Document Title:	**Use of Infrared Imaging, a Robust Matching Engine, and Associated Algorithms to Enhance Identification of Both 2D and 3D Impressions**
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Final Report
Incorporating Reviewer Comments and Suggestions

The Use of Infrared Imaging, a Robust Matching Engine, and Associated Algorithms to Enhance Identification of Both 2D and 3D Impressions

1. INTRODUCTION

Goal of the Project

Goal of this project was to demonstrate the potential for infrared imaging to substantially improve the utility of forensic firearm/toolmark evidence. The focus was on producing more timely and higher quality linkages of evidence bearing striated toolmarks and impressions. Evidence items studied during the project were: used cartridge cases, tool scrapes on metal, and footware impressions. Both two and three dimensional infrared imaging were evaluated relative to current visible light imaging procedures and systems.

Underlying Technology

Passive infrared (IR) imaging is the essential technology for the project. Although normally used to obtain temperature measurements, IR images are the result of both emissivity and thermal distributions across the imaged surface. Disturbing an item's surface texture (a striated mark or impression) creates an emissivity difference producing local changes in the infrared image, even in the absence of thermal changes. Infrared imaging requires no illumination and therefore eliminates shadows, reflections and other lighting-induced variations and artifacts associated with visible light imaging. No ring light or sidelighting is required for imaging in this portion of the electromagnetic spectrum. As a result, striated marks and impressions yield highly detailed images based on emissivity variations. The detailed IR images can be captured and compared without need to control illumination as is required when capturing visible light (VL) images.

Given they have the same spatial resolution, IR images contain all the topographical features seen in visible light images. Assuming corresponding feature extraction algorithms can be developed for each type of imagery, IR images could be compared against existing databases of visible light images. That would allow upgrading to a more consistent image collection technology while preserving utility of existing databases. FlashCorrelation®, a high-speed pattern matching engine employing advanced algorithms, is used to compare an IR image against both IR and VL databases. The system outputs quantitative correlation values, and rank orders database entries in order of similarity to a target image like the IBIS system. Existing databases of toolmark images would not become unusable, as happened as a result of previous upgrades.

Dual-spectrum imaging in both IR and visible bands permits immediate detection of apparent visible features that are in fact illumination-induced artifacts i.e., the shadowed effect usually used in conventional comparison microscopy to emphasize striations. Eliminating such artifacts could significantly reduce the false positive error rate in visible light matching with current systems. IR technology could be implemented as a front-end filter for current systems, or as a stand-alone system offering both IR and visible light image comparisons.

High-performance commercial IR cameras can detect temperature variations as small as $0.01^{o}C$. Although passive infrared imaging provides sufficient sensitivity for extracting marks of interest for the current project, there are situations in which active infrared imaging may be required. This refers to heating or cooling a surface to create greater contrast between marked and unmarked areas. Because methods of cooling may create condensation which affects emissivity, we generally heat the surface to a desired temperature and then image as the surface cools. Radiometric IR cameras provide precise realtime temperature measurements at every image pixel, for every image frame. When only slight contrast enhancement is needed, minimal airflow without added heating or cooling will often suffice.

Technical Project Team

Principal Investigator for the project was Francine Prokoski, inventor of the underlying technology, who has been independently developing infrared metrology techniques for twelve years, and has 25 years experience managing small to large rapid technology development programs involving infrared sensors. Jack Dillon, former FBI supervisor and current expert witness and trainer in the areas of firearm and toolmark evidence, was principal consultant. He also directed the project's outreach to government laboratories. James Hamby, former FBI firearms instructor and director of the Indiana State Police crime laboratory, provided a test set of cartridge cases fired from known weapons. Bill Bodziac, former FBI impression evidence manager, was consultant on footwear impressions. Jonathan George was mathematician and software developer. Jeffrey Coffin was system architect and data collection manager. Student interns assisted in data capture.

Project Plan and Performance Measures

Three types of evidence were to be considered: fired cartridge case from handguns, toolmarks made by screwdrivers on lead, and athletic shoe impressions made in dirt and sand. For each type, the objective was to demonstrate advantages from infrared imaging over current evidence collection methods. Both two and three-dimensional infrared imaging were to be considered.

Each type of evidence requires different imaging equipment and procedures. The small budget for equipment was used primarily to rent infrared and 3D cameras, lenses, analysis equipment, and software such as Matlab used for image processing. No equipment or software was to be developed under project funding or included in the deliverables.

Cartridge Cases

Primary emphasis of the project was on cartridge cases. The objective was to evaluate both the use of infrared images compared to current use of visible light images, and the use of novel matching methods against large databases including FlashCorrelation®.

Visible light images of cartridge cases are currently collected and compared against image databases using the IBIS system. The plan was to first access a collection of cartridge cases fired from known weapons that had been imaged, or could be imaged with an IBIS workstation. We would utilize the same raw (non-compressed and non-encoded) images in a double blind study using FlashCorrelation® to produce a correlation matrix and rank orderings of matches for each image. Performance of FlashCorrelation® would be compared to performance of IBIS by the percentage of siblings ranked in the top 1%, 2%, and 5% positions, as well as the overall distribution of all sibling rankings. Based on a similar test performed in 1998 against DrugFire images, we expected FlashCorrelation® might offer an immediate improvement in IBIS performance that could be quickly and cheaply implemented.

Second, infrared images would be collected of the same cartridge cases used in the first study. Correlation matrix and rank ordering for each image would be produced as with the visible light images. Performance of FlashCorrelation® with infrared vs visible light images would be compared with respect to sibling rankings as in the first study.

