_{i1}b_{i2}\dots b_{ij} \end{bmatrix}$$

- Analyze the correlation results based on the CMC criterion using the three *identification parameters*: CCF_{max}, the registration positions in *x*-*y*, and registration angle θ;

- Characterize the paired correlated topographies A and B as a Match (**Figures 6a and 6b**), Non-match (**Figure 6c**), or No-conclusion (**Figure 6d**);

- For the No-conclusion topographies (**Figure 6d**), align A and B at their initial registration angle Θ_0, which is determined by the initial correlations using the large cell size. At this registration position, a smaller cell size is used for accurate topography correlation, until a conclusion result of either "Match" or "Non-match" (or maybe still a "No-conclusion") is achieved.

6 Establishing a National Ballistics Evidence Search Engine (NBESE) Based on 3D Topography Measurements on Correlation Cells

A "National Ballistics Evidence Search Engine" (NBESE)" can be established using the three *identification parameters* with the following special features:

- The 3D topography measurements on correlation cells are used for ballistics evidence searches. Sources of uncertainty caused by variation of lighting conditions associated with reflectance optical images can be avoided, thus helping to improve the objectivity of evidence searching.

- The use of correlation cells and the proposed CMC method with three *identification parameters* (CCF_{max}, distribution position in *x*-*y*, and registration angle θ) can identify the

valid correlation area and eliminate the invalid correlation area, which can ensure high accuracy of ballistics evidence searches.

- High-speed evidence searches can be enabled by "synchronous processing" of dozens, even hundreds, of correlation cell pairs at the same time and by largely reducing the angular searching range for the registration of these cell pairs.

- The proposed NBIS and the NBESE can provide a single method of identifications to be used for correlations of both geometrical topographies and optical intensity images, and can be potentially applied for all case scenarios of fired bullets, cartridge cases, and toolmarks.

- An error rate report procedure can be developed for ballistics evidence searches, which can greatly add to the scientific support for the specialty of ballistics identification.

- The proposed NBIS and NBESE will be engineered to employ publicly available software and database file protocols, with published search algorithms and statistical models. In this way interoperability between different ballistics identification systems using this invention can be facilitated.

7 Initial Verification Tests and Results

Three check points were specified for initial go/no-go tests of the central concept in this invention--the proposed "Correlation Cells":

- High (vs. low) cross correlation function maximum (CCF_{max}) value;

- Same (vs. different) spatial x- and y-locations of successive correlation cells; and

- Same (vs. different) registration angle θ for the paired correlation cells.

For paired correlation cells in the valid correlation area of the paired KM topographies, all three check points must show positive results. For paired correlation cells on the KNM topographies, all three check points must show negative results.

In order to test the CMC method and to verify the proposed numerical identification criterion $C \geq 6$, 40 cartridge cases fired from handguns with 10 consecutively manufactured pistol slides are measured by a 3D confocal microscope and correlated by the CMC method. There are a total of 780 correlations including 63 known-matchings (KM) and 717 known-non-matchings (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. 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 identification parameters. The initial test repot will be published soon [20].

8 Future work

Our plan for future work includes:

- Acquire topography images for paired KM and KNM bullets and striated toolmarks; conduct the same tests as those described in Section 7 to verify the possible utilization of the proposed "correlation cells" for correlations of 2D striation signatures.

- Acquire optical intensity images for paired KM and KNM cartridge cases; conduct the same tests to determine the possibility of using the proposed "correlation cells" for correlations of 3D optical intensity images.

- Develop and test a correlation program using "synchronous processing" for the paired correlation cells to increase correlation speed.

- Optimize the correlation parameters including the cell size n, the control limit CCF_{low}, and the thresholds for the x-y spatial registration positions and registration angles θ, by which the paired correlations cells can be determined to have the same or different distribution pattern.

- Develop and optimize the *numerical identification criterion* for identifying matches using the proposed "Contiguous Matching Cells" (CMC) method.

- Conduct measurements and correlations for verification of the developed NBIS and the *numerical identification criterion* of the CMC method using a wide range of KM and KNM bullets and cartridge cases. Test firing is available at the NIST facility if necessary.

