Development of Ballistics Identification – From Image Comparison to Topography Measurement in Surface Metrology

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Abstract *Fired bullets and ejected cartridge cases have unique ballistics signatures left by the firearm. By analyzing the ballistics signatures, forensic examiners can trace these bullets and cartridge cases to the firearm used in a crime scene. Current automated ballistics identification systems are primarily based on image comparisons using optical microscopy. The correlation accuracy depends on image quality which is largely affected by lighting conditions. Because ballistics signatures are geometrical micro-topographies by nature, direct measurement and correlation of the surface topography is being investigated for ballistics identification. A Two-dimensional (2D) and Three-dimensional (3D) Topography Measurement and Correlation System was developed at the National Institute of Standards and Technology (NIST) for certification of Standard Reference Material (SRM) 2460/2461 Bullets and Cartridge Cases. Based on this system, a prototype system for bullet signature measurement and correlation has been developed for bullet signature identifications, and has demonstrated superior correlation results.*

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1. Introduction

Bullets and cartridge cases when fired or ejected from guns pick up characteristic surface topographies from the gun parts, resulting in a special kind of toolmarks, called “ballistics signature,” on the surface of the bullets and cartridge cases. 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.

Traditionally, ballistics identifications were based on image comparisons using an optical microscope. Since about 2000, the development of modern optical and computer science and technology has enabled topography measurements to be used for ballistics identification, and this procedure has demonstrated superior correlation results. In this paper, in Sections 2 and 3, we review the development history of microscope and calibration standards and describe the NIST SRM (Standard Reference Material) 2460 Bullets, 2461 Cartridge Cases, and NIST 2D/3D Topography Measurement System. We discuss the nature of ballistics signatures in Section 4, and compare the imaging and topography methods for ballistics identifications in Section 5. Finally, we describe the application of the NIST Topography Measurement System to ballistics identifications and initial correlation results in Section 6 and 7.

2. Development of Calibration Standard – “*Always Staying One Step Ahead*”

The rapid development of microscopes in the early part of the nineteenth century was plagued with two problems: microscopists were attempting to convert from a purely qualitative to a quantitative science in the absence of accurate calibration standards; and both the users and producers needed a standard test object to access and compare microscopes made by different manufactures [1]. Significant efforts were made by F.A. Nobert (1806-1881) in developing calibration standards with bands of lines of different spacing. As microscopes improved, Nobert introduced new test plates with finer spaced rulings [1]. When C. Evans reviewed the development history of microscopes and their calibration standards, he wrote that [1]: the development of calibration standards was “*always staying one step ahead of the microscopists*” until, inadvertently, it exceeded the theoretical limit of optical microscopy. The success in producing ever finer resolution targets for microscopes resulted in the invention of the diffraction grating [1].

Since the late 1980s, the development of automated ballistics identification systems was undergoing a similar process of converting from qualitative to quantitative comparisons. In the early 1990s, different automated systems were developed and used in the U.S. for ballistics database search and identification. Instrument makers developed different correlation algorithms and matching scores for

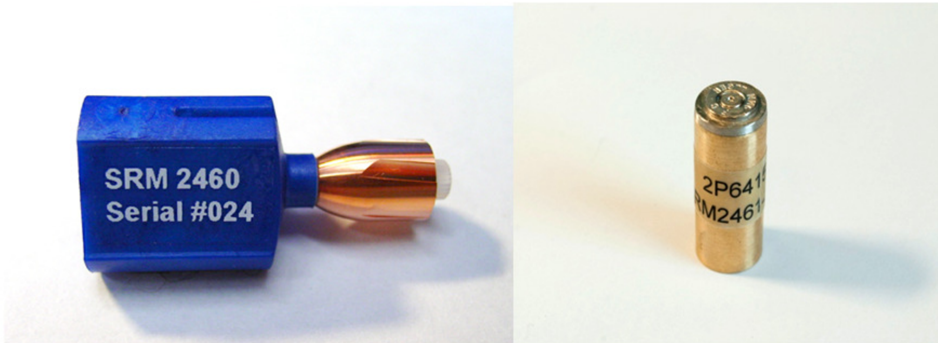

Fig. 1. A SRM 2460 Standard Bullet (left) and a SRM 2461 Standard Cartridge Case (right).

quantitative representation of image similarities; however, both the definitions and algorithms for the correlation scores were proprietary without an objective open test. Moreover, ballistics examiners needed a standard object for testing of different correlation systems for quality assurance, especially when these systems were integrated into a national network.

