FORENSICS @ NIST #NISTForensics

Congruent Matching Features (CMF) Method for Ballistics Identification with Subclass Characteristics

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In 2017, John was awarded a Ph.D. by the University of Warwick (UW), UK, for his published works in surface and forensic topography metrology at NIST from 1987-2017. The UW was established in 1965 in Coventry, UK. In 2016, UW was listed the #8 top university in UK and #45 in the world.

Outline:

- Motivation
- Previous work at NIST
- Proposed CMF method
- CMF for correlation of breech face images
- CMF for correlation of firing pin images with subclass characteristics
- CMF for database search of images
- Summary and future work

Motivation

- The NRC (2009) and PCAST (2016) report challenged US ballistics identification on the *"…fundamental assumption of uniqueness and reproducibility"* and *"…subjective decision without a statistical foundation for estimation of error rates."*
- To answer these challenges, researchers at NIST developed Congruent Matching methods for automatic and objective firearm evidence identification and error rate reporting, thus providing an objective scientific basis for firearm evidence identification.

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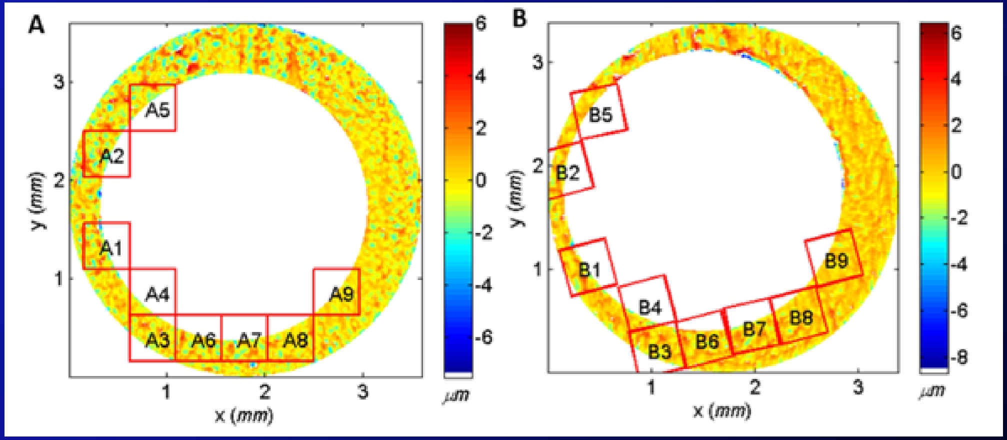
Proposed a Congruent Matching theory and developed correlation methods

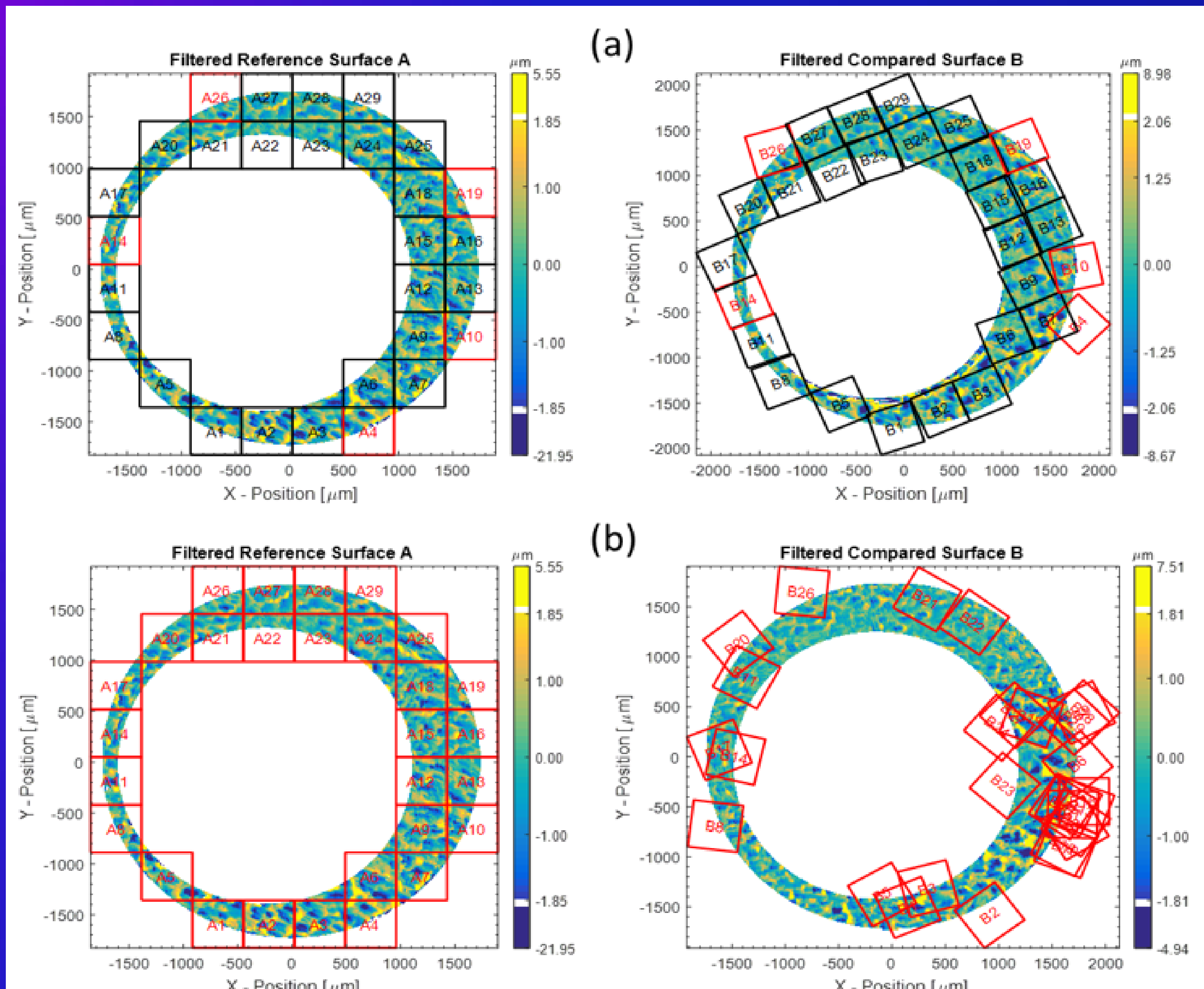
It is based on the principle of discretization:

- Divide the entire image into correlation cells.
- Derive multiple parameters for quantifying:
  1) Topography similarity of CMCs: CCF_{max}
  2) Pattern congruency of CMCs: ϑ and *x-y*
- Based on the statistical distribution of CMC, an error rate procedure was developed at NIST.



(Song, *J. AFTE*, ***45***, *2, 2013 &* ***47***, *3, 2015*)

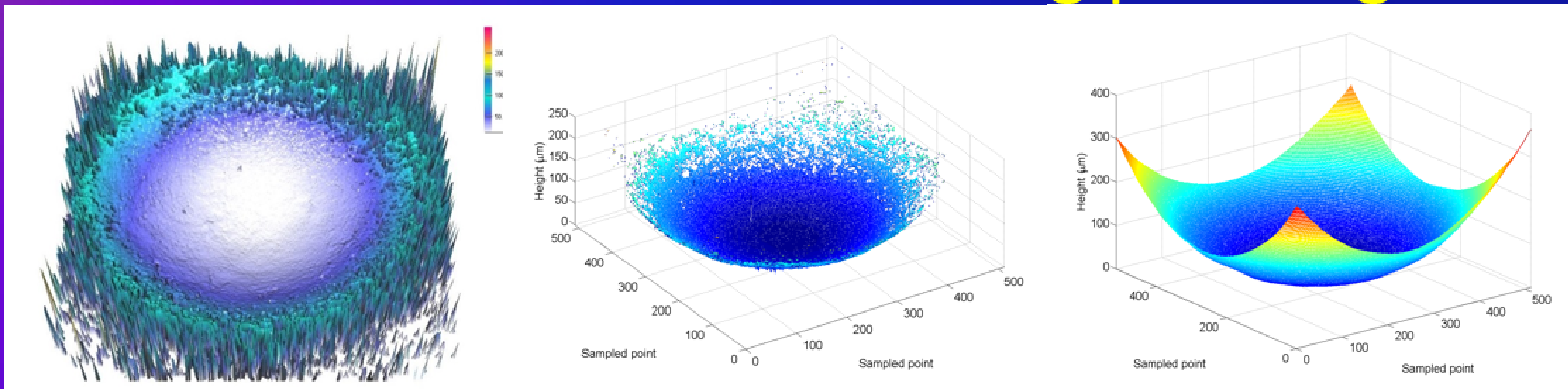
Developed Congruent Matching Cells (CMC) method for correlation of breech face images



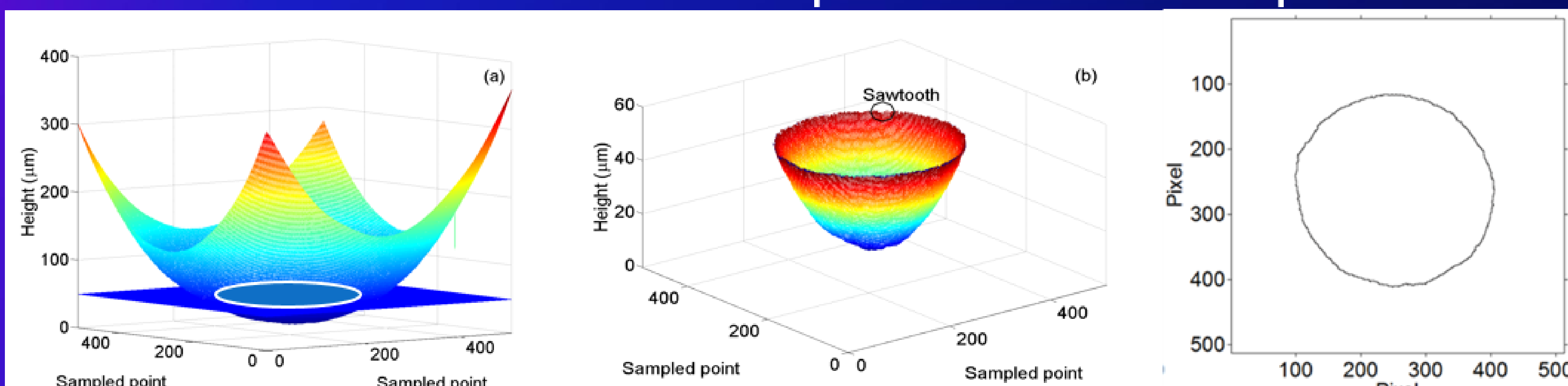
Cartridges fired from the same firearm (upper) and from different firearm (lower).

(Song et al, *Forensic Science International*, **284**, 2018, p15-32)

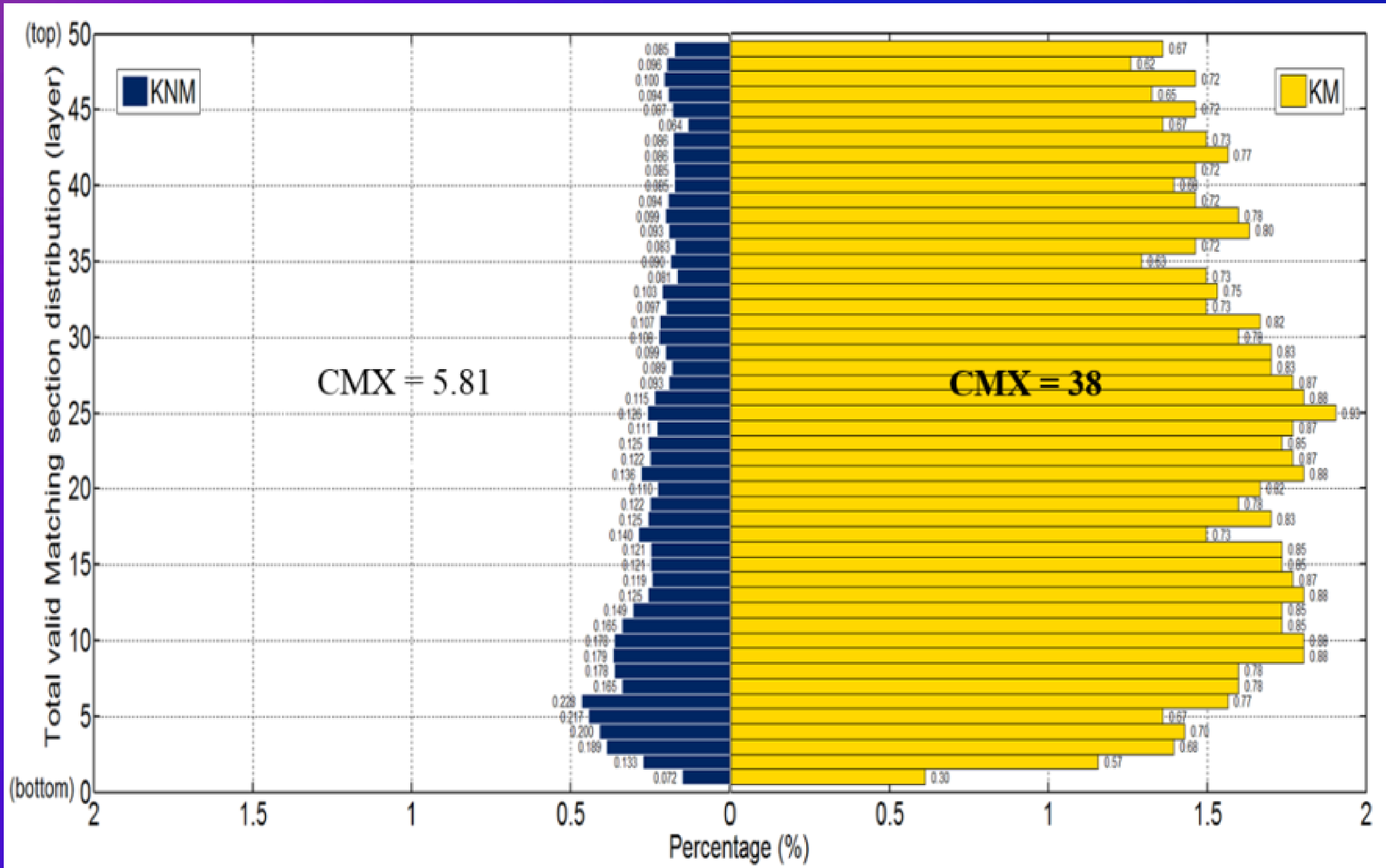
Congruent Matching Cross-sections (CMX) method for correlation of firing pin images