Third, if infrared images could be input into an IBIS workstation, with image format modification to suit its current processing algorithms, then performance of IBIS with an infrared camera in place of, or in addition to, its current visible light camera could be determined. Cost-free licenses to existing patents covering the use of infrared imaging for toolmark characterization and comparison have been provided to this project to facilitate such an evaluation. Our intent is to provide DOJ with exclusive license to all the related intellectual property.

Toolmark Striations on Metal

Forensic toolmark analysis generally involves comparing a limited number of crime scene marks against test marks made by an examiner using a limited number of suspected tools. In contrast with repetitive events that cause a given firearm to make similar marks on bullets and cartridge cases each time it is fired, marks made by a given tool such as a screwdriver, crowbar, or bolt cutter, have more degrees of variation. The angle, direction, and force with which the tool is employed may vary for both impression and striation marks. In addition, variations in the composition, surface condition, hardness, thickness, and geometry of the item marked will affect the appearance of the toolmark. Also, striations made by crime tools can vary along the path of the mark.

The objective for this project is to demonstrate advantages to using infrared imaging for the collection and comparison of tool marks on metal. No quantitative comparison will be made between the proposed use of infrared imaging and the current use of visible light imaging because no standard system for toolmark comparison is in use. Rather, techniques for automating the comparison of toolmarks, using infrared imaging, will be shown to be convenient, effective and fast. The potential degree of improvement over current methods using visible light imaging will be established through discussions with experienced toolmark examiners. Reduction in false positive candidate matches from NIBIN automated comparisons is expected to be the primary quantitative benefit.

Footwear Impressions in Dirt and Sand

Two primary benefits were expected from using infrared imaging in conjunction with collection of footware impressions at a crime scene. First, the combination of an infrared camera and simple filtering software could rapidly locate shoe and tire impressions without needing illumination. This could facilitate marking off those areas to protect the impressions, and prioritizing the collection of impression evidence at multiple locations. Second, the use of 3D/IR imaging would produce a digital 3D model of the impression which could reduce the need to make castings. The digital 3D representation would be dimensionally accurate to 1mm or better, which may be more precise than castings, depending on conditions at the collection site and materials used. Other benefits of 3D/IR digital modeling include its being non-destructive of the evidence, and its providing an immediate 3D visualization capability to guide additional imagings. Multiple 3D/IR images could be made of several partial footwear impressions, to produce a composite complete digital impression, which would be more difficult to achieve from multiple castings.

3D impression digital models from a crime scene could be automatically compared to 3D digital models of suspect footwear. Visualization of the degree of fit between the impression model and the footwear model would be enhanced by the ability to rotate the combined digital model in three dimensional space under computer control.

Developing the 3D comparison modeling capability is a significant task not within the budget of this initial project. Given the number of variables involved in footwear impressions, this project will address only the general benefits of 2D and 3D infrared imaging for collecting footwear impressions, including increased probability of finding impressions at the crime scene.

2. BACKGROUND TO PROJECT ACCOMPLISHMENTS

Quantitative performance data from IBIS was not available for comparison with this project, and could not be modeled since neither the raw image data used by IBIS nor its matching algorithms were available for comparison. Performance of the prior FBI system, DrugFire, was compared in 1998 against our FlashCorrelation® matching algorithm which was found to be significantly more accurate, with far fewer false positives, than the DrugFire method. A double blind test used visible light images only; since the casings were not available for imaging with an infrared camera. 1157 casings images from 229 weapons were provided.

FlashCorrelation® was used to compute the cross correlation value of each of the 1157x1157 (1,338,649) comparisons and provide 1157 rank ordered listings of compared images for each database image. The list of siblings was then provided by the DrugFire contractor, Mnemonics, for use in the performance evaluation. Position of siblings was determined in each of the rank ordered lists, and performance of both analysis techniques was determined. Relative performance was extrapolated for Mnemonics since they did not report rankings for P less than 10%

Mnemonics placement of 25% at the 2% level vs FlashCorrelation® placement of 46% at 2% represents 80% more correct matches at the 2% level. This would translate into significant savings of examiners' time to investigate false positive matches. The proposed next steps were to input infrared images of the same casings into the DrugFire system and compare performance results against FlashCorrelation® analysis of the infrared images. We projected significant further improvement in performance with further reduction in false positive matches. Mnemonics did not cooperate in further testing, and proposals to NIJ, TSWG, and FBI were not funded. The DrugFire system was subsequently replaced with IBIS.

1998 Comparison Test of FlashCorrelation against DrugFire using Visible Light Images

BALLISTICS MATCHING ENGINE COMPARISON TEST
1157 SHELL CASING IMAGES FROM 229 WEAPONS;
Siblings are casings fired from the same weapon
Percent of Siblings Ranked in the top P %

P %	MNEMONICS	MIKOS
2	no report	45.55 %
5	no report	57.56 %
10	49.40	68.03 %
20	63.60	79.56 %
30	72.30	85.68 %
40	79.30	90.76 %
50	84.80	94.38 %
60	88.70	97.04 %
70	93.20	99.38 %
80	96.50	100.00 %
90	98.90	100.00 %
100	100.00	100.00 %

3. Current PROJECT ACCOMPLISHMENTS regarding Cartridge Cases

Primary Project Goals Met

Due to the constancy of tool mark features in IR images, and by eliminating the need to adjust lighting to highlight features, infrared imaging and matching of cartridge cases required less time than current IBIS procedures, and produced a false positive rate less than 0.005%. Although the infrared image database represented fewer than 1000 cartridge cases, the results indicate a potential for significant savings in examiner time spent reviewing incorrect candidate matches to make conclusive identifications through conventional microscopy.

