Forensic Science International 284 (2018) 15–32

Contents lists available at ScienceDirect

Forensic Science International

journal homepage: www.elsevier.com/locate/forsciint

Estimating error rates for firearm evidence identifications in forensic science

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ARTICLE INFO

Article history:
Received 21 July 2017
Received in revised form 6 November 2017
Accepted 6 December 2017
Available online 13 December 2017

Keywords:
Forensics
Firearm
Ballistics identification
Error rate
Congruent matching cell
CMC

ABSTRACT

Estimating error rates for firearm evidence identification is a fundamental challenge in forensic science. This paper describes the recently developed congruent matching cells (CMC) method for image comparisons, its application to firearm evidence identification, and its usage and initial tests for error rate estimation. The CMC method divides compared topography images into correlation cells. Four identification parameters are defined for quantifying both the topography similarity of the correlated cell pairs and the pattern congruency of the registered cell locations. A declared match requires a significant number of CMCs, i.e., cell pairs that meet all similarity and congruency requirements. Initial testing on breech face impressions of a set of 40 cartridge cases fired with consecutively manufactured pistol slides showed wide separation between the distributions of CMC numbers observed for known matching and known non-matching image pairs. Another test on 95 cartridge cases from a different set of slides manufactured by the same process also yielded widely separated distributions. The test results were used to develop two statistical models for the probability mass function of CMC correlation scores. The models were applied to develop a framework for estimating cumulative false positive and false negative error rates and individual error rates of declared matches and non-matches for this population of breech face impressions. The prospect for applying the models to large populations and realistic case work is also discussed. The CMC method can provide a statistical foundation for estimating error rates in firearm evidence identifications, thus emulating methods used for forensic identification of DNA evidence.

1. Introduction

Tool marks are permanent changes in the topography of a surface created by forced contact with a harder object (the tool). 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 tool marks called “ballistic signatures” [1]. By examining these ballistic signatures side-by-side in a comparison microscope, 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.

Successful identification requires that the relevant firearm surfaces have individuality and that the tool marks are reproducible [1]. In general, tool marks have so-called “class characteristics” that are common to certain firearm designs and manufacturing methods, and “individual characteristics” arising from random variations in firearm manufacturing and wear [1]. While class characteristics can be used to exclude a firearm as a source of a recovered cartridge case or bullet, the patterns of individual characteristics are often unique to individual firearms and can therefore form the basis for identification [1]. These individual characteristics are marks produced by the random imperfections or irregularities of the firearm surfaces, which may arise during manufacture or by corrosion or damage during use [2]. In mechanical engineering terms, individual characteristics are approximately equivalent in scale to surface roughness irregularities [3].

Side-by-side tool mark image comparisons for firearm identification have a history of more than a hundred-years [1]. However, the scientific foundation of firearm and tool mark identification has been challenged by recent reports and court decisions. As stated in a 2008 National Academies Report [4], “*The validity of the fundamental assumptions of uniqueness and reproducibility of*

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https://doi.org/10.1016/j.forsciint.2017.12.013
0379-0738/