Raw data   Remove dropout & outlier   Spline filter



Slicing process   Raw cross-sections   Edge detection

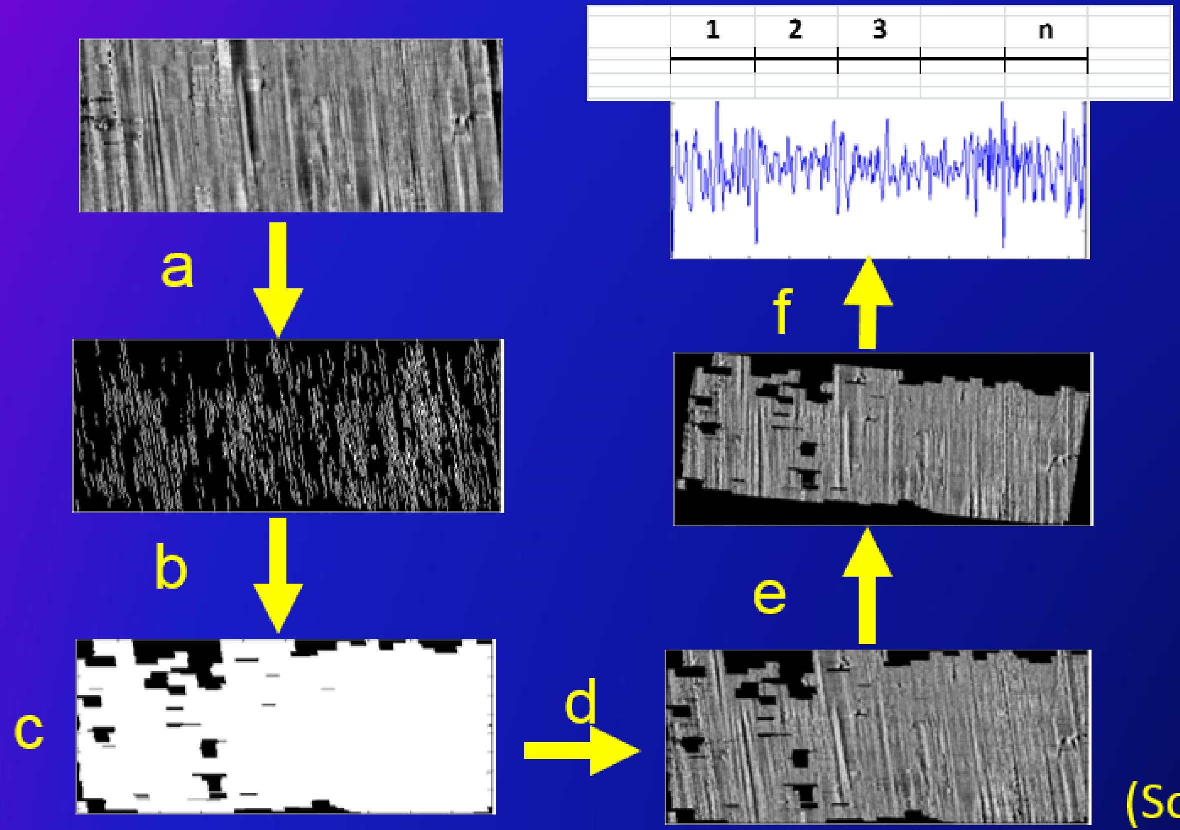


(Zhang, *et al*, *Forens. Sci, Int'l*, ***263***, *2016*)

The distribution of CMX scores by horizontal cross-sections. The average CMX for 60 KM image pairs is 38, and 5.81 for 720 KNM image pairs.

Congruent Matching Profile Segments (CMPS) method for correlation of bullet images

From a 3D confocal image to a set of compressed signature profile segments:

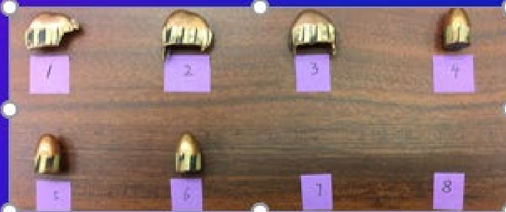


a. Flattened image after confocal imaging preprocessing
b. Striation edge detection
c. Mask image
d. Image with invalid area removed
e. Test twist angle θ
f. Compressed signature profile

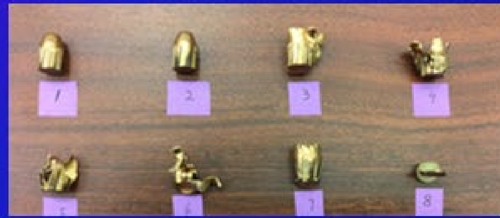
(Song, et al, 2016 AFTE meeting)

Congruent Matching Profile Segments (CMPS) method for correlation of 57 deformed bullets

Package 1:
6 Remington UMC

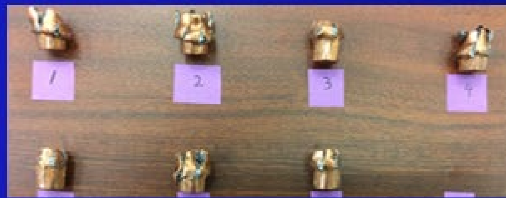


Package 2:
8 PMC Starfire



Package 3:
Speer Gold Dot

Package 4:
Hornady



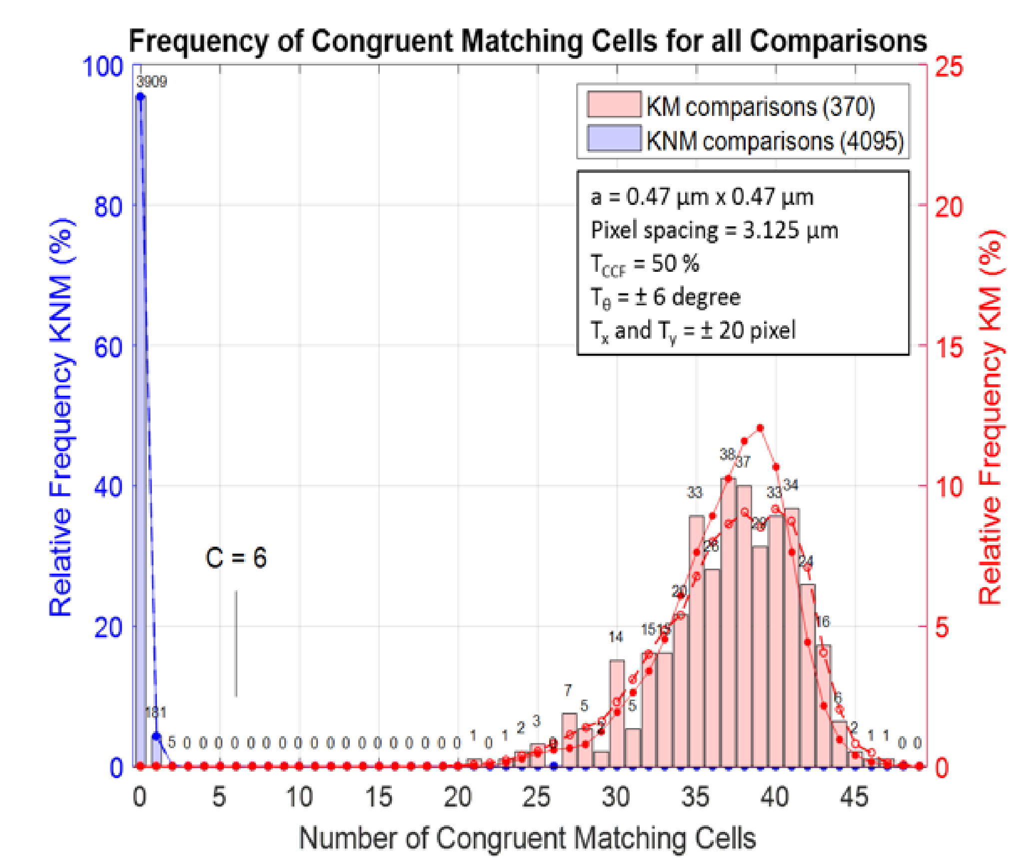
Package 5:
Federal Premium

Package 6:
Federal Classic

Package 7:
Remington Golden Saber

Conducted validation tests, developed an uncertainty procedure for error rate and likelihood ratio (LR) estimation

- 95 cartridges from guns with 10 consecutively manufactured pistol slides.
- 4465 image pairs: 370 KM-- (CMC = 21 to 47); 4095 KNM-- (CMC = 0 to 2).
- $E_1 = 5.9\times10^{-11}$, $E_2 = 3.8\times10^{-11}$.



(Song et al, *Forensic Science International*, **284,** 2018)

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ELSEVIER

Estimating error rates for firearm evidence identifications in forensic science

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A B S T R A C T

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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Estimating Error Rates for Firearm Evidence Identifications in Forensic Science

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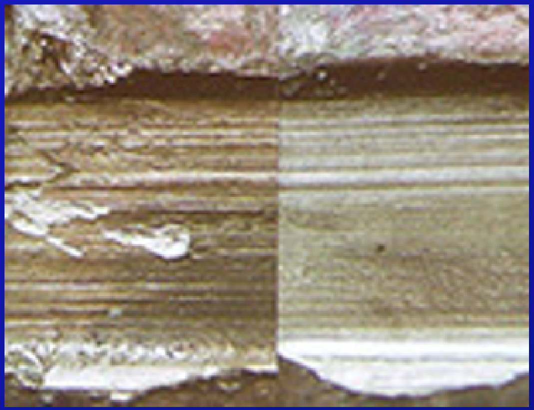
Available at https://www.sciencedirect.com/science/article/pii/S0379073817305200

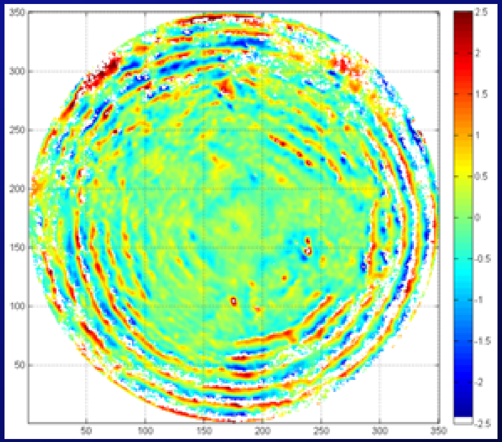
Subclass characteristics

Features that may be produced during manufacture that are consistent among items fabricated by the same tool in the same approximate state of wear. These features are not determined prior to manufacture and are more restrictive than class characteristics.