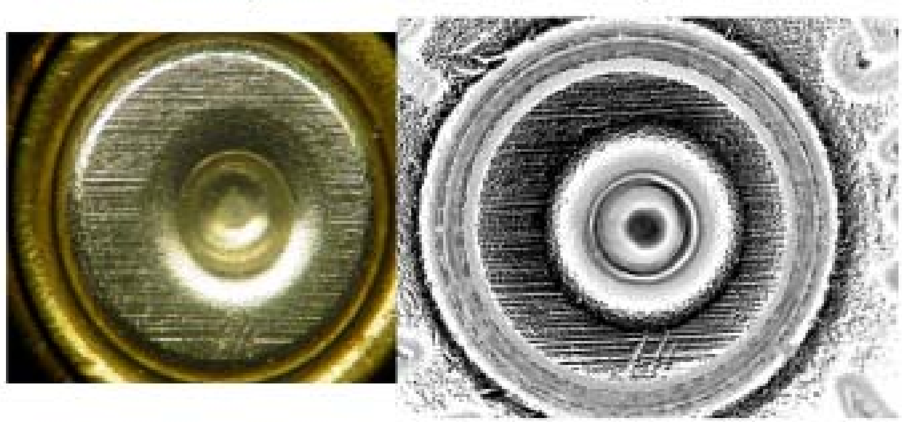
In addition, eliminating subjective adjustments of cartridge case rotation and lighting angles provided more consistent correlation values; a necessary step to establishing a scientific baseline for toolmark analysis. Further research is needed to relate weapon-induced marks on cartridge cases to the features apparent in the infrared image. IR features result from emissivity changes induced in the metallurgy by manufacturing and weapon contact. A model must be developed relating the apparent temperature of a toolmark surface feature to the material composition, surface geometry, texture, depth and width of the mark, and the spectral response, sensitivity, optics, and resolution of the IR camera. The model will provide a link between description of the firearm components and analysis of the cartridge case image; it should enable comparison of different types of ammunition fired from the same weapon. The modeling effort and subsequent tests will establish a statistical basis for the degrees of variation in each type of mark as a function of firearm, ammunition, and other parameters.

Technology Underlying Accomplishments

The clarity of emissivity-induced infrared features is shown in the comparative images below in which the visible light image contains glare from the illumination source. While certain striations appear with greater contrast in the visible light image, that is the effect of lighting strength and angle. As the direction and intensity of the illumination is varied, different features become more or less apparent. The infrared image, however, remains constant regardless of lighting conditions including total darkness.

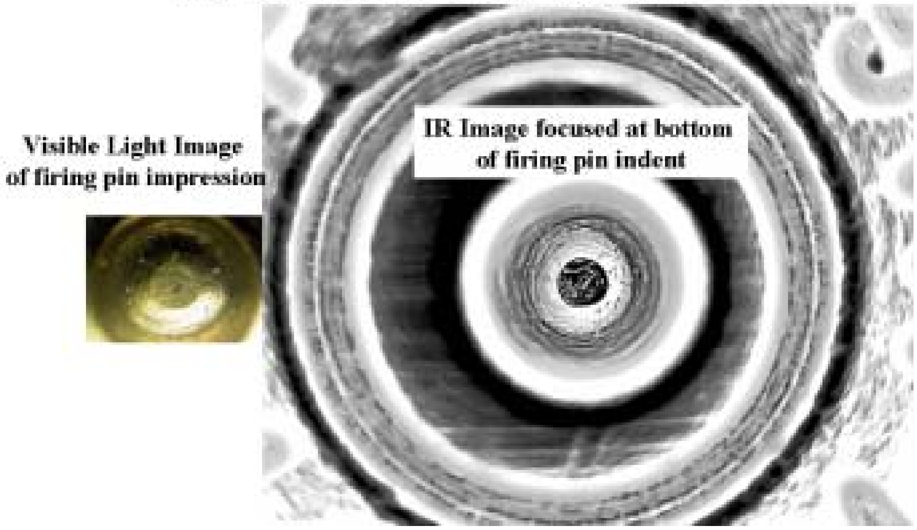
Primer Area of Magnum .44 cal – cc18

Visible Light image of Breechface Impressions — Infrared image of Breechface Impressions



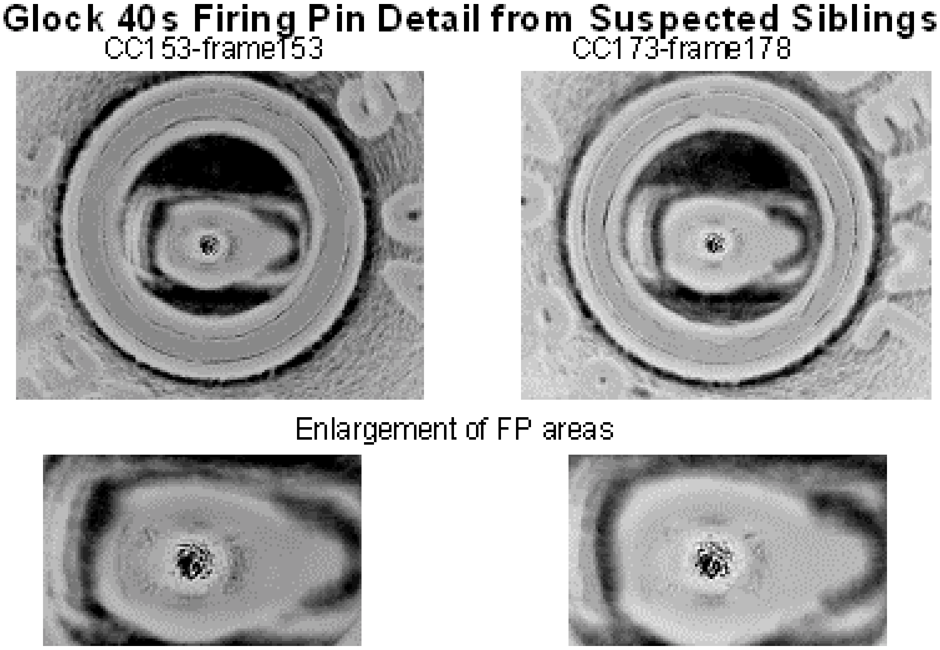
Although infrared cameras generally have relatively low spatial resolution compared to visible light cameras, resulting IR images may contain more information as to feature details. Firing pin indentation details seen in this infrared image cannot be seen in the visible light image because attempt to illuminate the deep indentation result in reflected glare masking the details.

