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A Review of NIST Projects in Surface and Topography Metrology for Firearm Evidence Identification in Forensic Science

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A Review of NIST Projects in Surface and Topography Metrology for Firearm Evidence Identification in Forensic Science

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Abstract. This is a review of the National Institute of Standards and Technology's (NIST) efforts in surface metrology and topography measurements for firearm evidence identifications in forensic science. Based on the research projects in surface metrology and standardization, NIST researchers have developed Standard Reference Material (SRM) Bullets and Cartridge Cases and established a 2D/3D Ballistics Topography Measurement System. They formulated a Traceability and Quality System to support nationwide ballistics identifications within the National Integrated Ballistics Information Network (NIBIN) in the U.S. They have recently proposed a Congruent Matching Cells (CMC) method for accurate ballistic identification and error rate estimation, which provides a statistical foundation and a practical method to promote firearm evidence identifications from qualitative image comparisons to quantitative topography measurements.

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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 toolmarks on their surfaces called "ballistic signatures" [1]. Striation signatures (2D profile toolmarks) on a bullet are caused by its passage through the gun barrel. Impression signatures (3D topography toolmarks) on a cartridge case are caused by impact with the firing pin, breech face and ejector [1]. By microscopically comparing these ballistic signatures, firearm examiners can determine whether a pair of bullets or cartridge cases was fired or ejected from the same firearm. Firearm examiners can then connect a recovered firearm or other firearm evidence to criminal acts [1].

The field of firearm evidence identification is more than 100 years old and the field of surface topography is at least 80 years old, but the combination of the two—using topography measurements and correlations for identification of fired bullets and cartridge cases—has only been around for about 15 years. The combined field is so new that current firearm identifications at crime labs for bullets or cartridge cases are still performed manually by experts in side-by-side

[*] Certain commercial equipment, instruments, or materials are identified in this paper to specify adequately the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

image comparison using optical microscopes; and the conclusion of a "match" or 'non-match" is mainly based on experts' experience. Nevertheless, this interdisciplinary field brings a vision that one day firearm related investigations and identifications might be accomplished or affirmed through database searches using surface measurement data of the ballistics evidence and automated correlation programs, both are based on surface and topography metrology. Further, a conclusion that certain firearm evidences is a match or a non-match could include an uncertainty (or error rate) report, which could also be developed from surface and topography metrology [2].

In this paper, we discuss challenges to firearm evidence identifications, followed by development of standard bullets and cartridge cases and a 2D/3D topography measurement system, and the formulation of a traceability and quality system and error rate procedure for firearm evidence identification in forensic science.

2. Challenges to firearm evidence identifications in the United States

Despite a long history of use in court, the scientific foundation of firearm and toolmark identification has been challenged by recent court decisions and by the 2008 and 2009 National Academies Report [3,4]. We review a series of NIST research projects addressing these challenges, which are aimed at providing scientific support to firearm evidence identification in the United States:

- Developing reference standards—NIST SRM (Standard Reference Material) 2460 Bullets and SRM 2461 Cartridge Cases, for instrument calibration and establishing a measurement traceability and quality system to support nationwide firearm identifications [5].
- Developing a 2D/3D Ballistics Topography Measurement System [6,7].
- Developing a Traceability and Quality System using the NIST SRM Bullets and Cartridge Cases [8,9].
- Developing a Congruent Match Cells (CMC) method for accurate ballistics identification and error rate report [10-13].

3. The SRM standard bullets and cartridge cases are manufactured by the same techniques used for manufacturing surface roughness specimens

The SRM bullets were designed as a virtual/physical bullet signature standard [5]. The virtual standard is a set of six digitized profile signatures based on six fired bullets at the National Laboratory Center of the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) and the Central Laboratory of the Federal Bureau of Investigation (FBI). These master bullets underwent profile measurements at NIST's Surface Calibration Laboratory using a commercial stylus instrument. Each bullet was traced along one selected Land Engraved Area (LEA) [5]. The resulting set of six digitized bullet profile signatures was stored in a NIST computer as the virtual standard for both the fabrication and the measurement of SRM bullets [5].

The Engineering Physics Division at NIST has a long history of developing surface roughness specimens [14-16]. In 1998, a virtual/physical random profile surface roughness standard was developed at NIST using a numerically controlled (NC) diamond turning process at the NIST's instrument shop [15]. Based on the same NC diamond turning technique for manufacturing random profile roughness specimens, the SRM standard bullets were manufactured [5].