(AFTE GLOSSARY 6th Edition, Version 6, 2013)



Double-broaching manufacture marks on a group of Ruger firearms



Firing pin marks on a group of firing pins made by the same process

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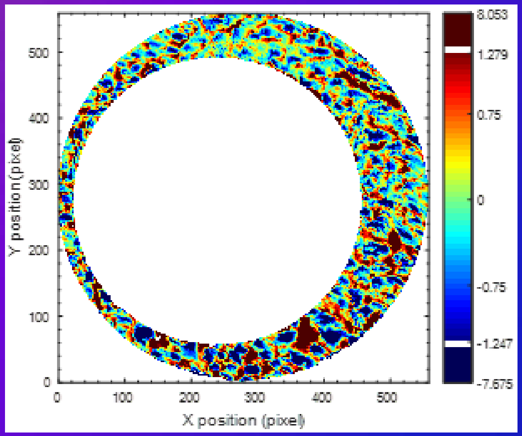
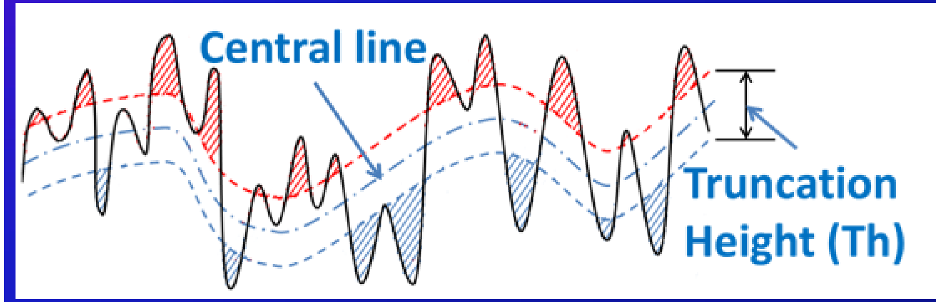
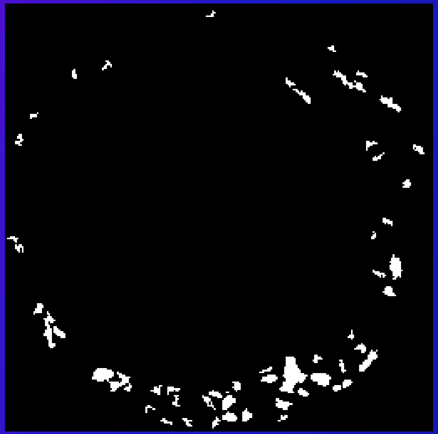
Feature extraction of the CMF method – Central truncation – Truncation height (*Th*)



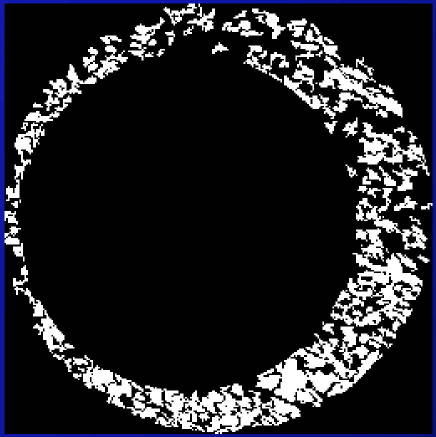


Th =
$2 \times k \times Sq$
Sq: rms roughness

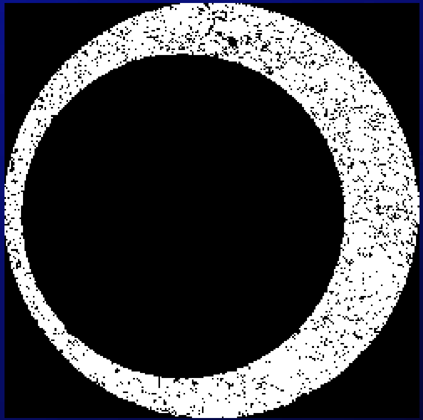
Optimize truncation height (*Th*)



$k = 1.5$,
Feature No. $= 55$

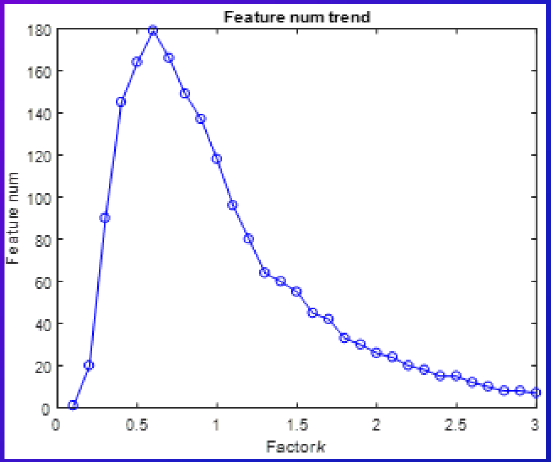


$k = 0.5$,
Feature No. $= 164$



$k = 0.1$,
Feature No. $= 1$

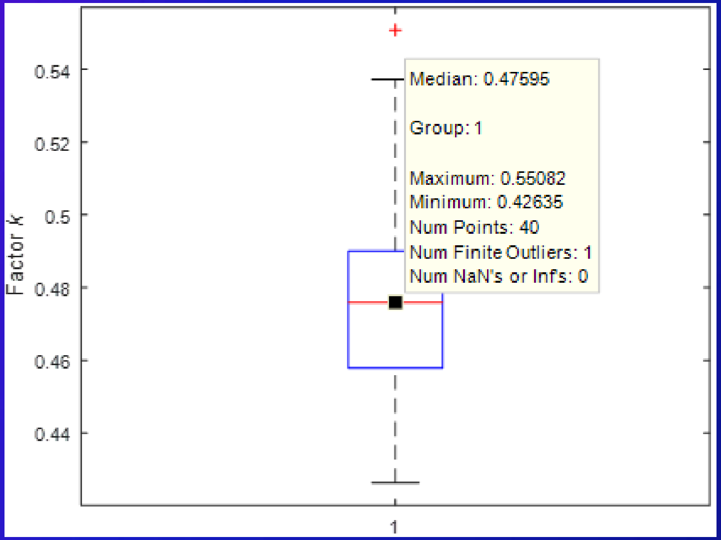
Optimize the truncation height (*Th*)



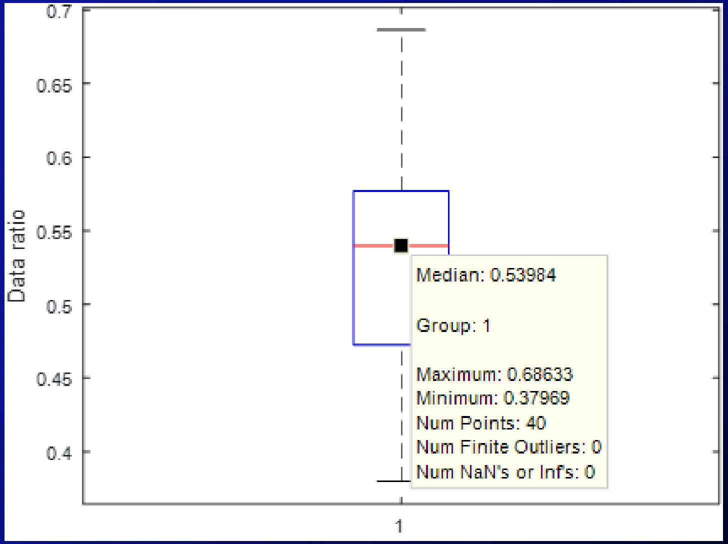
$$Th = 2 \times k \times Sq$$

Using advanced optimization algorithm in Matlab to find optimum data ratio of the 40 samples of Fadul dataset.

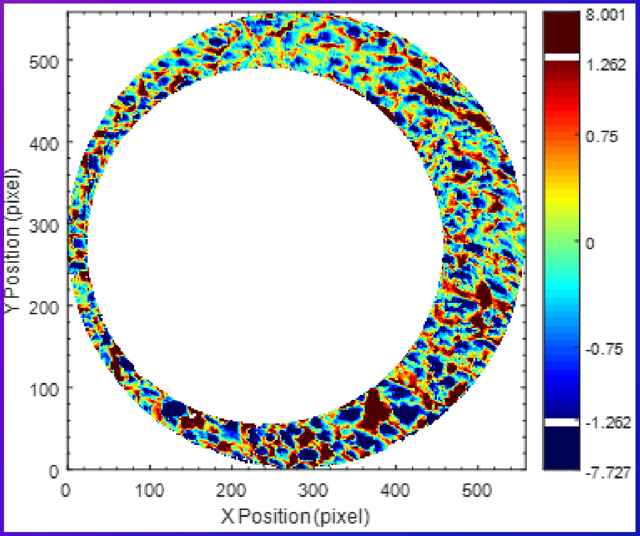
Factor $k = 0.476$, $k \approx 0.5$



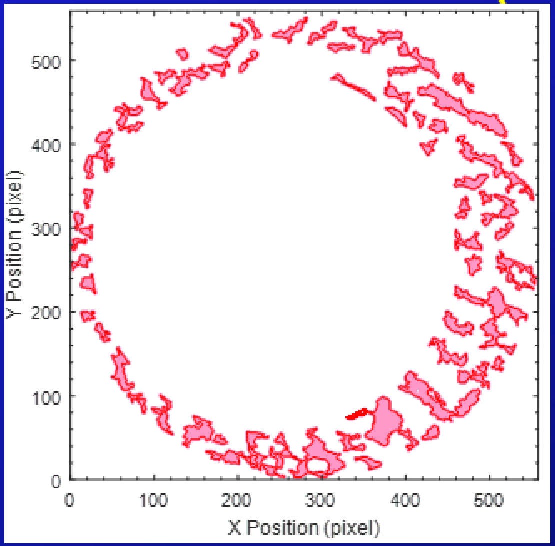
Data ratio = 54.0%



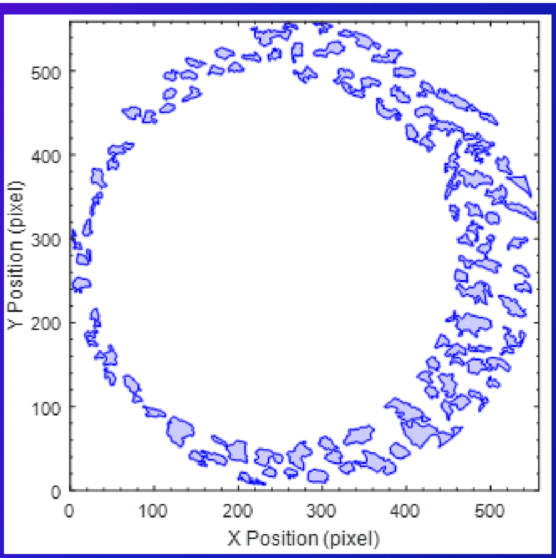
Extracted features from a breech face (BF) image



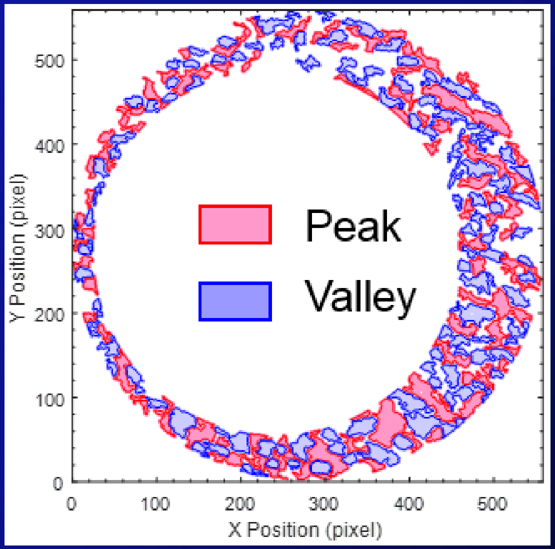
Topo-Map (TM)



Peak Feature (+1)



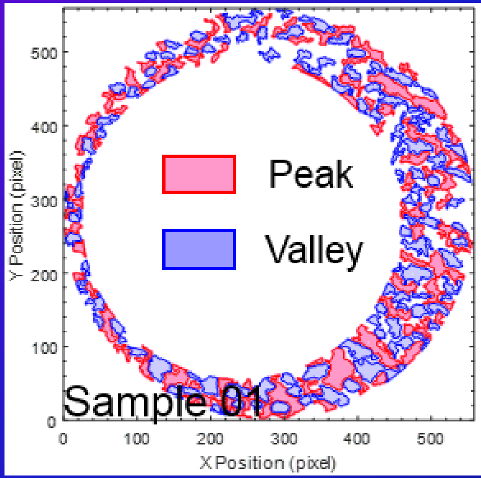
Valley Feature (–1)



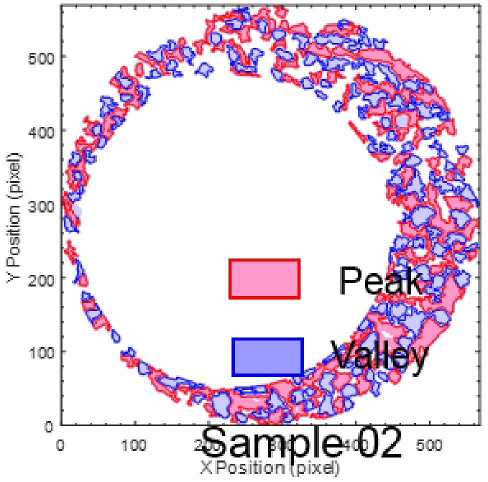
Feature Map (FM) (+1 / 0 / –1)

Feature registration by feature search score (FSS)