- Develop an optical system for topography measurement with a new capability of acquiring both the breech face and firing pin signatures with a single measurement setup, and develop the software for correlating both areas jointly with a single

correlation procedure.

- Measure and test relevant ballistics and toolmark topography signatures, including those from complex-shaped firing pins and ejectors, damaged bullets and toolmarks.

- Develop the "National Ballistics Evidence Search Engine" (NBESE) using the three *identification parameters* for accurate and fast ballistics evidence searches.

- Conduct statistical analyses for the development of a procedure for reporting the probability of false negative and false positive identifications using the CMC method, which can be used for error rate reporting of ballistics identifications.

- Use the developed NBIS and NBESE for database searches with the National Integrated Ballistics Information Network (NIBIN) database for benchmarking the performance accuracy of the new system with respect to an acceptable error rate.

9 Summary

9.1 "Correlation Cells" are proposed for accurate and fast ballistics identification and evidence searching

The Correlation Cells and 3D topography measurements are proposed for the NIST Ballistics Identification System (NBIS) and the National Ballistics Evidence Search Engine (NBESE), which can provide accurate and fast ballistics identification and evidence searches. 3D topography measurements are traceable to the SI unit of length, which can provide objective data acquisition without involving uncertainties caused by optical imaging and lighting conditions. High accuracy ballistics identifications can be potentially facilitated by paired cell correlations using three *identification parameters* (CCF_{max}, spatial distribution position in *x-y* and registration angle θ), which can effectively identify valid correlation areas and eliminate invalid areas from consideration. A fast correlation speed can be achieved by using "synchronous processing" of dozens, or even hundreds, of paired correlation cells at the same time, and by largely reducing the angular searching range for the registration of the paired correlation cells. The use of correlation cells can also eliminate manual operations in the current identification systems (such as imaging trimming), and can combine the identification of breech face and firing pin signatures of cartridge cases into a single process. These developments can promote the NBIS as an objective and automated system for accurate and fast ballistics identifications.

9.2 The "Contiguous Matching Cells (CMC)" method is proposed as a quantitative measure for ballistics identifications and evidence searches

The proposed "Contiguous Matching Cells (CMC)" method can be potentially used for ballistics evidence searches involving both 2D signatures of bullets and striated toolmarks and 3D signatures of cartridge cases and impression toolmarks. The CMC method, supported by three *identification parameters* of the paired correlation cells (CCF_{max}, spatial distribution pattern in *x-y* and registration angle θ), can provide high accuracy ballistics identification and evidence searches. All the parameters and algorithms used in the correlation program will be in the public domain and subject to open tests. An error rate reporting procedure can be developed that can greatly add to the scientific support of the ballistics identification specialty, and give confidence to the trier of fact in court proceedings. The error rate report can also be used for laboratory assessment and accreditation in accordance with the current ISO 17025 standard [21].

The proposed NBIS and NBESE will be engineered to employ publicly available software and database file protocols with published search algorithms and statistical models. In this way interoperability between different ballistics identification systems using this invention can be achieved. This interoperability will make the NBESE suitable for use with large national databases, such as those of the National Integrated Ballistics Information Network (NIBIN) in the United States, and national databases in European countries within the European Network of Forensic Science Institutes (ENFSI).

Acknowledgements

The funding for this research is provided by NIST 2012 Forensic Measurements Challenge Program (FMC2012) and by the Law Enforcement Standards Office (OLES) at NIST. The author is grateful to T.V. Vorburger, R.M. Thompson, W. Chu, L. Ma, and S. Ballou of NIST for their discussion, review and comments.

References:

[1] Song, J., "An automated ballistics identification system based on 3D topography measurements on correlation cells", NIST Invention Disclosure (NIST #11-012, confidential), June 30, 2011.
[2] "The theory of identification, range of striae comparison reports and modified glossary definitions – An AFTE Criteria for Identification Committee Report," AFTE Journal 24, 3, 337, 1992.