The SRM standard cartridge cases were manufactured by an electro-forming technique which was used for replication of surface specimens [17]: a master specimen is put into a tank with electrolytes to produce a negative replica on the surface of the master. By repeating the same process on the negative replica, a positive replica is created with the same surface topography as the master specimen. The electro-forming technique was used for production of SRM 2461 Standard Cartridge Cases [5]. In order to ensure that the SRM cartridges are produced with virtually the same surface topography with the master, NIST's 3D Topography Measurement System was used to test the "decay factors" of the replication process. Based on the decay factors, an optimum production plan for a large amount of SRM cartridges was developed to ensure uniformity of surface topography within specified tolerances [18].

Figure 1: A SRM 2460 Standard Bullet (left) made by the numerically controlled (NC) diamond turning process and a SRM 2461 Standard Cartridge Case (right) made by the electro-forming technique. Both procedures are based on the techniques previously used for manufacturing surface roughness specimens.

4. A 2D/3D topography measurement system for firearm evidence identification

Most current ballistics identification systems are primarily based on comparisons of optical images acquired by microscopes. Typically such microscopes produce images of inconsistent quality based on lighting conditions such as the type of light source, lighting direction, intensity, material color, material reflectivity, and image contrast [19]. Since ballistics signatures are surface topographies by nature [1], it is proposed to develop a 2D/3D Topography Measurement System, which is independent of optical lighting conditions, for quantitative and objective ballistics topography measurements and correlations [19].

Most metrics for describing surfaces are used to quantify the characteristics of a surface in vertical, horizontal or some combination of both dimensions [20,21]. However, topography metrology—as termed by us [2]—aims to compare the overall features of two profiles of surfaces and quantify the similarity of the compared 2D or 3D topographies relative to each other. Researchers at NIST proposed the use of cross-correlation function [6], commonly used in the field of surface metrology, as a unique parameter for quantifying the similarity of 2D/3D topographies. This parameter was used to develop a 2D/3D Topography Measurement System for production quality control and certification of the NIST SRM Bullets and Cartridge Cases [5-7]. The 2D/3D Topography Measurement System was used for the NIST Ballistics Imaging Database Evaluation (NBIDE) [22] and the National Ballistics Imaging Comparison (NBIC) project [9]. It has also been used for establishing a measurement traceability and quality control system [8,9], and for developing an error rate procedure to support nationwide ballistic identifications [10-13].

5. Establishing a traceability and quality system for nationwide ballistics measurements

According to the *International vocabulary of metrology - Basic and general concepts and associated terms (VIM)* [23], *metrological traceability* is defined as a

> *property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty.*

From the above definition, three key steps for establishing metrological traceability for ballistics measurements are proposed [8]:

- Establishing a reference standard for ballistics signature measurements. The NIST SRM Bullets and Cartridge Cases are used as a reference standard for both the topography measurements at NIST and the imaging correlations for NIBIN acquisitions [5].
- Establishing an unbroken chain of calibrations from the national laboratories (NIST and the National Laboratory Center of ATF) to local laboratories and customers using the SRM Bullets and Cartridge Cases as reference standards. The unbroken chain of calibration covers both topography measurements at NIST and image correlations at NIBIN. For the topography measurements, the measurement traceability is established using the virtual/physical SRM standard and the proposed parameters—signature difference D_s and cross-correlation function maximum CCF_{max} [6]. For the image correlation systems like the Integrated Ballistics Identification System (IBIS) [24], the traceability is established by image acquisitions of SRM Bullets and Cartridge Cases at local IBIS sites, and correlations with the image standard, termed the "Golden Images" [9] established on the IBIS at the National Laboratory Center of ATF.
- Evaluating measurement uncertainty and error rate, establishing control limits for both the topography measurements and imaging correlations [9,11].

In order to establish a Nationwide Traceability and Quality System for ballistics identifications in the United States, the National Ballistics Imaging Comparison (NBIC) project was initialized in 2008 [9]. A total of 19 ballistics examiners from 13 U.S. crime laboratories participated in this project. They each took 24 acquisitions of NIST SRM Bullets and Cartridge Cases over the course of a year. The acquired images were correlated with the Golden Images at the National Laboratory Center of ATF, from which control charts and control limits were developed and used for promoting the proposed Traceability and Quality System in NIBIN [9] and for future assessments and accreditations for U.S. ballistics laboratories in accordance with the ISO 17025 Standard [25] and ASCLD/ LAB procedures [26].