Feature map 01



Feature map 02



Feature Search Score (FSS) $= \sum\left(\begin{array}{|c|c|}\hline a_1 & a_2 \\ \hline a_3 & a_4 \\ \hline \end{array} \text{ vs. } \begin{array}{|c|c|}\hline b_1 & b_2 \\ \hline b_3 & b_4 \\ \hline \end{array} \right)$

$$= a_1 \times b_1 + a_2 \times b_2 + a_3 \times b_3 + a_4 \times b_4$$

Peaks to peaks: $1 \times 1 = 1$ (positive contribution to FSS)

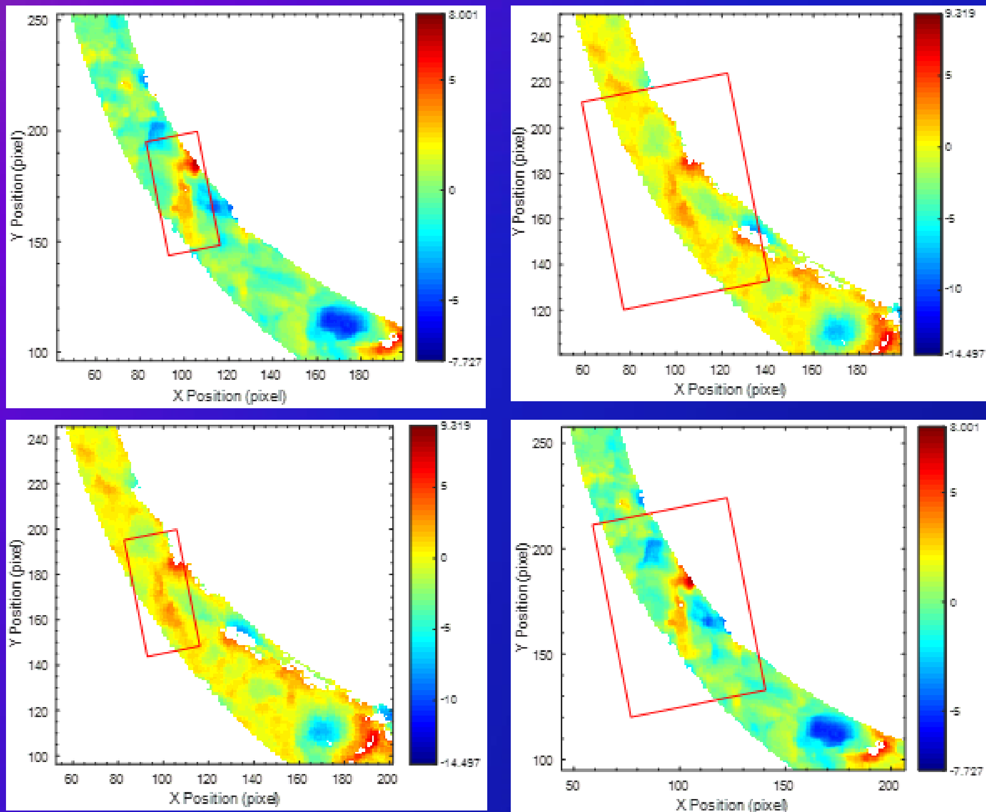
Valleys to valleys: $-1 \times -1 = 1$ (positive contribution to FSS)

Peaks to flat: $1 \times 0 = 0$ (zero contribution to FSS)

Valleys to flat: $-1 \times 0 = 0$ (zero contribution to FSS)

(P vs. V) or (V vs. P): $1 \times -1 = -1$ (negative contribution to FSS)

Feature correlation for KM image pairs



Forward correlation

CCF = 0.73 (T_{CCF} = 0.5)

x = -1 (T_x = 20)

y = 1 (T_y = 20)

Backward correlation

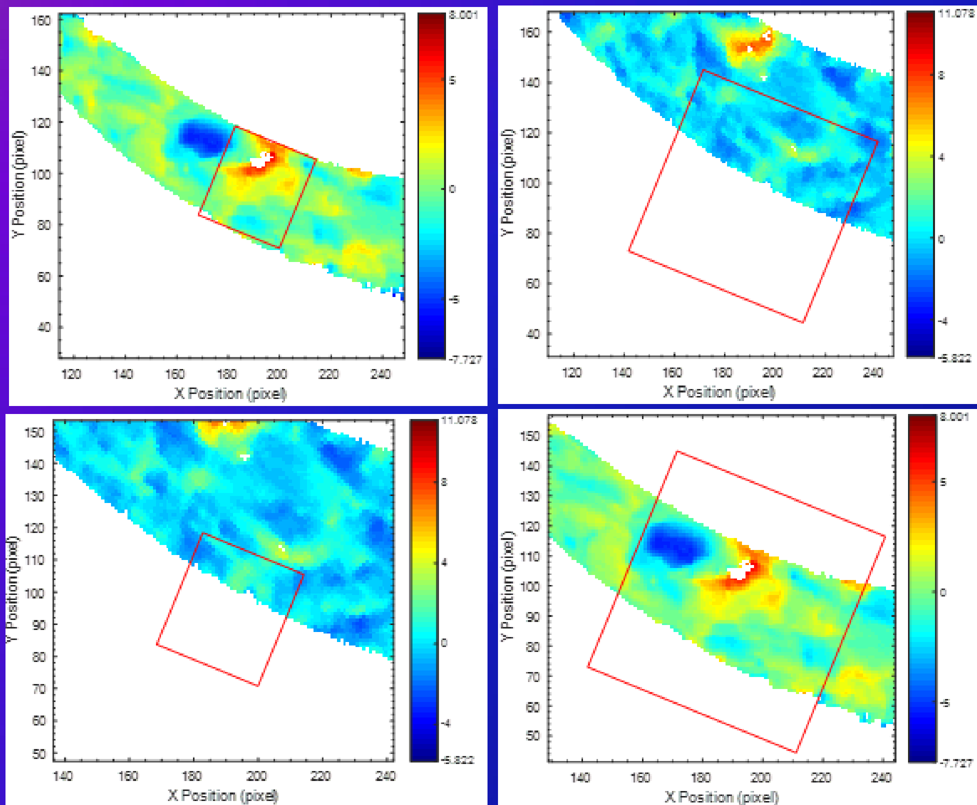
CCF = 0.73 (T_{CCF} = 0.5)

x = 2 (T_x = 20)

y = -1 (T_y = 20)

- The [x, y] value of forward and backward correlation are both relatively small, within a threshold range T_x and T_y.
- The sum of [x, y] (forward) and [x, y] (backward) is very small, since there exists an absolute maximum correlation position.

Feature correlation for KNM image pairs



Forward correlation

CCF = 0.51 (T_{CCF} = 0.5)

x = 2 (T_x = 20)

y = 0 (T_y = 20)

Backward correlation

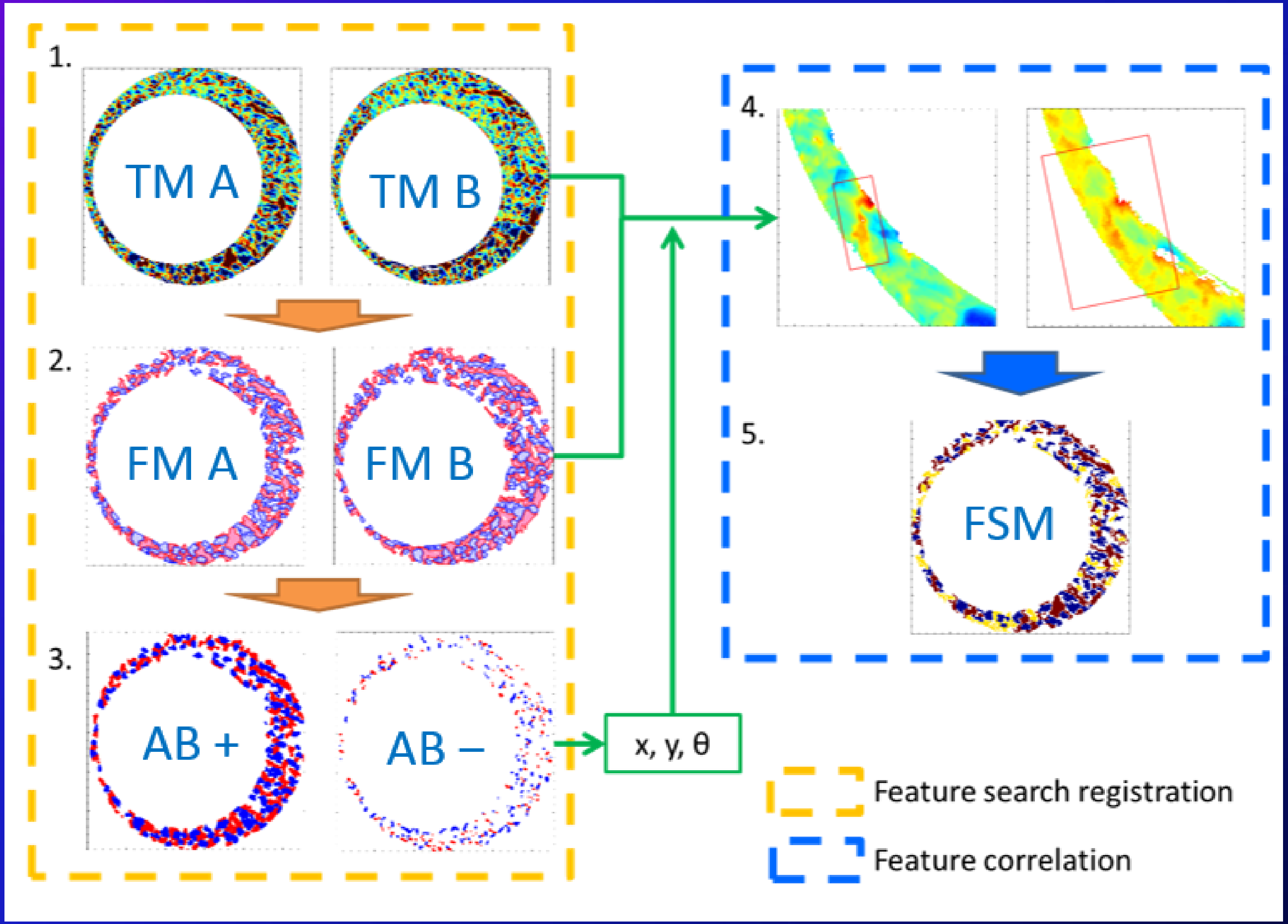
CCF = 0.55 (T_{CCF} = 0.5)

x = -30 (T_x = 20)

y = -31 (T_y = 20)

- The [x, y] value of forward and backward correlation are not both within a threshold range T_x and T_y.
- The sum of [x, y] (forward) and [x, y] (backward) is relative large, since there is not a "matching" position for KNM image pairs.

Process of the CMF method



1. Topography map (TM); 2. Feature map (FM); 3. FSS map;
4. Individual feature correlation; 5. Feature similarity map (FSM)

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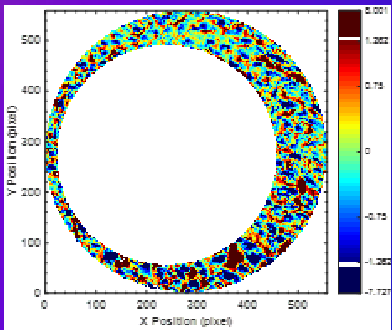
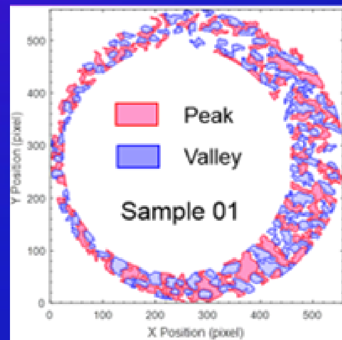
A comparison of a KM / BF image pair

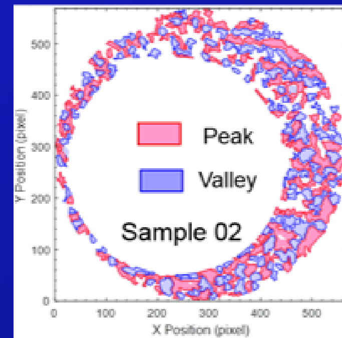
KM Topo-Map 01



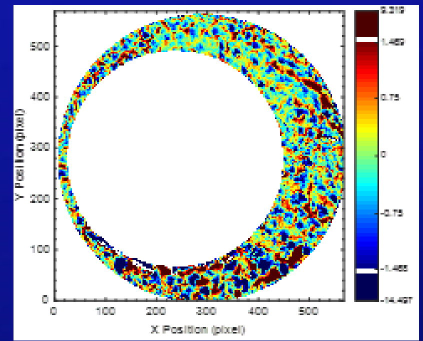
Feature Map 01



Feature Map 02

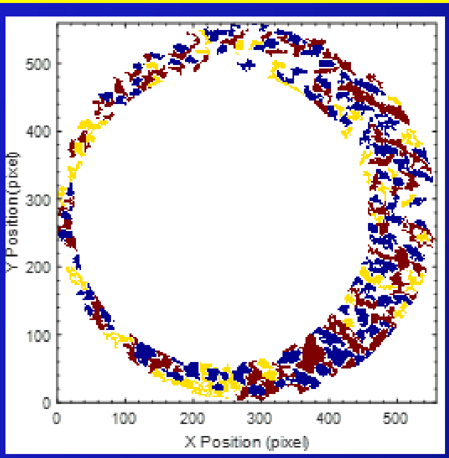


KM Topo-Map 02



FSS registration & KM features' correlation

KM Feature Similarity Map



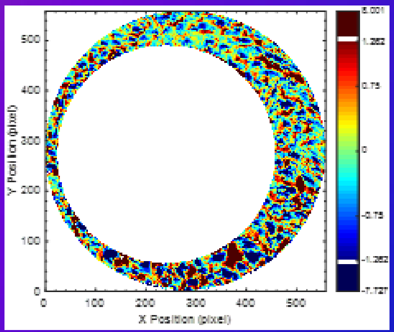
KM Sample 01 vs. 02

The feature similarity map shows the consistency of the ballistics features.