[3] Song, J., Chu, W., Vorburger, T.V., Thompson, R., Yen, J., Renegar, T.B., Zheng, A., Silver, R., "Development of ballistics identifications – from image comparison to topography measurement in surface metrology," Meas. Sci. Technol. 23, 4, 2012, online publication at: http://stacks.iop.org/0957-0233/23/054010.

[4] DeKinder, J., Bonfanti, M., "Automated comparisons of bullet striations based on 3D topography," Forensic Science International, 101, 85-93, 1999.

[5] Song, J., Vorburger, T. V., "Topography measurement and applications" in Proc. SPIE -The 3rd International Symposium on Precision Mechanical Measurements (ISPMM), SPIE 6280: 1T1-1T8, SPIE, Bellingham, WA, 2006.

[6] Song, J., Vorburger, T.V., Ballou, S., Thompson, R., Yen, J., Renegar, T.B., Zheng, A., Silver, R., Ols, M., "The national ballistics imaging comparison (NBIC) project," Forensic Science International, 216,168-182, 2012. Online publication at: http://dx.doi.org/10.1016/j.forsciint.2011.09.016.

[7] Song, J., Whitenton, E., Kelley, D., Clary, R., Ma, L., Ballou, S., "SRM 2460/2461 standard bullets and cartridge cases project," J. Res. Natl. Inst. Stand. Technol., 109, 6, 533-542, 2004.

[8] Vorburger, T.V., Yen, J., Bachrach, B., Renegar, T.B., Filliben, J., Ma, L., Rhee, L.H., Zheng, A., Song, J., Riley, M., Foreman, C., Ballou, S., "Surface topography analysis for a feasibility assessment of a National Ballistics Imaging Database," NISTIR 7362, NIST, 2007.

[9] Chu, W., Song, J., Vorburger, T., Yen, J., Ballou, S. and Bachrach, B., "Pilot study of automated bullet signature identification based on topography measurements and correlations," Journal of Forensic Sciences, 55, 2, 341-347, 2010.

[10] ISO 80000-2, "Qualities and units – Part 2: Mathematical signs and symbols to be used in the natural sciences and technology," ISO, 2009.

[11] Song, J., Vorburger, T.V., "Proposed bullet signature comparisons using autocorrelation functions," Proc. 2000 NCSL, Toronto, 2000.

[12] ASME B46.1-2009, Surface Texture (Surface Roughness Waviness and Lay), ASME, New York, 2009.

[13] Blunt L, Jiang XQ. Advanced techniques for assessment surface topography, Kogan Page Science, London and Sterling, VA, 2003.

[14] Biasotti, A. "Bullet Comparison, A Study of Fired Bullets Statistically Analyzed." Unpublished Thesis, 1955, University of California, Berkeley, California (see ref. #15 for a condensed summary).

[15] Biasotti, A.A. "A Statistical Study of the Individual Characteristics of Fired Bullets." Journal of Forensic Sciences, 4, 1, 34-50, 1959.

[16] Biasotti, A.A., Murdock, J., "Criteria for identification or state of the art of firearm and toolmark identification," AFTE Journal, 16, 4, October 1984.

[17] Biasotti, A.A., Murdock, J., Firearm and Toolmark Identification, Chapter 23, Vol. 2, pp. 140 in Modern Scientific Evidence: The Law and Science of Expert Testimony, Faigman DL, Kaye DK, Saks MJ, Sanders, J. Eds., St. Paul: West,1997.

[18] DeKinder, J., Tulleners, F., Thiebaut, H., "Reference ballistic imaging database performance", Forensic Sci. Int.140, 207, 2004.

[19] Weller, T., Zheng, A., Thompson, R., Tulleners, F., "Confocal microscopy analysis of breech face marks on fired cartridge cases from 10 consecutively manufactured pistol slides," Journal of Forensic Sciences, 57, 4, 912-917, 2012.

[20] Chu, W., Tong, M., Song, J., "Validation tests for the congruent matching cells (CMC) method using cartridge cases fired with consecutively manufactured pistol slides," passed NIST review, to be presented at the 2013 AFTE Annual Training Seminar and to be published at the AFTE Journal.

[21] ISO 17025, General requirements for the competence of testing and calibration laboratories, ISO, Geneva (2005).