Firing Pin Detail of Magnum .44 cal – cc18

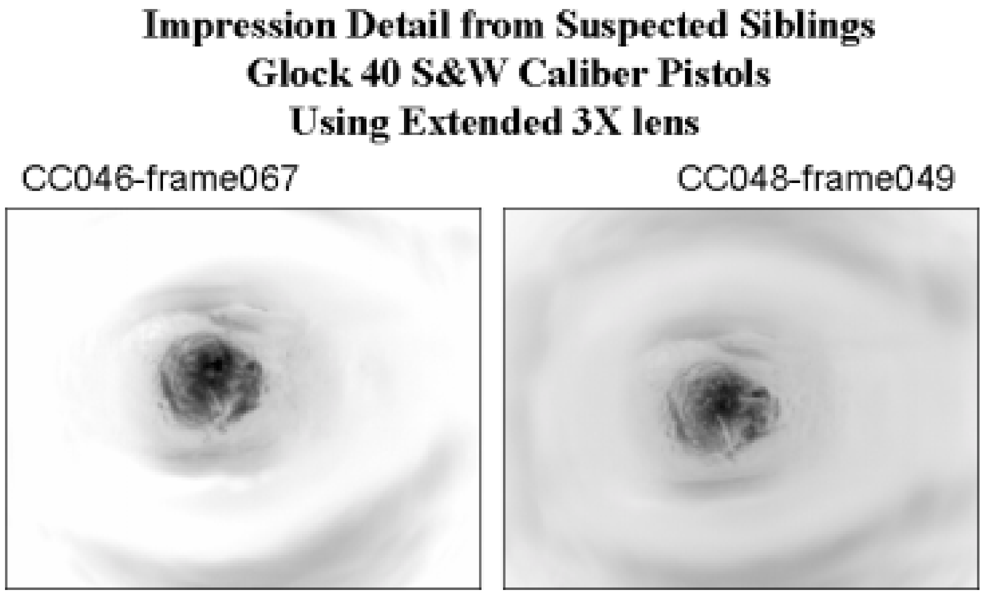


Weapon-induced marks on sibling cartridge cases, those fired from the same weapon without modification, may be readily detected in the infrared images. Breech face and sheering marks are primarily used for matching infrared images just as they are for visible light images. However, firing pin impression details offer another potential source of matchings.

Glock 40s Firing Pin Detail from Suspected Siblings

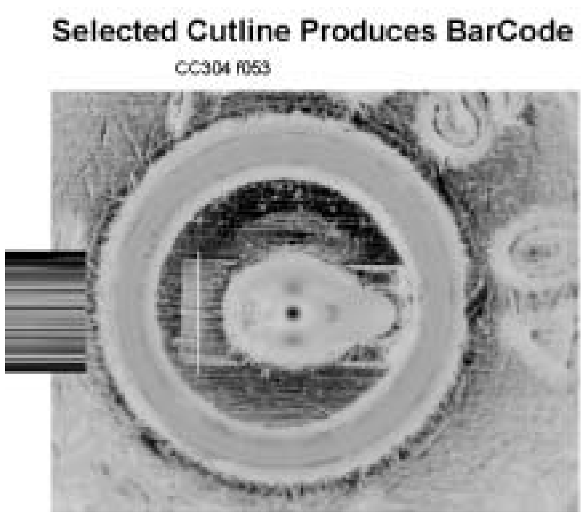


Comparing the above and below images from two sibling pairs illustrates the degree of variation found in firing pin indent details from the same type of firearm and same type ammunition.