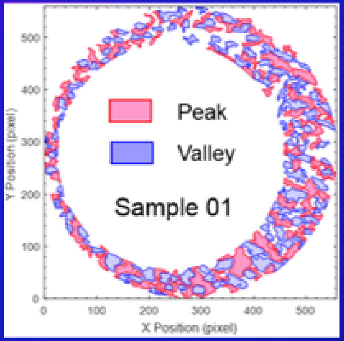
- Matching peaks
- Matching valleys
- Non-matching features
- Irrelevant regions

A comparison of a KNM / BF image pair

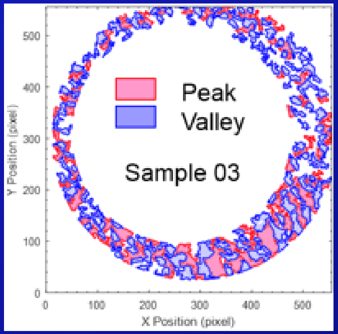
KNM Topo-Map 01



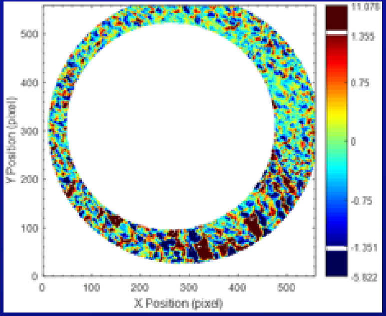
Feature Map 01



Feature Map 03

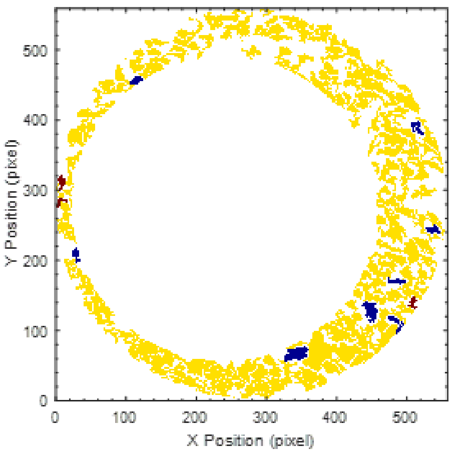


KNM Topo-Map 03



FSS registration & KNM features' correlation

KNM Feature Similarity Map



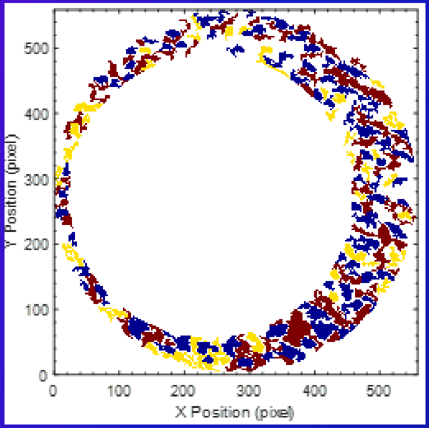
KNM Sample 01 vs. 03

Most of the regions show non-matching features.

- Matching peaks
- Matching valleys
- Non-matching features
- Irrelevant regions

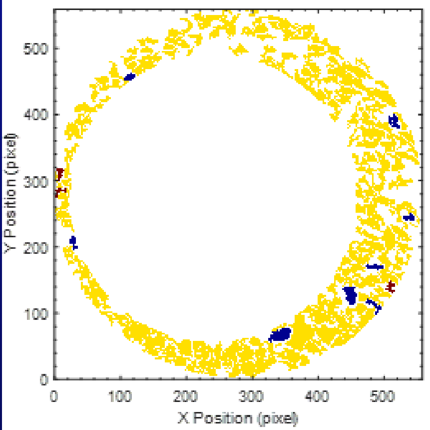
Three parameters for CMF method

1. Feature Search Score (FSS) X, reflects the similarity of overall features.
2. Congruent feature number N, reflects the total number of congruent matching features.
3. Relative feature size Z (%), equals (total CMF size) / (total extracted feature size), reflects the validity (or weight) of the congruent matching features.



KM #01 vs. #02

CMF	KM	KNM
X (FSS)	29,466	4,265
N	107	12
Z (%)	69.27%	6.12%



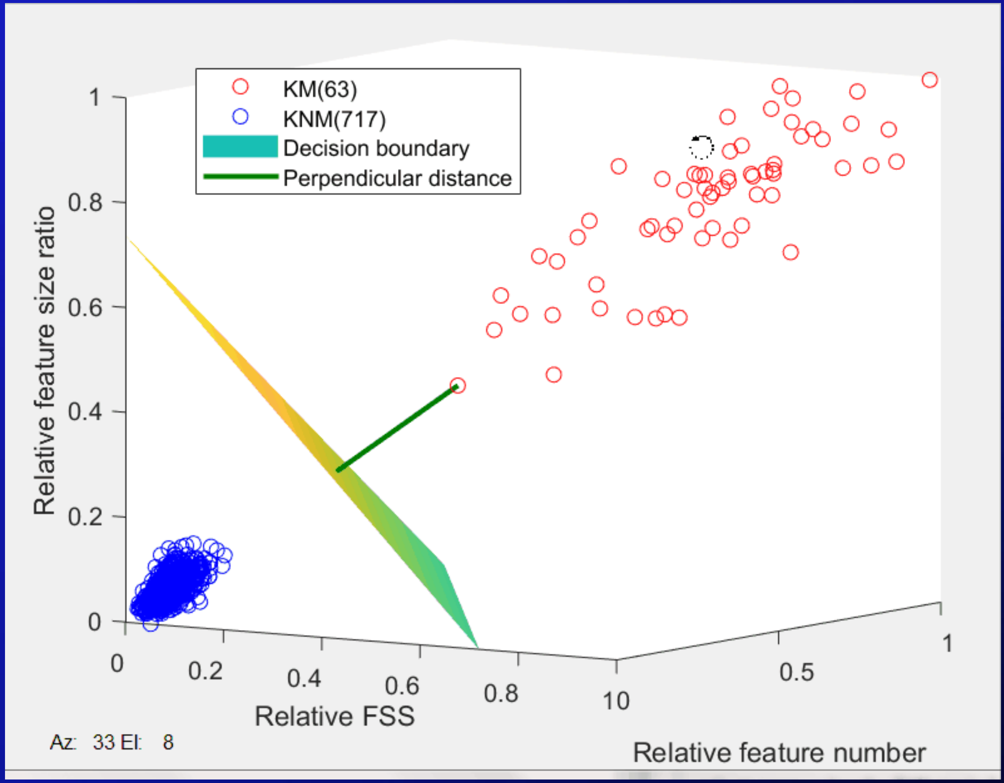
KNM #01 vs. #03

Test of CMF method using 40 Fadul breech face (BF) images

By combining the three identification parameters:

1) FSS,
2) Feature numbers N,
3) Relative feature size (Z%)

A decision boundary is determined by the Support Vector Machines (SVM) Method*. The KM and KNM CMF scores show clear separation.



(*Trevor et al., The Elements of Statistical Learning, Springer, NY, 2008.)

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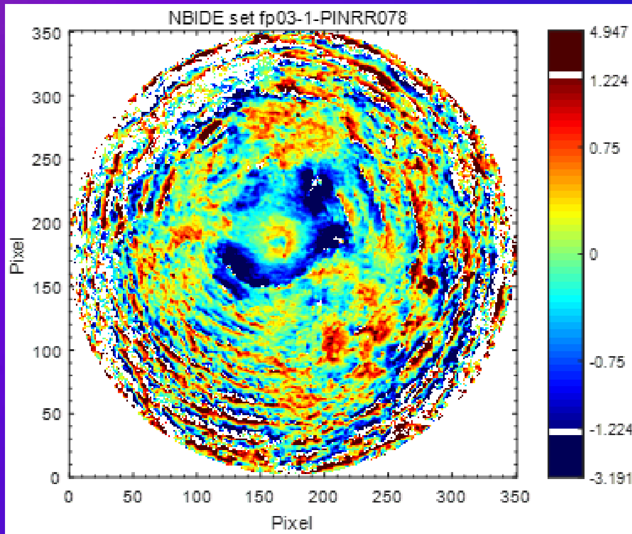
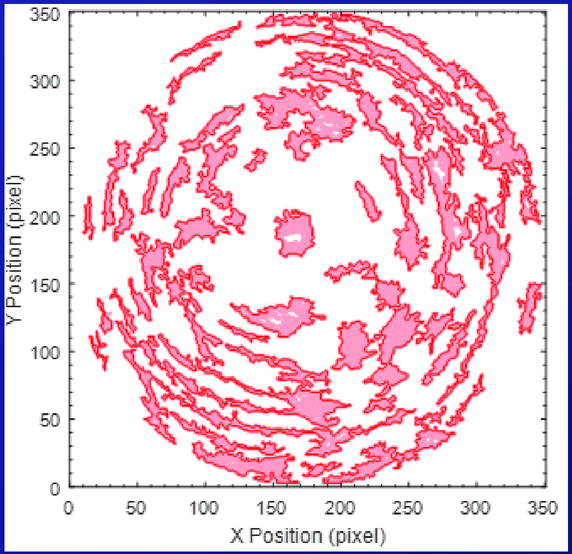
- CMF for correlation of firing pin images with subclass characteristics
- CMF for database search of images
- Summary and future work

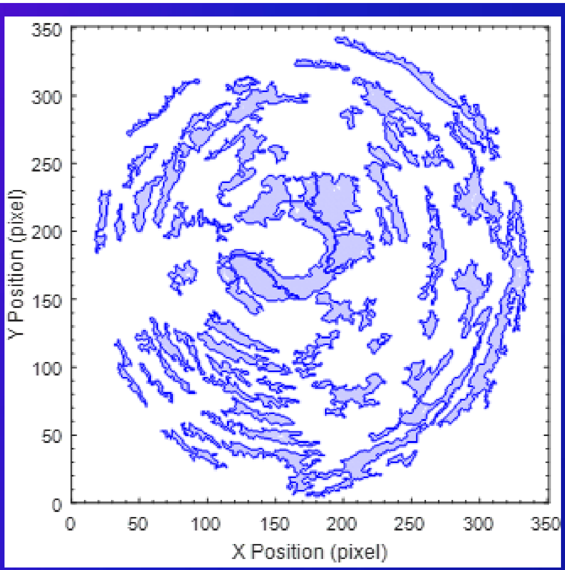
A FP image with sub-class characteristics



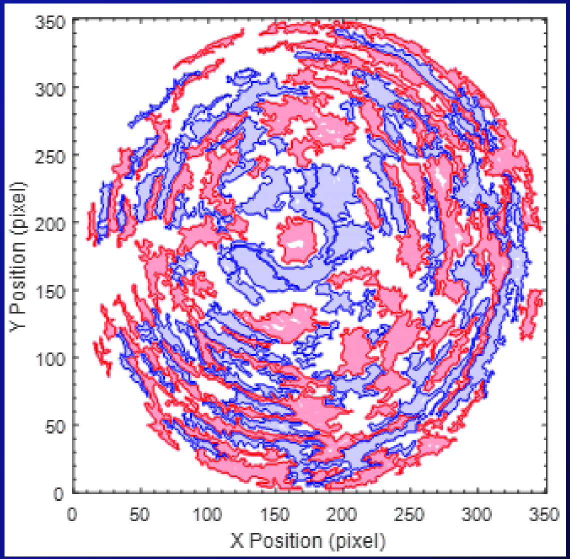
Topo-
Map
(TM)



Peak
Feature
(+1)



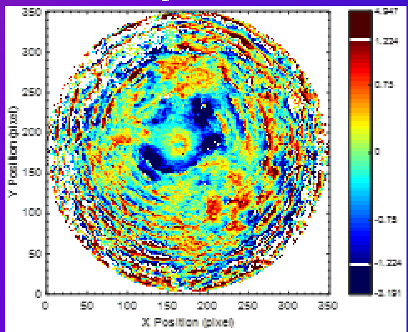
Valley
Feature
(–1)