3. NIST SRM Bullets and Cartridge Cases and NIST 2D/3D Topography Measurement System

In 1997, NIST was asked by the Bureau of Alcohol, Tobacco Firearms, and Explosives (ATF) to develop “Standard Bullets” as a reference standard to support quality assurance for U.S. automated ballistics identification. The SRM 2460 Bullet was designed as both a virtual and a physical ballistics signature standard [2]. The virtual standard is a set of digitized bullet profile signatures that provides the profiles for machining the bullet signatures on the physical standards, the SRM bullets. The virtual standard also provides reference profiles for the measurements of the machined bullet signatures on the SRM bullets. The virtual standard was originally obtained from topographic profiles traced by a stylus instrument on master bullets fired at the ATF and the Federal Bureau of Investigation (FBI) under standardized shooting and recovery procedures [2]. The virtual standard was stored in a computer and used for control of the tool path of a numerically controlled (NC) diamond turning machine at the NIST Instrument Shop. The machine was then used to produce the bullet signatures on the SRM bullets [2]. The SRM 2461 Cartridge Cases were developed from replications of an ATF master cartridge case using the electro-forming technique [2].

The NIST 2D/3D Topography Measurement and Correlation System was originally designed for the measurement and inspection of 2D and 3D topographies of the SRM Bullets and Cartridge Cases [2-4]. Two correlation parameters, a NIST proposed parameter called the topography difference D_s and the cross correlation function maximum CCF_{max}, were used for quantifying the differences of the two correlated 2D/3D ballistics signatures [3]. When the two compared topographies are exactly the same, D_s is equal to zero (and CCF_{max} must be 100 %). And when D_s equals to zero, the two compared surface topographies must be exactly the same (point by point) [3]. These two parameters have a strong linear-function relationship, but CCF_{max} is not sensitive to a difference in scale height between two topographies with similar shape, whereas the parameter D_s is sensitive to a scale difference [4].

Besides the topography measurements for SRM bullets and cartridge cases, the NIST Topography Measurement System has been used for test of ballistics identifications in designed experiments, and has demonstrated strong correlation results [5,6]. It can also be used in other areas such as instrument characterization in surface metrology [7] and surface defect tests [8].

In response to the guidelines issued by the American Society of Crime Laboratory Directors/Laboratory Accreditation Board (ASCLD/LAB-International) to establish traceability and quality assurance in U.S. crime labs [9], NIST and ATF have recently completed a joint project entitled the National Ballistics Imaging Comparison (NBIC) aimed to establish a National Traceability and Quality System for ballistics identifications, in which the SRM Bullets and Cartridge Cases are used as reference standards [10]. During the NBIC project, different quality problems related to ballistics identifications have been discovered, explored and corrected [10].

4. Ballistics Signature – Optical Image or Surface Topography?

Ballistics signatures are 2D or 3D toolmarks and therefore, must be geometrical surface topographies by nature. It was clearly stated in the “Theory of Identification” issued by the Association of Firearm and Toolmark Examiners (AFTE) that “…the comparison of toolmarks…” are to be made on the “…unique surface contours…”

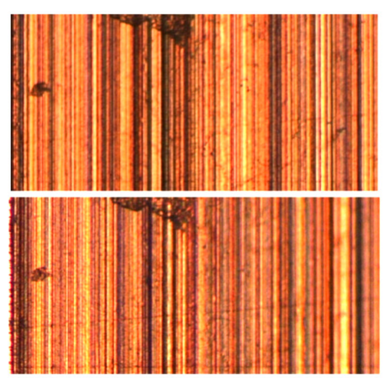

Fig. 2. Two images captured on the same area of the SRM 2460-001 bullet by the same microscope under different lighting directions. (Top) – Area aligned perpendicular to microscope optical axis, (Bottom) – The same area tilted by approximately 6°.