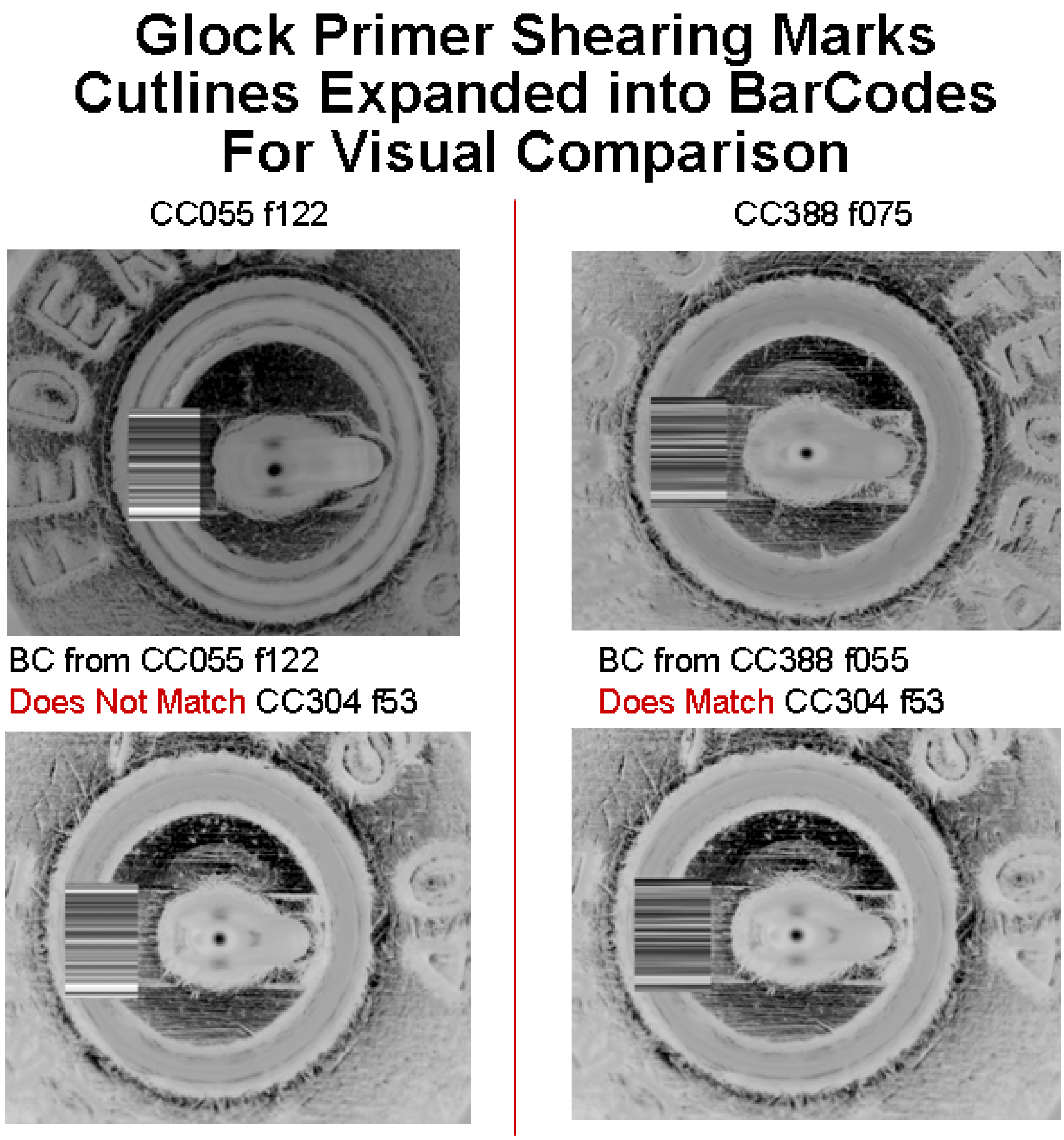


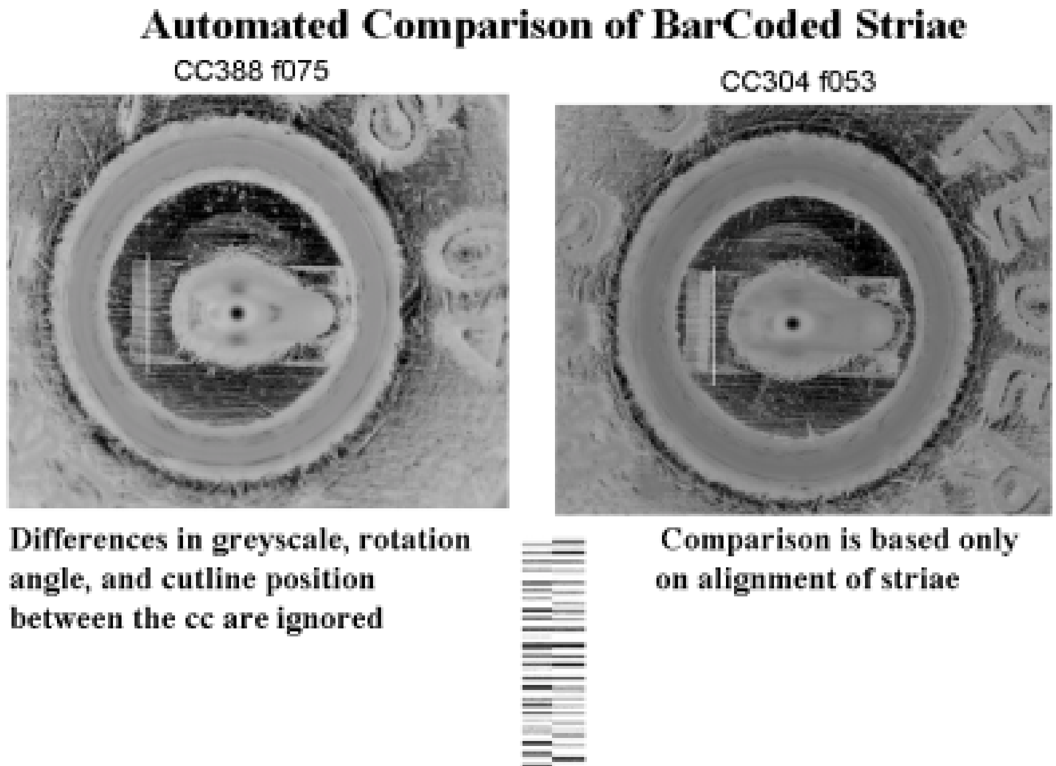
Various algorithms were used for matching cartridge cases in this project. Breechface and primer shearing marks had similar characteristics in both IR and VL images. Firing pin indent details, however, were not similar in the two imaging modes and so they were not used for matching during this project. The most attractive method used is to draw a "cutline" perpendicular to the breechface or sheering marks to be used for identification. Greyscale values along that one pixel wide line are used to create a grayscale barcode by replicating the cutline values to form a wider pattern more convenient for visualization. Normalizing the grayscale histogram provides further enhancement.