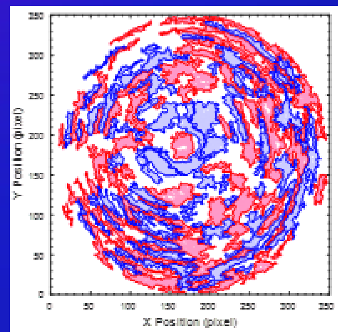
Feature
Map
(FM)
(+1 / 0 / –1)

A comparison of a KM FP image pair–

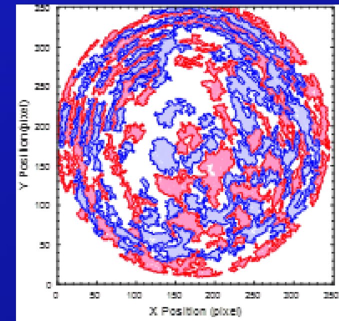
KM Topo-Map 3.1



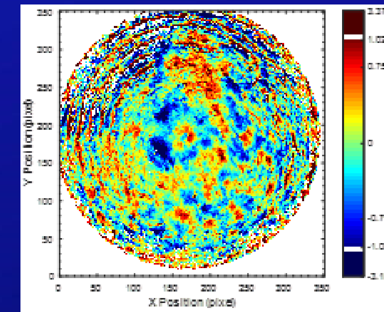
Feature Map 3.1



Feature Map 3.2

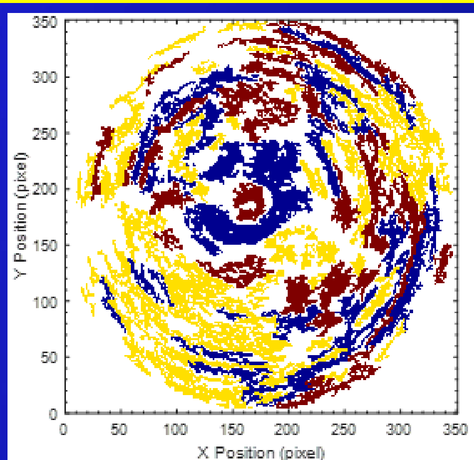


KM Topo-Map 3.2



FSS registration & KM features' correlation

KM Feature Similarity Map



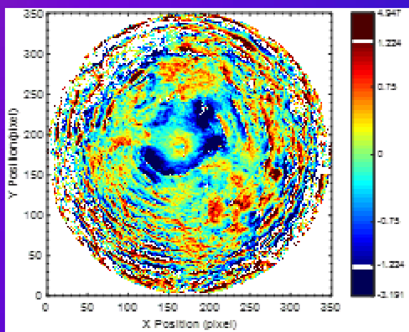
KM Sample 3.1 vs. 3.2

The feature similarity map shows the consistency of the ballistics features.

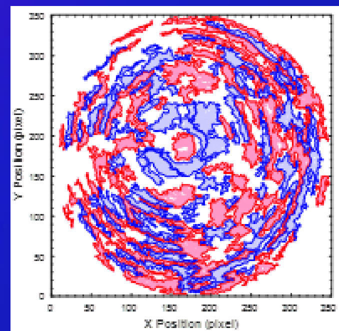
- Matching peaks
- Matching valleys
- Non-matching features
- Irrelevant regions

A comparison of a KNM FP image pair

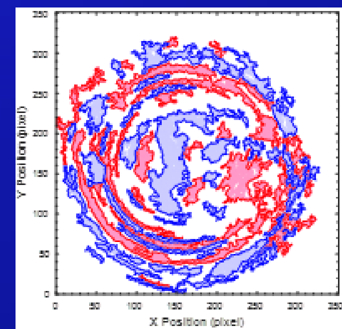
KNM Topo-Map 3.1



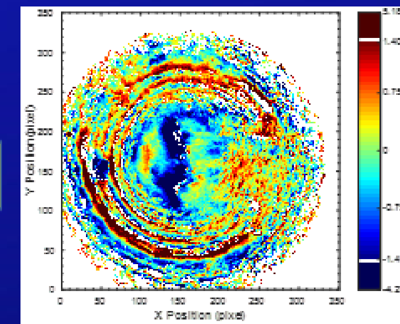
Feature Map 3.1



Feature Map 5.3

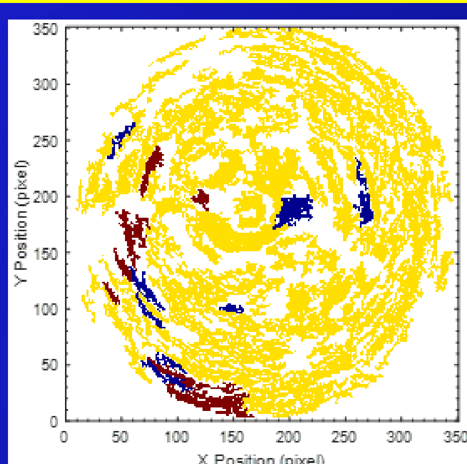


KNM Topo-Map 5.3



FSS registration & KNM features' correlation

KNM Feature Similarity Map



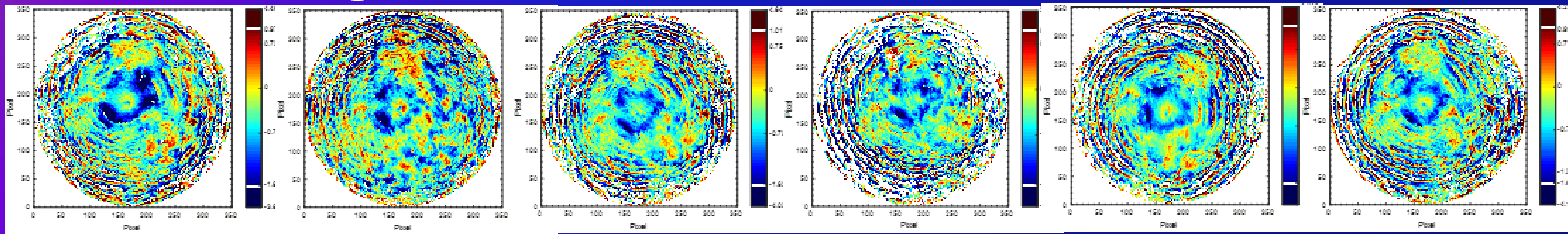
KNM Sample 3.1 vs. 5.3

Most of the regions show non-matching features.

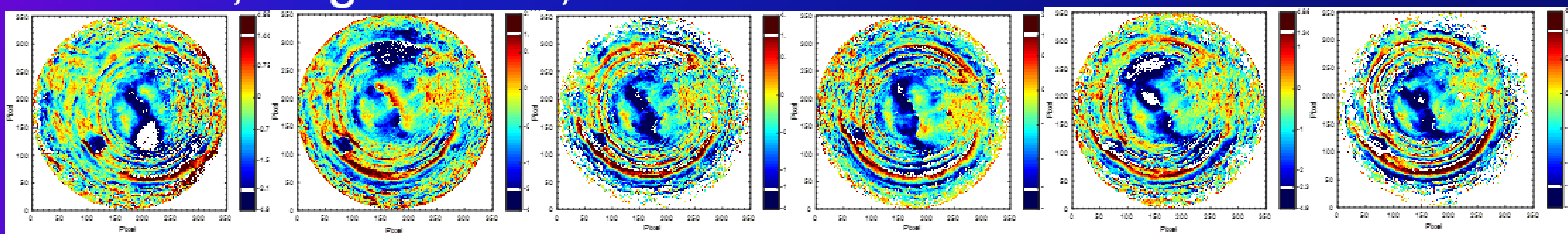
- Matching peaks
- Matching valleys
- Non-matching features
- Irrelevant regions

18 cartridges from 3 guns / 3 ammos all with circular subclass characteristics

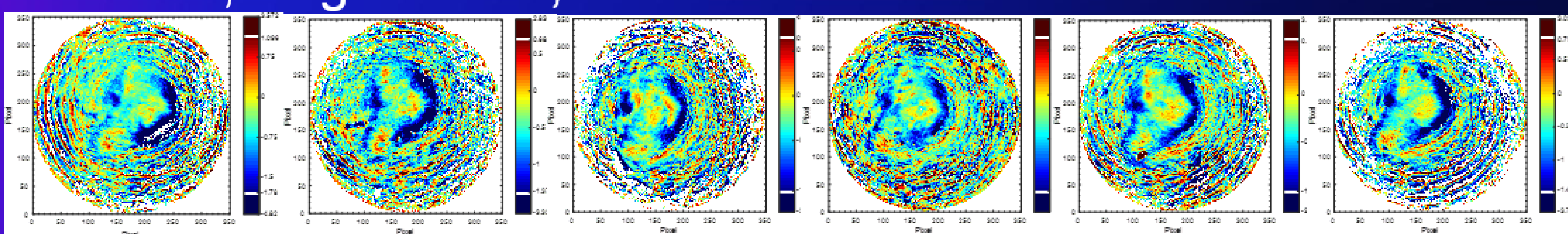
Gun #3, Ruger P95D, Serial#31545341



Gun #5, Ruger P95D, Serial#31545342



Gun #9, Ruger P95D, Serial#31545346

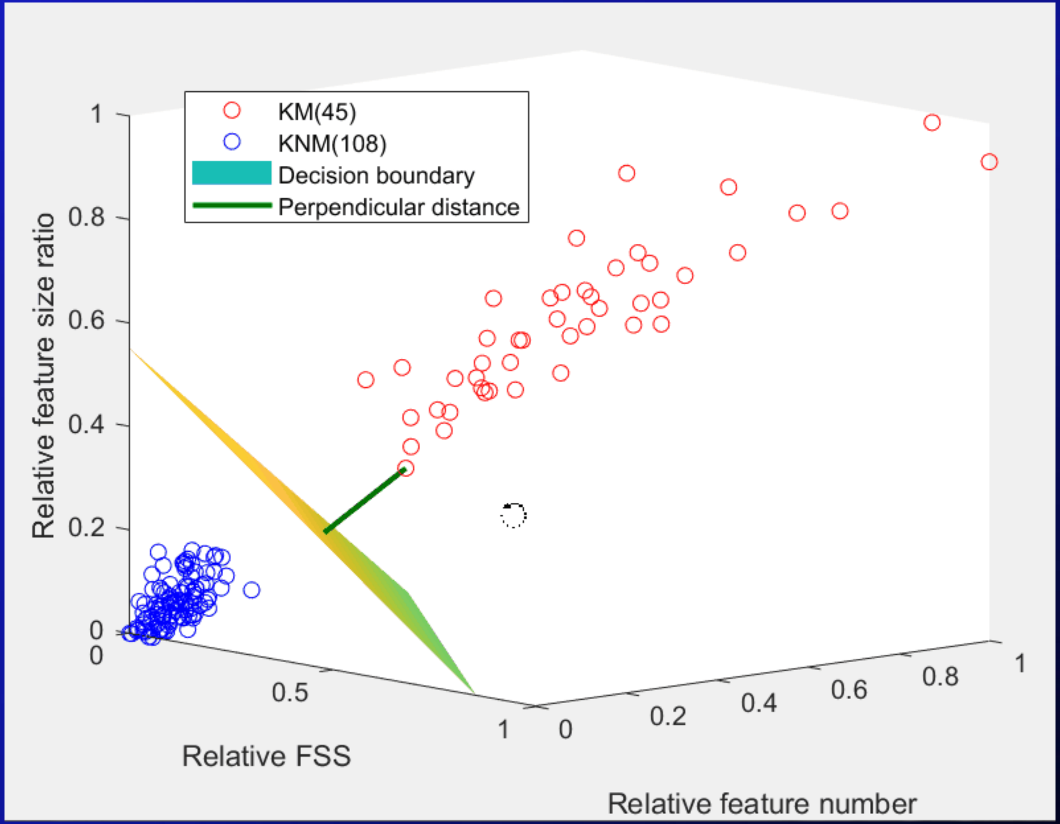


Test of CMF method using 18 NBIDE firing pin (FP) images

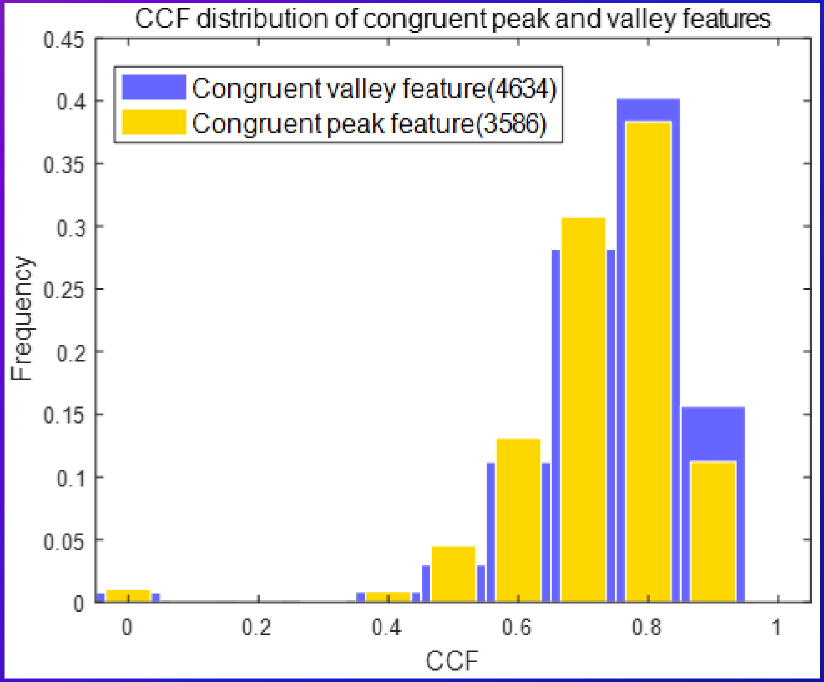
18 firing pin samples from 3 guns / 3 ammos, including 45 KM and 108 KNM image pairs.