6. Developed a Congruent Match Cells (CMC) method for ballistics identification and error rate estimation

Accurate ballistics identification depends not only on image quality, but also on the capability of correlation software to identify the "valid correlation areas" and to eliminate the "invalid correlation areas" [10-13] from calculations. Currently, the final determination of a match (identification) or non-match (exclusion) in ballistics comparisons is mainly based on visual comparisons made by an examiner having the experience required to exclude invalid correlation areas.

The Congruent Matching Cells (CMC) method developed at NIST systematically divides measured 3D forensic topographies and optical images into "correlation cells." The CMC method is based on correlations of pairs of small correlation cells instead of correlations performed on the entire images. This is done because a firearm often produces characteristic marks of the ballistic signature, or "individual characteristics" [1], on only a portion of the surface termed "valid correlation area" [10-13], that can be used effectively for firearm identification. Conversely, a region of the surface topography that does not contain individual characteristics of the firearm's ballistic signature is termed an "invalid correlation region" [10-13], which should not be considered during firearm identification. Invalid correlation areas can occur, for example, due to insufficient contact between the firearm surface and the bullet or cartridge case during firing. The use of small correlation cells allows the CMC method to separate valid and invalid correlation cells in a manner similar to forensic examiners.

Three sets of identification parameters are devised by the CMC method for uniquely identifying correlated cell pairs originating from the same firearm: the cross correlation function maximum CCF_{max}, spatial registration positions in x-y and registration phase angle θ [10,11], The selection algorithm for determining matching cells has been implemented by different correlation programs for geometrical topography [12] and optical image correlation [13]. The CMC method also enables an approach to estimating error rates based on statistical analysis of the total number of correlation cells, the number of the Congruent Match Cells (CMC), and the statistical distribution of three sets of identification parameters [11].

An initial validation test of the CMC method was conducted using a set of cartridge cases that has achieved prominence in the firearms identification community when it was produced for a study of visual firearm identifications by ballistics examiners initiated by Fadul et al. at the Miami-Dade Crime Laboratory [27]. The set contains 40 cartridge cases ejected from handguns with 10 consecutively manufactured pistol slides. Ballistics correlations involving a population of consecutively manufactured gun parts represent the most challenging scenario for testing the capability to accurately identify bullets or cartridge cases as being fired or ejected from the same firearm, because the consecutively manufactured gun parts could produce mostly similar surface topographies on the fired bullets and ejected cartridge cases [27].

The validation test result is shown in Fig. 2 [12], that includes 780 pair-wise topography image comparisons of breech face impressions: 63 image pairs came from known match (KM) images; 717 image pairs came from known non-match (KNM) images. The number of congruent matching cell pairs (CMCs) for the 63 KM image pairs ranges from 9 to 26, while the number of CMCs for the 717 KNM image pairs ranges from 0 to 2. There is a clear separation between the KM and KNM distributions, meaning that the CMC method didn't produce any false identifications or false exclusions. Additional validation tests on optical images showed similar results [13]. Based on the CMC method, a statistical procedure for estimating error rates has been developed [11].