These virtual bar codes can be moved about on the display screen so the examiner can consider candidate matches that the system presents. The system automatically generates and compares bar codes to locate high probability matching database images it presents to the examiner.



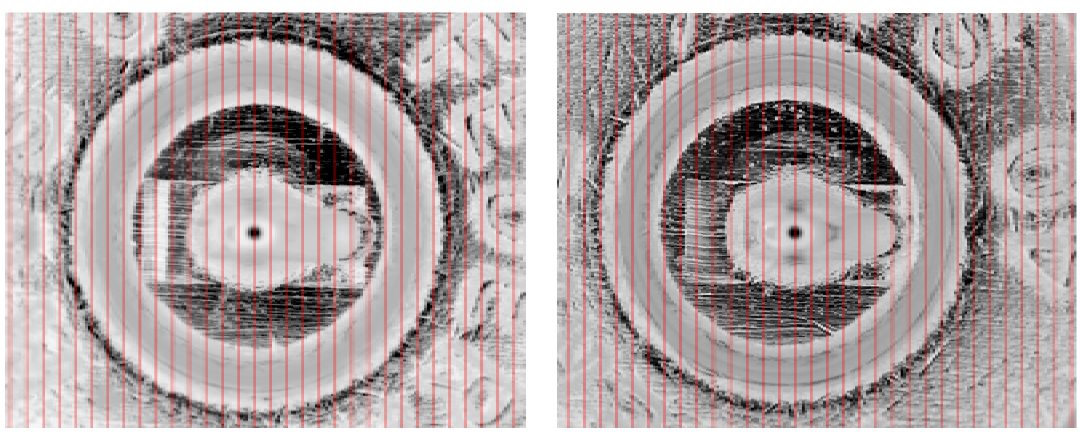
The examiner can display multiple bar codes in realtime on the display monitor and move them into alignment on candidate siblings presented by the system to assist in match determination.





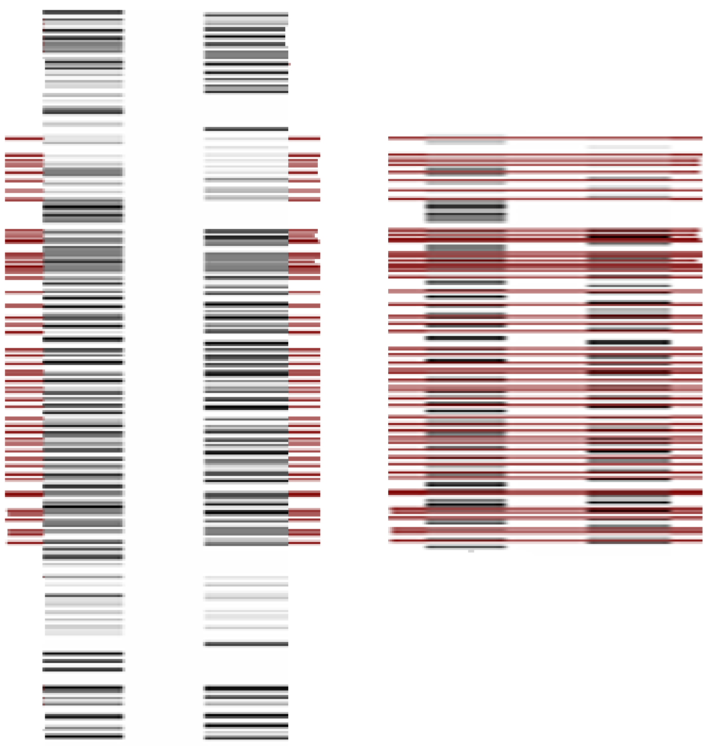
Cutlines drawn manually are automatically converted to barcodes and compared against a database by the system. The match algorithm finds best alignment between two barcodes and counts the number of corresponding lines. The line count is the match value for that pair of images.

Alternately, the system superimposes a standard pattern of vertical lines and produces a barcode for each line. In the current example, the vertical line pattern is shifted so that the center line goes through the center of the firing pin indent. Then the fifth line to the left is used to produce bar codes for comparison.



CC388 **CC304**

Resulting barcodes are vertically aligned and corresponding bars within the primer area are shown in red. Illustration below on the left shows the two grayscale barcodes with those that correspond having red extensions. On the right is the primer area of each barcode, with redlines through the corresponding bars. The match value used is the red bar count. Other values such as the percentage of corresponding bars could alternately be used. Also, barcodes from multiple cutlines could be considered, and the match value could be the total number of corresponding bars, highest number from the multiple cutlines, or other resulting measure from the combination of cutlines.

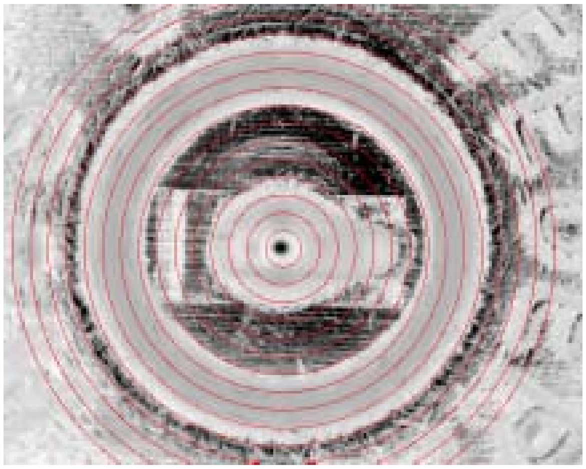


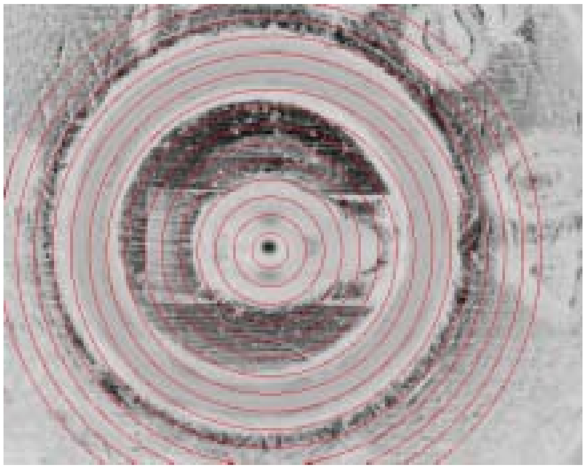
Barcodes derived from CC388 and CC304 using linear cutlines, with corresponding bars in red