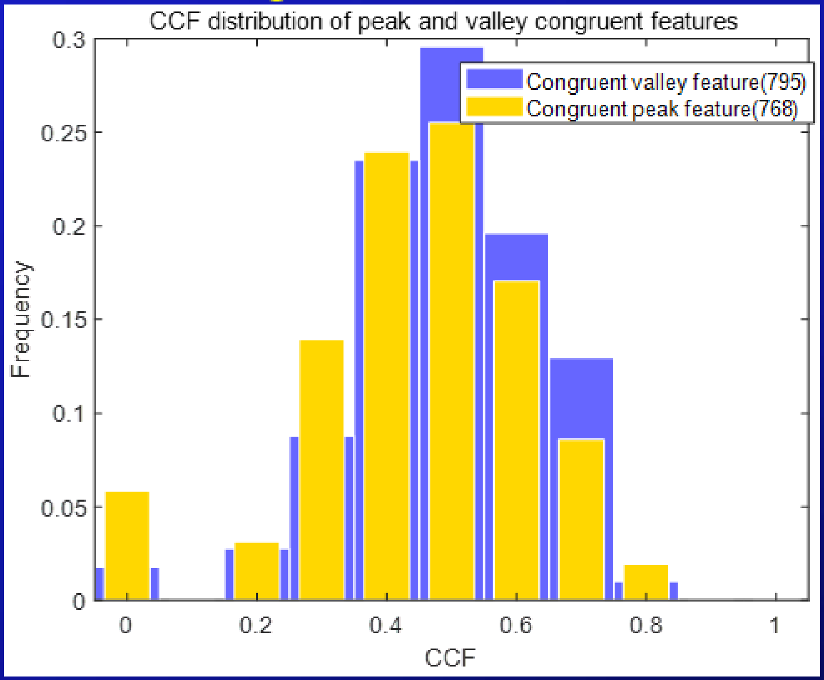
All with strong circular sub-class characteristics caused by the turning manufacturing process of firing pin.

Due to the curvature shape of the firing pin, images may have large area of dropouts.



Peak features vs. Valley features





CCF distribution of congruent peaks and valleys of 63 KM BF image pairs

CCF distribution of congruent peaks and valleys of 45 KM FP image pairs

It can be seen that:

- Congruent matching valleys are more than that of peaks.
- The CCF values of congruent matching valleys are larger.
- That suggests a larger influence of valley features for ballistics ID, and this effect is more significant for FP image pairs.

Outline:

- Motivation
- Previous work at NIST
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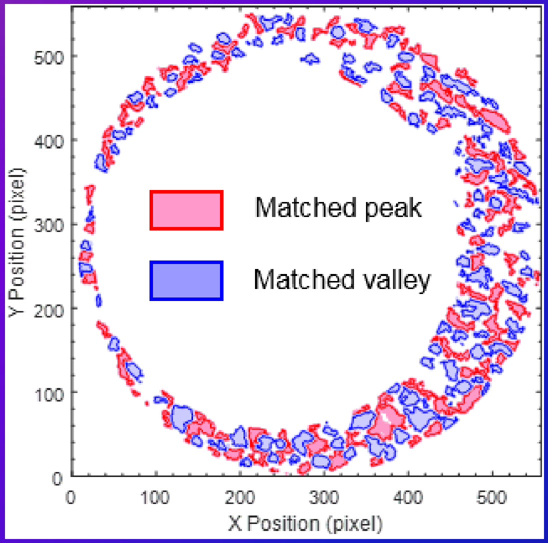
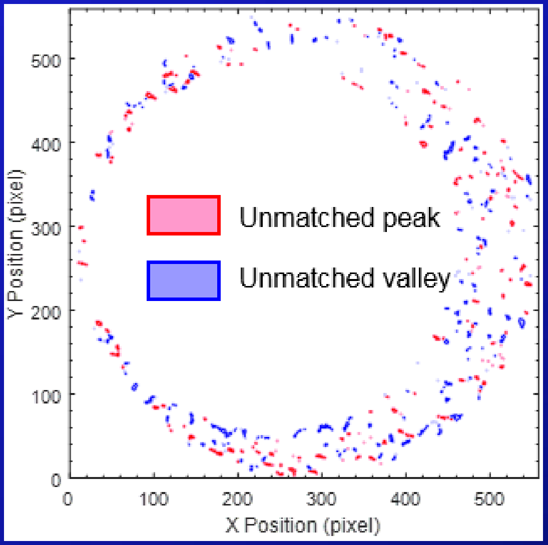
FSS for KM and KNM BF image pairs