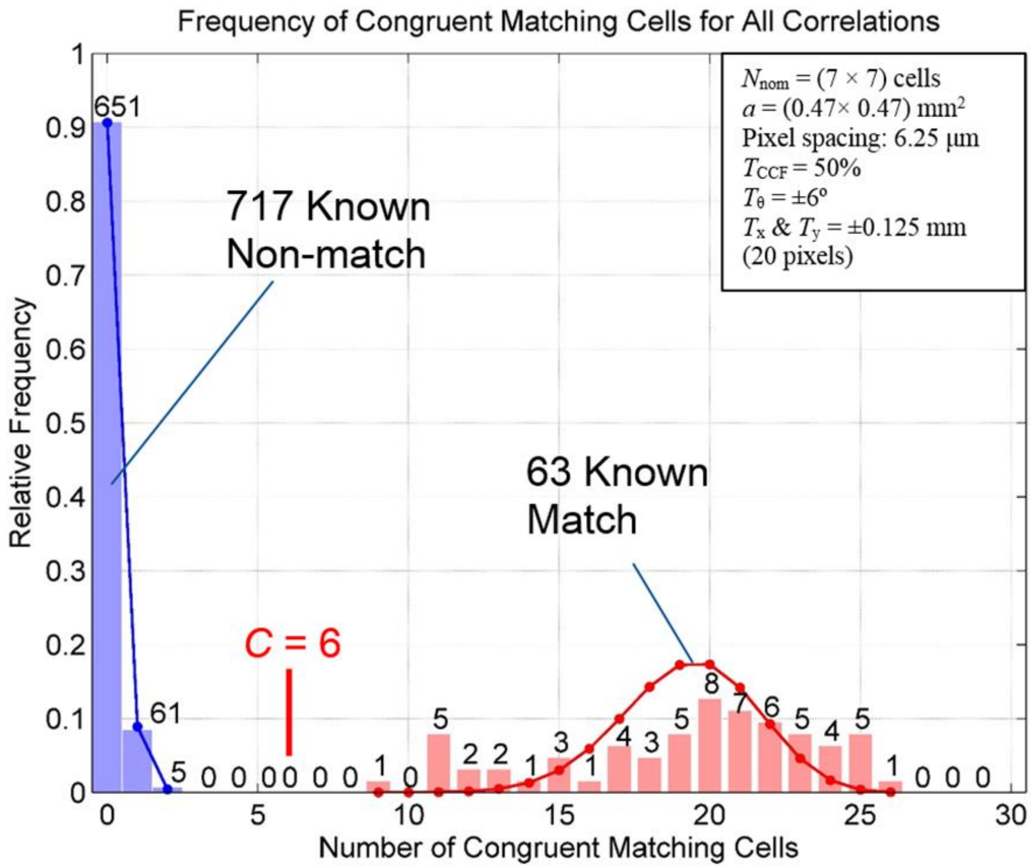

Figure 2. Relative frequency distribution of CMC numbers for KM and KNM image pairs (the KM and KNM distributions are each scaled to their particular sample size) [12]. For the 63 KM cartridge pairs, the CMC ranges from 9 to 26. For the 717 KNM cartridge pairs, the CMC ranges from 0 to 2. The KM and KNM distributions show significant separation without any false identifications or false exclusions. The blue and red curves represent the statistical fitting using the theoretical binomial function for both the KNM and KM distributions [11].

The proposed CMC method can be used for correlation of both geometrical topographies [12] and optical images [13], and can be potentially applied for all case scenarios of fired cartridge cases (including breech face, firing pin and ejector mark), fired bullets, and toolmarks. The CMC parameters and algorithms are in the public domain and subject to open tests. Based on the CMC method, an error rate procedure is proposed for establishing a statistical foundation to support nationwide ballistics identifications in forensic science, and to potentially provide an error rate report for court proceedings, in a manner similar to the method used for reporting the Coincidental (Random) Match Probability (CMP or RMP) in forensic identification of DNA evidence [3,4].

The proposed CMC method and error rate procedure may also serve as a foundation for manufacturers to develop next generation ballistic identification systems characterized by high correlation accuracy and error rate reporting, which would represent a decided advance over current automated ballistic identification systems. An error rate procedure could also be used for laboratory assessment and accreditation in accordance with the ISO 17025 standard [25] and ASCLD/ LAB procedures [26].

We envision a time when ballistic examiners can input either topographies or optical intensity images into a program that automatically conducts correlations using the CMC method, and displays the correlation conclusion (matching or non-matching) with an error rate report. The CMC method and statistical analysis can provide a scientific foundation and a practical method to estimate error rates for supporting ballistic identifications in forensic science.

7. Summary

Surface and topography metrology provides strong support to firearm evidence identifications in forensic science. Based on the research projects in surface metrology and standardization, researchers at NIST developed SRM Standard Bullets and Cartridge Cases and a 2D/3D Topography Measurement System. They formulated a Traceability and Quality System for ballistics identifications within the National Integrated Ballistics Identification Network (NIBIN) in the United States. They proposed a Congruent Match Cells (CMC) method for accurate firearm evidence identification, which can provide a statistical foundation and practical method for estimating error rate to support firearm evidence identification in forensic science. The CMC method and error rate procedure can be used for promoting the Next Generation Ballistics Identification System characterized by conclusive identification (or exclusion) with error rate report, in a similar way that reporting procedures have been established for forensic identification of DNA evidence [3,4].

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