As suggested by a reviewer of the draft version of this report, cutlines could be curved. In particular, concentric circular cutlines could be processed the same as vertical linear cutlines. Alignment of resulting bar codes would require rotation rather than vertical displacement. Placing the center of the circles at the firing pin indent center appears to yield strong similarity in the location of region intersections with the circles. For example, corresponding edges of the rectangular impression of the firing pin aperture, and edges of the drag mark, appear to intersect the same numbered circles at the same rotation angles for both CC images. Location and extent of the upper swirling marks, which we describe as "Teletuby antennae" can be designated by polar coordinates and reference to the concentric circle pattern.

For both linear and circular references the spacing between references was arbitrarily set to 20 pixels for these examples. That spacing was chosen for clarity of the printed images; a different spacing may be better for analysis.

Accuracy of linear and circular derivations of cutline barcodes will be compared in future studies.





Relation to Current Criminal Justice Initiatives

In the report earlier this year by NIST to the National Academies Committee investigating NIBIN, the critical question was: "*1. Are the markings (firing pin, breech face, ejector markings), which an individual gun leaves on its fired casings, unique enough to distinguish it from other guns of the same type?"* Other important questions included: 2. Is our ability to distinguish guns and gun types affected by different ammunition types? 3. What is the relative usefulness of each casing region (firing pin impression, breech face impression, ejector marks) for gun discrimination? 4. How do three-dimensional (3D) surface topography imaging methods compare with the optical imaging technologies currently in wide use? Extracts from the NIST report are paraphrased below in relation this current project.

The National Academies' charge to NIST was to assess the feasibility of a high-success ballistics national database by any means—not just the current use of 2D visible light images by IBIS. NIST was thus free to explore other imaging/analysis systems, and decided to emphasize a topography imaging approach as the most feasible alternative or enhancement to existing technology.

NIST analyzed two small collections of fired casings, The DeKinder collection was created to test the performance of the Integrated Ballistics Identification System (IBIS) in a large database. The NBIDE collection was created in May 2005 by NIST personnel as a part of the current feasibility study.

De Kinder's collection used 600 autoloading pistols, all the same Model P226 Sig Sauer, to make 4200 test fires, seven for each gun. NIST used the test fired casings from ten of these guns, providing 70 casings for analysis as part of this feasibility study. The 70 DeKinder casings were imaged by both reflectance based (2D) and surface topography (3D) methods and analyzed via a cross-correlation method.

Advantages of the De Kinder database:

1. allows to observe the variability in surface markings caused by different ammunition
2. and to assess the implications for gun distinguishability.
3. and assessment of how distinguishable nominally identical guns can be.

Limitations of the De Kinder database:

1.single gun manufacturer and model employed, the Sig Sauer P226.
2.cartridges are of different manufacture (brand), variability within each brand cannot be determined

NIST's own collection, called the NBIDE database, included three gun types (Sig Sauer, Ruger, and Smith&Wesson), four guns of each type, three ammo types, and three firing repetitions for each ammo type taking place over three days.

Advantages of the NBIDE database:

1. allows to determine impact of gun type and ammo type on gun distinguishability.

Limitations of the NBIDE database:

1. Conclusions are limited in scope to the three gun types and the three ammo types

2. Small number of analyzed casings (108) are not statistically significant for scaling up to a national database
3. All guns used for NBIDE were brand new.

Image Analysis Methods

NIST compared two image analysis methods

• IBIS 2D system, based on reflection optical microscopy and running the BrassCatcher software application, Version 3.4.5. The software has the capability for acquiring images of three marks on spent cartridge cases, namely firing pin impressions, breech face impressions, and ejector marks. We refer to this system as I-2D.

• NIST experimental system, not intended for commercialization, based on imaging of 3D surface topography using confocal microscopy and having correlation software developed by the NIST/IAI analysis team. We refer to this system as N-3D.

NIST compared the I-2D and N-3D technologies is by examining their performances on Top Ten list exercises. This is a list of the ten other entries in the database that have the highest correlation scores with respect to a reference entry.

De Kinder set. For each of the 70 De Kinder casings, there were six correct matches. Ideal Top Ten lists should include 6.0 correct matches. Actual Results gave averages of:

Using firing pin impressions:	IBIS I-2D: 3.1 matches	NIST N-3D: 3.3 matches
Using breech face impressions: :	1.0 matches	2.8 matches
Using both:	3.4 matches	4.8 matches

NIST Conclusion was that NIST 3D is better than IBIS 2D.
Our Conclusion :is that their results don't indicate whether the imaging method produces more discriminating information or the matching algorithm discriminates better or both

NBIDE casings: Each of the 108 NBIDE casings has eight sibling casings among the other 107 so the Ideal Top Ten Lists should have 8.0 matches.