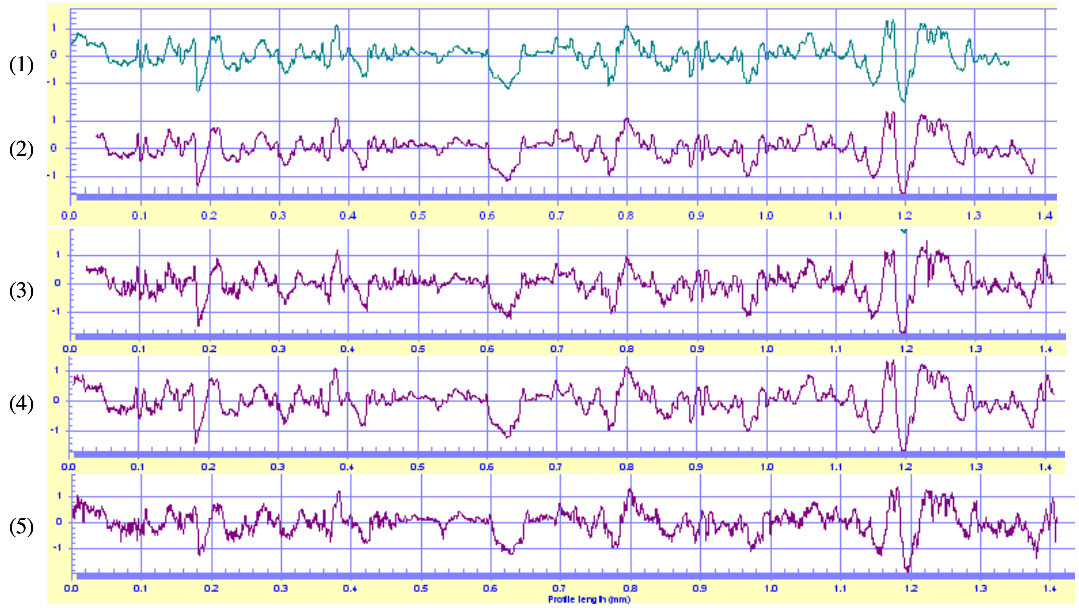

Fig. 3. The signature profiles of LEA 1 of SRM 2460-001 bullet were measured by four techniques (2 to 5) and correlated with the stylus profile of the virtual standard (1). Profile 2 was traced by a stylus instrument, CCF_{max} = 99.6 %; Profile 3 was traced by an interferometric microscope, CCF_{max} = 92.1 %; Profile 4 was traced by a Nipkow disk confocal microscope, CCF_{max} = 99.0 %; Profile 5 was traced by a laser scanning confocal microscope, CCF_{max} = 95.3 %. The vertical scale covers ±1 µm, the horizontal scale covers 0 - 1.4 mm.

and "surface contour patterns comprised of individual peaks, ridges and furrows. Specially, the relative height or depth, width, curvature…" [12]. Generally speaking, these geometrical ballistics signatures can be characterized into two categories: bullet signatures consisting of striations that can be represented by 2D profiles, $Z = F(x)$; and impression signatures on different regions of the cartridge cases, including the firing pin, breech face and ejector mark signatures, that can be represented by 3D topography images $Z = F(x, y)$.

Side-by-side image comparisons using an optical comparison microscope for ballistics identification has more than a hundred year history [12]. Since the late 1980s, different automated ballistics identification systems, such as the Integrated Ballistics Identification System (IBIS)* [13] were developed. Such systems typically include a digitized optical microscope, a signature analysis station and correlation software. Most of these systems are based on image comparisons of the optical intensity images $I = \Phi(x, y)$ acquired by the microscope, which is largely affected by lighting conditions such as the type of light source, lighting direction, intensity, color and reflectivity of the material, and the image contrast.

5. Image vs. Topography – "Seeing is Believing" or "Measuring is Believing"?

The significant effect of lighting conditions on the optical image can be demonstrated with a standard test object, the SRM bullet. One of the test results is shown in Fig. 2, in which the same land engraved area (LEA) of a SRM bullet was captured by the same microscope under slightly different lighting directions (about 6°). These two signature patterns show significant differences caused by the slight difference of the lighting direction and would likely be considered as "non-matching". However, the presence of the same surface defects in both photographs indicates that the two images are actually captured at the same area on the bullet surface.

In another test the same LEA of a SRM bullet was imaged by an optical microscope with the lighting directions varied from ±1° to ±5° [10]. The resulting images were compared with the image at 0°. It was found that when the lighting direction was changed to ±2° to ±3°, the image patterns showed significant differences from the image at 0°. When the light direction was changed to ±4° to ±5°, the difference of image patterns became so significant that they would likely be concluded as "non-matching" when compared with the reference image at 0° [10].

The significant effect of lighting conditions to the image quality was observed to be a major cause of large deviations in the correlation scores for bullets. During the National Ballistics Imaging Comparison (NBIC) project mentioned above [10], which included the participation of 19 ballistics examiners from 13 U.S. crime laboratories, each person conducted 24 image acquisitions on a SRM bullet and a SRM cartridge case over the course of about a year, and correlated the images with the "Golden Image" developed at the National Laboratory Center of ATF [10]. The mean value for the "Max Phase" score [13] of the SRM bullets, which represents the sum of six LEA's correlation scores at their maximum correlation position, was 5562 with a standard deviation of 1373, or a relative variation of 24.7%.