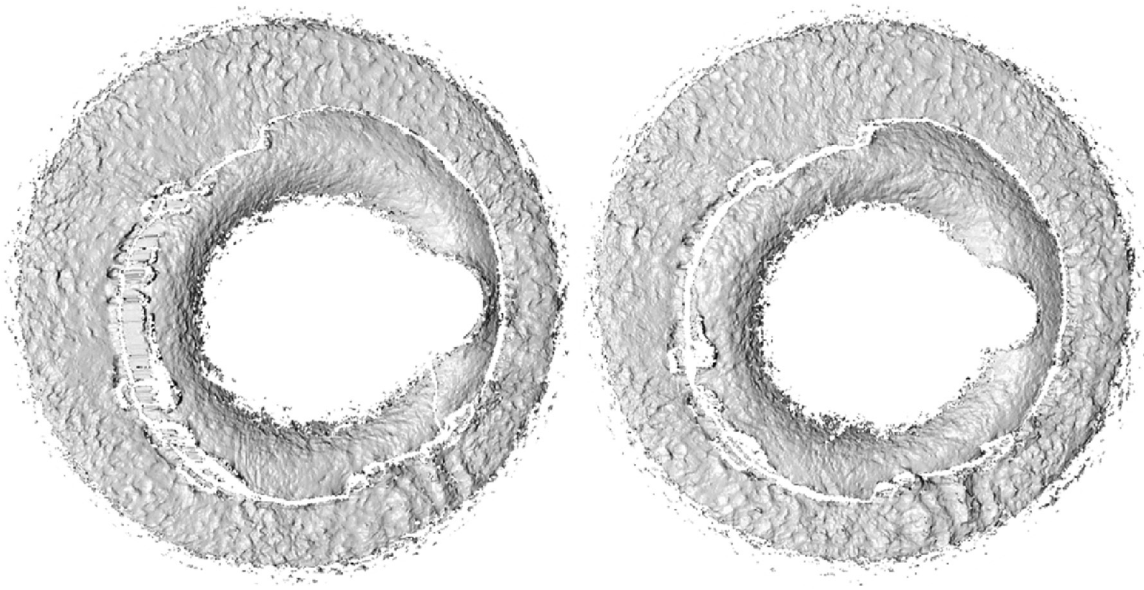

Fig. 1. Topography images of breech face impressions obtained from a pair of cartridge cases ejected from slide 3 in the Fadul data set [19] discussed here. The data set consisted of test fires of Federal[1] cartridges from consecutively manufactured Ruger 9 mm slides. The images have several features in common. The diameter of each image is about 3.5 mm. The topography contrast is rendered with a virtual light source from the left.

firearms-related tool marks has not yet been fully demonstrated . . . " and "*Since the basis of all forensic identification is probability theory, examiners can never really assert a conclusion of an 'identification to exclusion of all others in the world,' but at best can only assert a very small (objective or subjective) probability of a coincidental match.*"

The legal standard for the acceptance of scientific evidence contained in the U.S. Supreme Court decision, called the Daubert standard [4], "*places high probative weight on quantifiable evidence that can be tested empirically and for which known or potential error rates may be estimated, such as identification using DNA markers*" [4]. However, as stated in a 2009 National Academies Report [5], "*But even with more training and experience using newer techniques, the decision of the toolmark examiner remains a subjective decision based on unarticulated standards and no statistical foundation for estimation of error rates.*"

Since the 1980's, estimates of coincidental match probability (CMP) have been used for specifying uncertainty of DNA identifications: "*The courts already have proven their ability to deal with some degree of uncertainty in individualizations, as demonstrated by the successful use of DNA analysis (with its small, but nonzero, error rate)*" [5]. It is therefore a fundamental challenge in forensic science to establish a scientific foundation and statistical procedures providing quantitative error rate reports to support firearm identifications, in the same way that reporting procedures have been established for forensic identification of DNA evidence [5]. Several experimental and theoretical efforts have been pursued along this line including the computer learning approach of Petraco et al. [6,7], the work on likelihood ratio by Riva and Champod [8], the study of examiner error rates by Baldwin et al. [9], the feature-based matching algorithm of Lilien [10,11], the work on image cross correlation and congruent matching cells (CMC) of Song et al. [12–17], and the random forest approach of Hare et al. [18].

[1] Certain commercial equipment, instruments, or materials are identified in this paper to foster understanding. 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.

In this paper, we apply the CMC method [14–17] to estimations of error rates for false identifications and exclusions for two sets of topography image data of breech face impressions from fired cartridge cases. We discuss the CMC method in Section 2, then describe validation tests, error rate estimation procedures and initial results in Sections 3–5, and provide observations about future directions and the prospect for application to case work in Section 6.

2. Congruent matching cells (CMC) method

We begin with pairs of measured 3D topography images of breech face impressions whose similarity we wish to quantify (see Fig. 1). A common approach would be to calculate the value of the normalized cross-correlation function (Pearson's correlation coefficient) for the pair of images as a whole [12,13], when they are registered at a position of maximum correlation. Instead, the CMC method divides the reference image into a rectangular array of cells as shown in Fig. 2. For each cell on the reference image, an automated search is made on a compared image for a highly similar region. The cell-by-cell analysis is done because a firearm often produces characteristic marks, or individual characteristics [1], on only a portion of the bullet or cartridge case surface, depending on its degree of contact with the firearm during firing. Carrying over the terminology from previous research in firearms identification [14,15], a region of the surface topography is termed a "valid correlation region" if it contains individual characteristics of the ballistic signature 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" that should be eliminated from consideration for firearm identification. Invalid correlation areas can occur, for example, due to insufficient contact between the firearm's surface and the bullet or cartridge case during firing.

If two ballistic topographies A and B originate from the same firearm, both will likely contain valid and invalid correlation regions. When A and B are compared with each other, their common valid correlation region is the overlap of the individual valid correlation regions of A and B, which comprise only part,