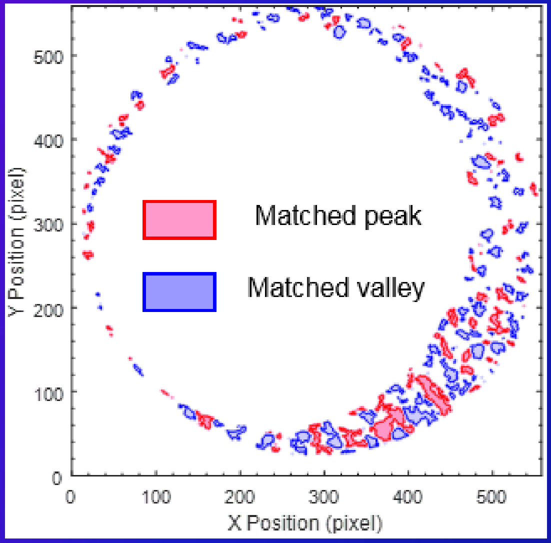


KM
01 vs. 02
p-p/v-v
FSS:
32,065

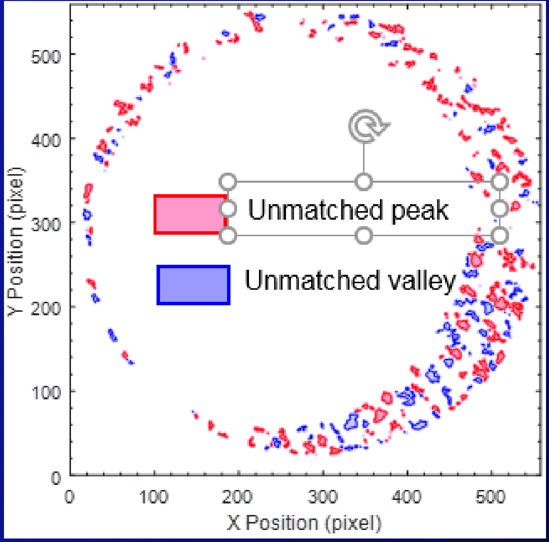


KM
01 vs. 02
p-v/v-p
FSS:
– 2,599

Sum FSS
29,466



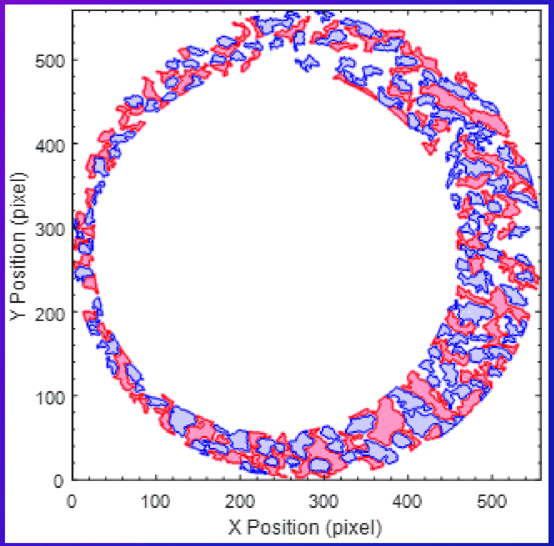
KNM
01 vs. 03
p-p/v-v
FSS:
12,041



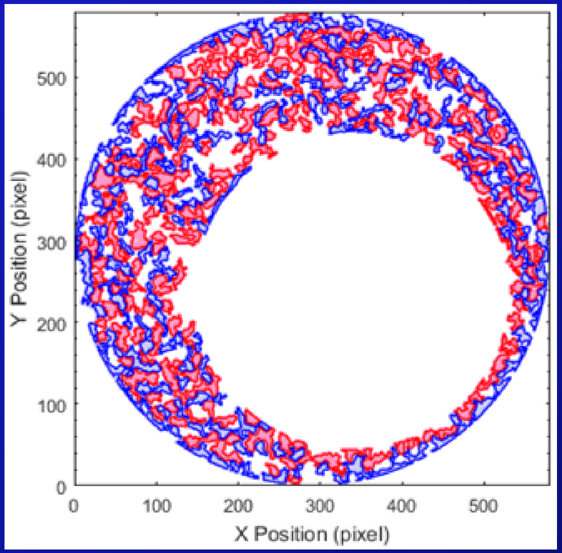
KNM
01 vs. 03
p-v/v-p
FSS:
– 7,776

Sum FSS
4,265

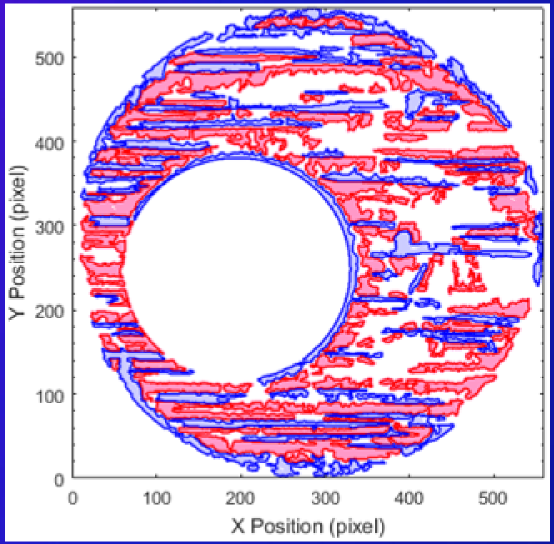
Database search on four datasets



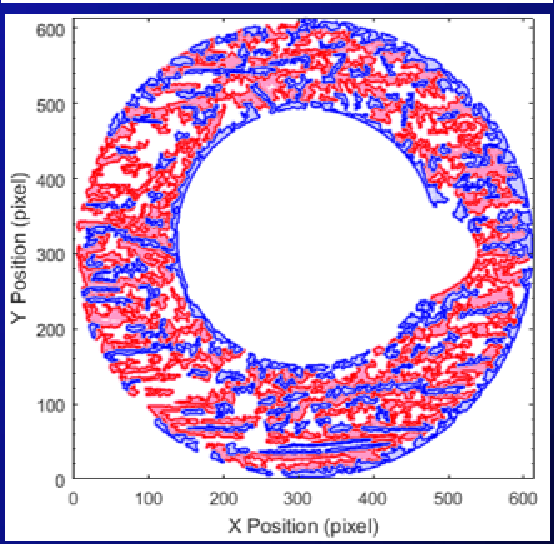
Fadul, 40 BF, 126 KM 1434 KNM



Weller, 95 BF, 740 KM 8190 KNM

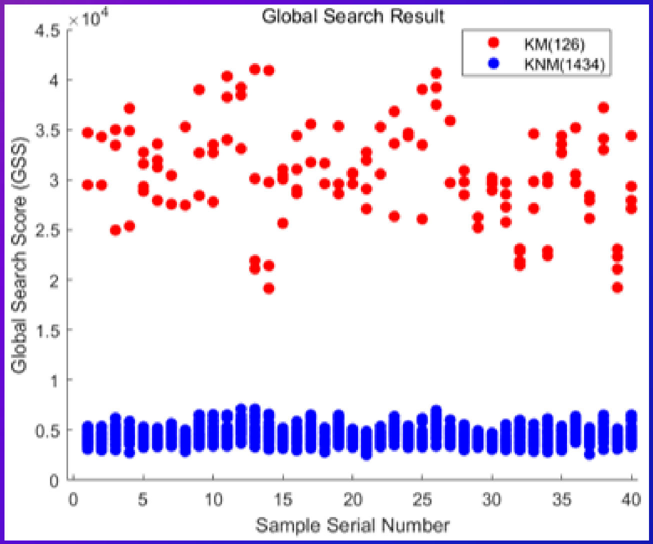


Hamby, 30 BF, 60 KM 810 KNM

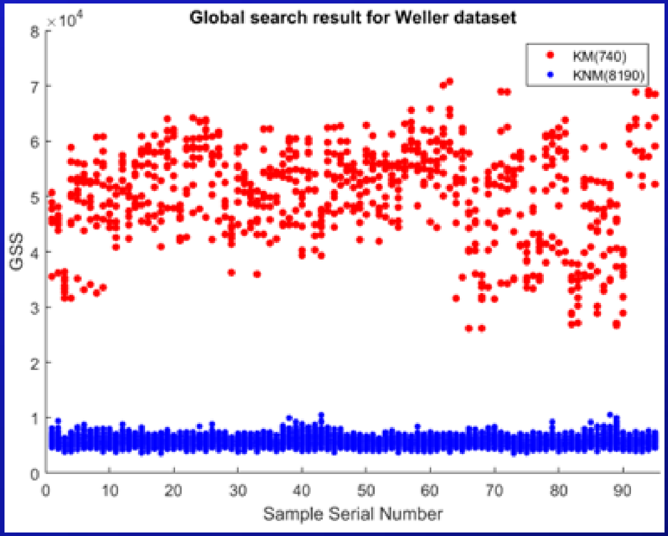


Light-stone, 30 BF, 60 KM 810 KNM

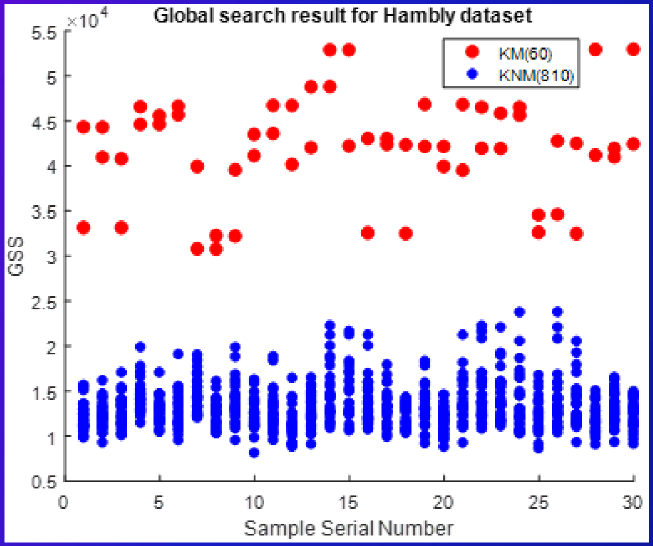
Database search on four datasets



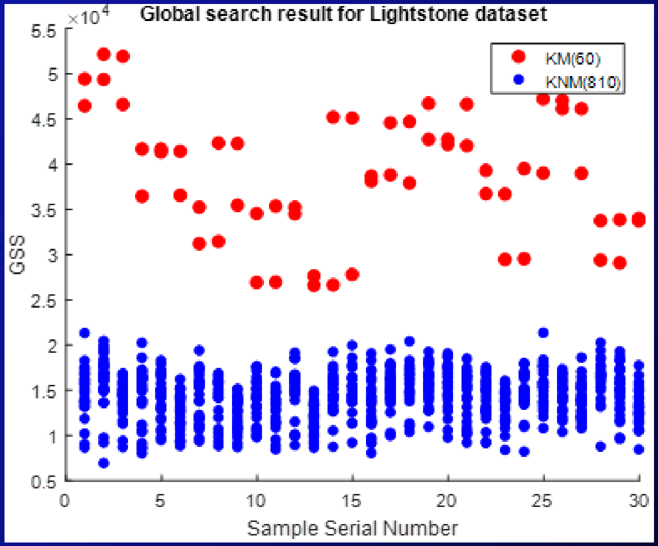
Fadul, 40 BF, 126 KM 1434 KNM



Weller, 95 BF, 740 KM 8190 KNM



Hamby, 30 BF, 60 KM 810 KNM



Light-stone, 30 BF, 60 KM 810 KNM

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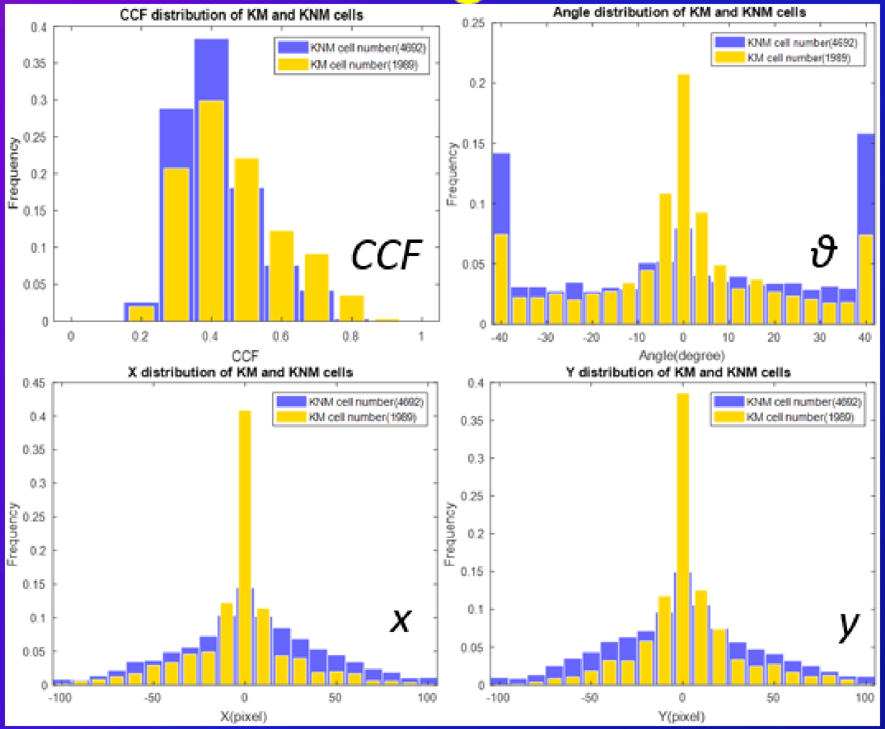
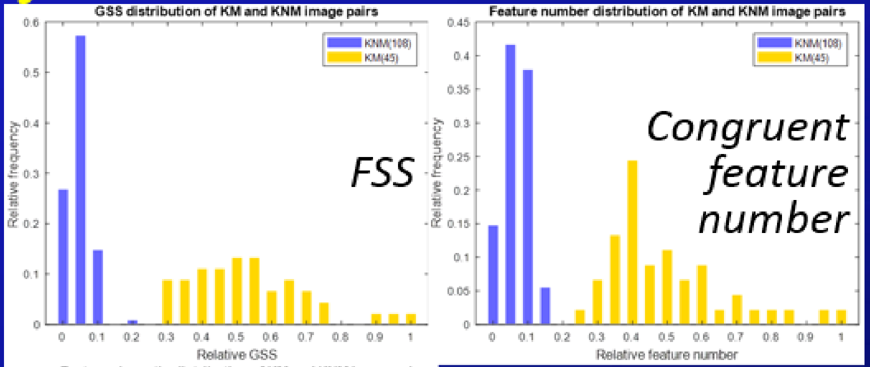
Advantages of the proposed CMF method

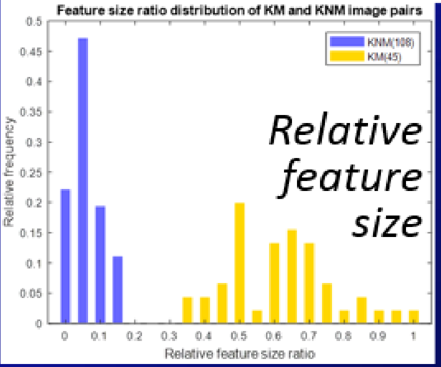
- Can be used for correlation of different types of BF and FP signatures, especially for those with subclass characteristics.
- Can provide a powerful tool -- Feature Similarity Map, to support visual examination by ballistics examiners.
- Image correlation based on binary feature maps with Feature Searching Score (FSS) can largely increase the correlation speed.
- CMF provides a new way for large database searching.

Advantages of the proposed CMF method
(continued)

- Potential higher accuracy: CMC vs. CMF







Three parameters.

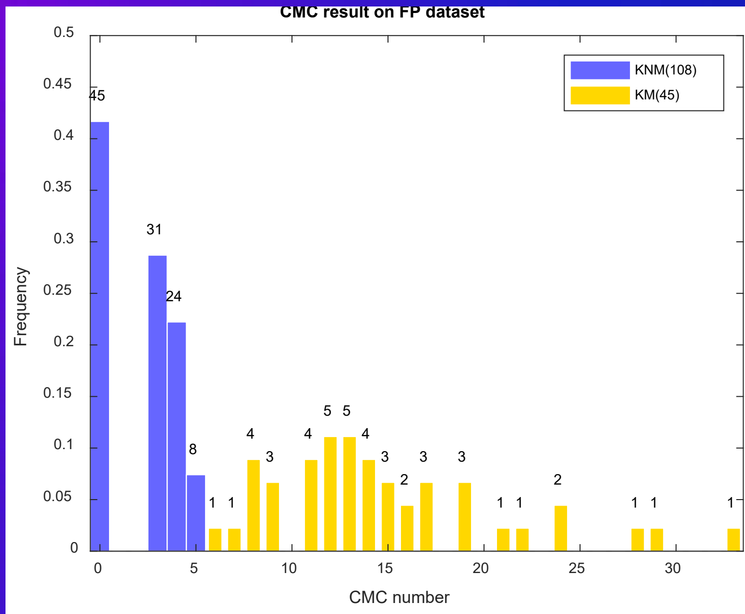
1. *FSS,*
2. *Congruent feature number,*
3. *Relative feature size.*

CMC method uses four parameters: *CCF, x, y,* and *ϑ,* each shows overlaps between the correlated cell pairs from KM and KNM image pairs.

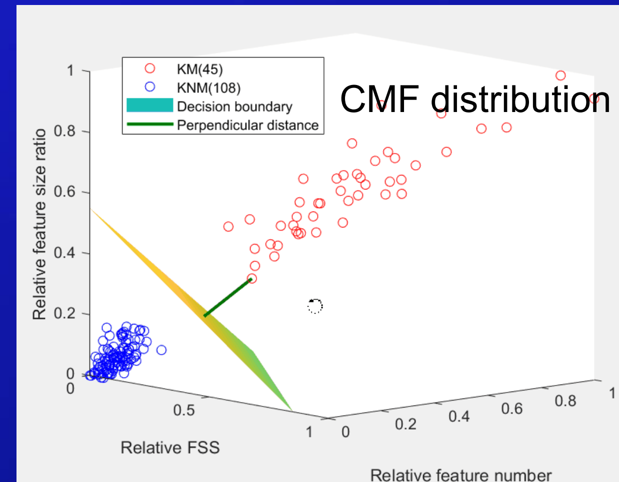
CMF method uses three parameters, all show separation between the correlated KM and KNM image pairs.

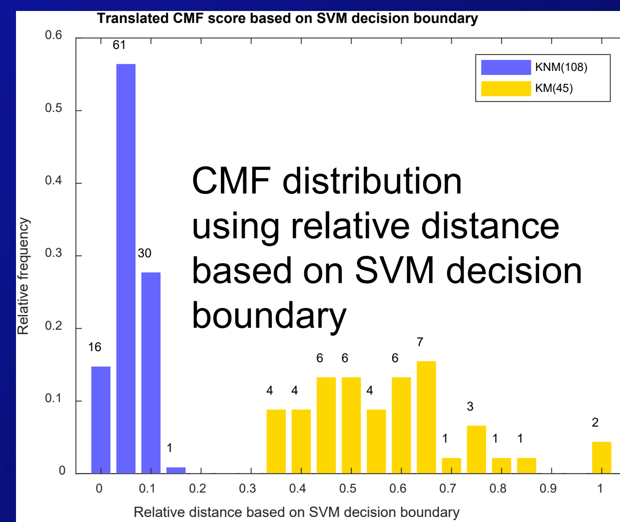
Advantages of the proposed CMF method *(continued)*

- Potential higher accuracy:



CMC vs. CMF





The difference between the CMC and CMF distributions is due to the difference in each single-parameter distribution.

Future Work

- Refine parameters, algorithms and score metric for the existing CMF method for better identification results.
- Develop synchronized algorithm using C++, Java… and using multi-core computer to improve the speed of database searching.
- Apply the database search algorithm to large datasets and test its searching speed and accuracy.
- Develop an error rate and likelihood ratio procedure for the CMF method.
- SBIR phase 2 project (2019 – 2020) -- *Commercialize CMC/CMF/CMPS methods and error rate procedures to support firearm examiner's case works and demonstrate support of court proceedings.*

National Institute of Standards and Technology

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Questions?

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