However, when we use topography technologies for the direct measurement of the ballistics signature of the SRM bullet, their signature patterns show high agreement, and their correlation values represented by the cross correlation function maximum CCF_{max} [3] show a relatively small variation. Figure 3 shows the topography

* 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.

measurement results on LEA 1 of the SRM 2460-001 bullet (the same bullet LEA as shown in Fig. 2) by four operators at four laboratories using four different techniques [7]: a stylus instrument (the second profile, CCF_{max} = 99.6 %); an interferometric microscope (the third one; CCF_{max} = 92.1 %); a Nipkow disk confocal microscope (the fourth one, CCF_{max} = 99.0 %), and a laser scanning confocal microscope (the fifth one, CCF_{max} = 95.3 %). These profiles were correlated with the first profile of the virtual standard of the SRM bullet [2]. The mean value of the CCF_{max} was 96.5% with a standard deviation of 3.5%, or a relative variation of 3.6%. And all the correlation values CCF_{max} were higher than 90%. Based on our previous study [6], CCF_{max} > 90 % is a good criterion for demonstrating a high degree of similarity for a pair of bullet signature patterns.

6. Development of Ballistics Identification – From Image Comparisons to Topography Measurements

The problem of imaging quality affected by the lighting conditions has been addressed by the instrument designers of different automated ballistics identification systems. Standardized lighting conditions, such as automatic lighting, are used for image capture [13]; and the measurement conditions including measurement setup and operation procedures are specified in detail [13]. However, even for the automatic lighting conditions [13] used in the Integrated Ballistics Identification System (IBIS), variations caused by the measurement setup and acquisition process may significantly affect signature acquisitions and correlation scores [10].

Because ballistics signatures are geometrical micro-topographies, direct measurement and correlation of the surface topographies can avoid the effect of lighting conditions, and likely improve the correlation accuracy for ballistics identification. Since the 1980s, with the help of modern computer technology, different optical instruments have been developed capable of precise measurement of 3D surface topography. These notably include the confocal microscope [14] and the interference microscope [15]. That has made it possible to use topography measurements for ballistics identifications. Recently, Forensic Technology Incorporation (FTI) announced the development of the new bullet and cartridge case imaging system (IBIS-TRAX 3D™) [13]. For the Bullet TRAX-3D system, a specially designed 3D confocal sensor can capture digital images and create a 3D topographic model of the surface of a bullet for correlation. This system has produced superior correlation results with respect to the previous IBIS system [16].

At NIST, based on the 2D/3D Topography Measurement System, a prototype system has been developed for bullet signature identifications in which the 3D topography data of the land engraved areas (LEA) of fired bullets are captured by a commercial confocal microscope and processed by an "edge detection algorithm" to calculate the "striation density" [17]. This parameter enables one to identify and mask out areas with low striation density, called "invalid correlation areas" [17]. The modified 3D micro-topography data on the remaining "valid correlation areas" are compressed into a 2D profile which represents the 2D ballistics signature of the LEA [17]. A correlation program using two methods have been developed for matching the paired bullet signatures: the "CMS" (Consecutive Matching Striae) method currently used by some U.S. and International ballistics examiners [18], and the CCF_{max} (cross correlation function maximum) method investigated by NIST for topography measurements in surface metrology [3,5].

7. Initial Result

In July 2010, a set of 20 known-matching bullets fired from 10 consecutively manufactured gun barrels (two bullets fired from each barrel) were tested. The fact that the bullets were fired from consecutively manufactured barrels sets up a "worse case scenario", in which the surface topography of these barrels might have potentially the highest similarities. As a result, any potential misidentification caused by the similarity of the barrels' surface topographies could be maximized and tested. Their 3D topography images were captured by the confocal microscope at NIST, and correlated by the prototype ballistics identification system using the cross-correlation function maximum (CCF_{max}) as a correlation indicator. Ideally, the CCF_{max} value for the matching pair bullets must be the highest comparing with the CCF_{max} value of the other pairs of non-matching bullets. The correlation result was excellent: correlation values of all ten pairs of known-matching bullets occupy the topmost position on their respective correlation lists, yielding a correct correlation rate of 100 %. For the 60 pairs of matched LEAs (each bullet includes six LEAs), correlation values of 59 pairs out of 60 occupy the topmost positions on the correlation lists, yielding a correct identification rate for individual LEAs of 98.3 % [19].

In August 2010, a new set of 15 unknown matching bullets fired from the same set of 10 consecutively manufactured gun barrels was blind tested. These bullets were correlated with the set of 20 known-matching bullets mentioned above, in which only two bullets fired from the same barrel could match one of the second set of 15 unknown matching bullets. So the total correct matching pairs must be $2 \times 15 = 30$. Both the CCF and CMS method were used and showed excellent correlation results. When using the CMS method, one matching pair did not meet the CMS criterion for a "matching", and 29 out of 30 pairs of matching bullets were correctly identified, yielding a correct identification rate of 96.7 %. When using the CCF method, all 30 pairs of matching bullets scored the highest on their respective correlation lists, yielding a correct identification rate of 100 % [19]. Note that the CMS criteria were applied to topography images here and not to traditional reflectance microscopy images.

8. Surface Metrology Supports Ballistics Identification

Topography measurements for ballistics identifications in these series of tests have demonstrated superior correlations results. Topography measurements can directly measure and correlate geometrical ballistics signatures without being affected by lighting conditions. Topography measurements are traceable to the SI unit of length, and can utilize standardized surface parameters and algorithms for quantitative measurements of topography features. These parameters, including the NIST proposed parameters of topography difference D_s and cross correlation function maximum CCF_{max}, are in the public domain [3,20] and are subject to an open test. Furthermore, different topography measurement procedures such as form fitting, noise removal, data smoothing and filter [20], could be used for ballistics identifications and promote the correlation accuracy within large search databases.

One of the most commonly used procedures in surface metrology is the bandwidth filter [20]. Surface topographies (3D) and profiles (2D) normally include a wide range of surface spatial wavelengths, from the form deviation in the extreme long wavelength domain, through surface waviness in the meso-wavelength domain to surface roughness in the short wavelength domain [20]. However, for many topography comparisons and measurements, only a limited wavelength range, such as surface roughness, is of interest. An unambiguous extraction of the surface roughness from waviness and form deviation plays a key role in topography comparisons and measurements. High-pass Gaussian filters characterized by a long wavelength cutoff λc [20] can be used for this purpose.

Ballistics signatures, either the 2D striation signatures of the bullets or the 3D impression signatures of the cartridge cases, also include a wide range of wavelengths. The form and waviness components can be said to represent macro topography features, arising from the form and waviness of the firearm parts, and can be categorized as "Class Characteristics" or "Sub-class Characteristics" in forensic science [11], which are similar for bullets or cartridge cases fired or ejected from guns manufactured by the same process. In forensic science, "Class Characteristics" are used for assessing the potential type and manufacturer of a firearm [11]. On the other hand, the short wavelength components of ballistics signatures arise from the micro topography, or surface roughness, of the firearm parts. They represent, in addition to stochastic differences, the unique characteristics of the firearm parts. The micro topographies are unique for different guns, even those manufactured from the same manufacturing line one after another [11]. When the micro topography of the gun parts produces striations or impress marks on the surface of the bullets or cartridge cases, they produce the "Individual Characteristics" [11] of the ballistics signatures. In forensic science, "Individual Characteristics" are used for the identification of an individual firearm, and to connect the fired bullets or ejected cartridge cases to a firearm, a criminal act, and a possible suspect [11].

In ballistics identification, evidence bullet and cartridge case are compared with the firearm's test fired bullet and cartridge case to determine whether or not these bullets and cartridge cases are from the same firearm. Examiners first compare "Class Characteristics" to determine whether these bullets or cartridge cases are fired or ejected from weapons of the same type and manufacturer. Then examiners compare "Individual Characteristics" to determine whether these bullets or cartridge cases are from the same firearm. An unambiguous extraction of "Individual Characteristics" from the "Class Characteristics" and "Sub-class Characteristics" has particular importance in ballistics identification. If the "Class Characteristics" or "Sub-class Characteristics" are inappropriately included in the "Individual Characteristics", it could result in an inaccurate correlation. The optimum selection of a Gaussian filter long-wavelength cutoff length might be helpful for an unambiguous extraction of "Individual Characteristics" from "Class Characteristics" and "Sub-class Characteristics", and promote better correlation results [21].

9. Summary

Ballistics signatures are geometrical surface topographies. Traditionally, ballistics identifications are based on image comparisons using optical microscopes. The correlation accuracy depends on image quality which can be affected by lighting conditions. Since the 1980s, development of computer technology and optical instrumentation has helped make possible direct measurement and correlations of topography signatures for automated ballistics identifications.

A prototype bullet signature identification system has been developed at NIST based on a commercial confocal microscope and the NIST Topography Measurement System with special analysis software. Initial tests using a set of 20 known-matching bullets and a set of 15 unknown matching bullets, all fired from 10 consecutively manufactured gun barrels, have shown accurate correlation results.

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