Using firing pin impressions:	IBIS I-2D: 3.7 matches	NIST N-3D: 5.6 matches
Using breech face impressions:	5.6 matches	7.9 matches
Using both:	6.2 matches	7.99 matches

NIST Conclusions:were that:
1. NIST 3D is better than IBIS 2D.
2. Very little separation between matches and non.matches occurs for some guns
3. Type of gun, type of ammo, new vs. old guns, and size of database could have large impact on actual error from NIST 3D imaging
4. Only 108 casings fired by only 12 guns covering 3 different brands were studied. Probably much larger errors would be seen in larger databases.
5. Low-cost guns may give poorer results; other gun/ammo combinations may give poorer results than those studied.

Our Conclusion is that there is a need to separately consider the information content from the two different imaging techniques; and the degree of separation each matching technology offers for: autocorrelations, selfcorrelations, and crosscorrelations.

NIST's Summary Statement relative to the primary question of Distinguishability was:
"For a technology to be feasible for a very large database, it should have been practically error free in these small studies. Nothing we have seen here comes close to achieving such high performance standards except for the N-3D performance on the NBIDE breech faces, which suggests that 3D topographic methods are a significant advance for breech face analysis. Gun brands and models not covered in the NBIDE study (e.g., low-cost guns high on the ATF's list of crime gun usage) may well be more difficult to distinguish and identify than those included. It's very difficult to design a model for large database applications based on the small studies performed."

NIST emphasizes that the N-3D analysis scheme is non-proprietary, and this openness should facilitate development of improved algorithms by the technical community. NIST also states that a *"disadvantage of the NIST topography approach is that the time required to record the data is much longer than the current I-2D technology. The data gathering and perhaps the correlation algorithms will need to become much more efficient for practical application to a large database."* NIST does not highlight the time required to image with their 3D technique. Deep in their report, NIST mentions matching a single image against their database of 108 images took three days on 3 PCs.

Addressing the accuracy of current IBIS identification, NIST mentions a California Department of Forensic Services study consisting of an image database of 792 Smith&Wesson semiautomatic pistols and a reference subset of 50 of the same model pistols. "*IBIS I-2D placed the correct weapon in its top 15 list only 62 % of the time−even though the ammunition were all the same type. . . . the success rate fell to 38 % if the ammunition were different. Studies by De Kinder and George obtained similar results*."

NIST links the performance of IBIS to its use of an optical microscope.
"It is well known that tool-marks, including casing and bullet signatures, are mainly geometrical features by nature. When these geometrical features are observed under a microscope, the appearance of the optical image is significantly affected by the optical properties of the surface, such as color, refractive index, and extinction coefficient, as well as by multiple reflections and the lighting conditions that cause the shadowing effects. As a result, the optical image does not precisely represent the surface geometry, especially the micro geometry, which is an important part of the casing and bullet signatures.

On the other hand, a topography map can more precisely represent the surface geometric and micro-geometric characteristics of the casing or bullet signatures, independent of the effects caused by optical properties of the surface and lighting conditions."

Furthermore, since international standards for surface metrology have already been developed, NIST concludes that topography measurements could be a better alternative for ballistic item identification, and make the ballistics measurements traceable to national and international standards.

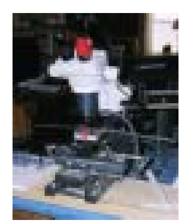
We propose that potential advantages of 2D and 3D infrared imaging, with respect to speed and cost of image collection and matching, merit further investigation of infrared surface metrology as a scientific basis for ballistic item identification. Several thousand infrared microscopes are in use around the world in forensic laboratories for trace evidence analysis and in industrial plants for production quality control of integrated circuits and other materials. Future systems may combine some of those capabilities with toolmark identification.

Methods & Procedures of this Project

Three sets of cartridge cases were imaged in infrared. Procedures for extracting and matching individual marks were developed for each. The first was 80 44 Magnum caliber cartridge cases fired from two handguns. Breechface marks were used for matching within this set. The second was 400 40 S&W caliber cartridge cases fired from an unknown number of Glock pistols. These were chosen due to the extensive use of this combination of cartridge and firearm by law enforcement. In addition, the striated primer shearing marks produced by the interaction of just fired cartridge cases with the firing pin aperture of Glock pistol are widely recognized for their quality by firearms examiners. These were obtained from the Fairfax County Police Pistol range with their cooperation. Each was engraved with a unique number using a miniature air grinder with a diamond tip. Since we did not know which casings were fired from the same weapon, this set was used to investigate the general types of variations in weapon marks produced by the 40 Glock. Also, provisions and procedures for mounting deformed cartridge cases were established.

It is essential that the top surface of the cartridge case be precisely normal to the infrared camera axis. If the case is slightly deformed, it may be reshaped by hammering-in a wooden dowel of the correct diameter. We combined a solution to moderately deformed cases with a provision for uniquely marking each cartridge with a clearly legible identifier. Precision cut dowels are inserted into each cartridge case and a 2D barcoded ID number is affixed to each. The ID label is indented below the edge of the cartridge case to protect it. A small optical barcode reader scans the ID of each cartridge case before it is imaged, and automatically applies that ID tag to each image frame and metadata file created. The reshaping and plugging operations can be combined in a manual or automatic device. At the present time, the two functions are manually performed separately.

Imaging of these two sets of cartridge cases used a stationary infrared camera on a tripod and a specimen mount with manually adjustable x,y,z stages to control centering, and focus distance via precise machine screw adjustments. Rotation of the cartridge case was done manually while viewing the infrared image. Reference parallel horizontal lines were drawn on the computer monitor to aid the operator in establishing rotational alignment. The x, y, and z stages were each manually adjusted for each cartridge case to center the case in the image and move it through the range of focus positions so that each mark of interest would be in clear focus in at least one frame of imagery. The infrared camera was computer controlled to capture 100-500 frames automatically while the cartridge case was raised manually.

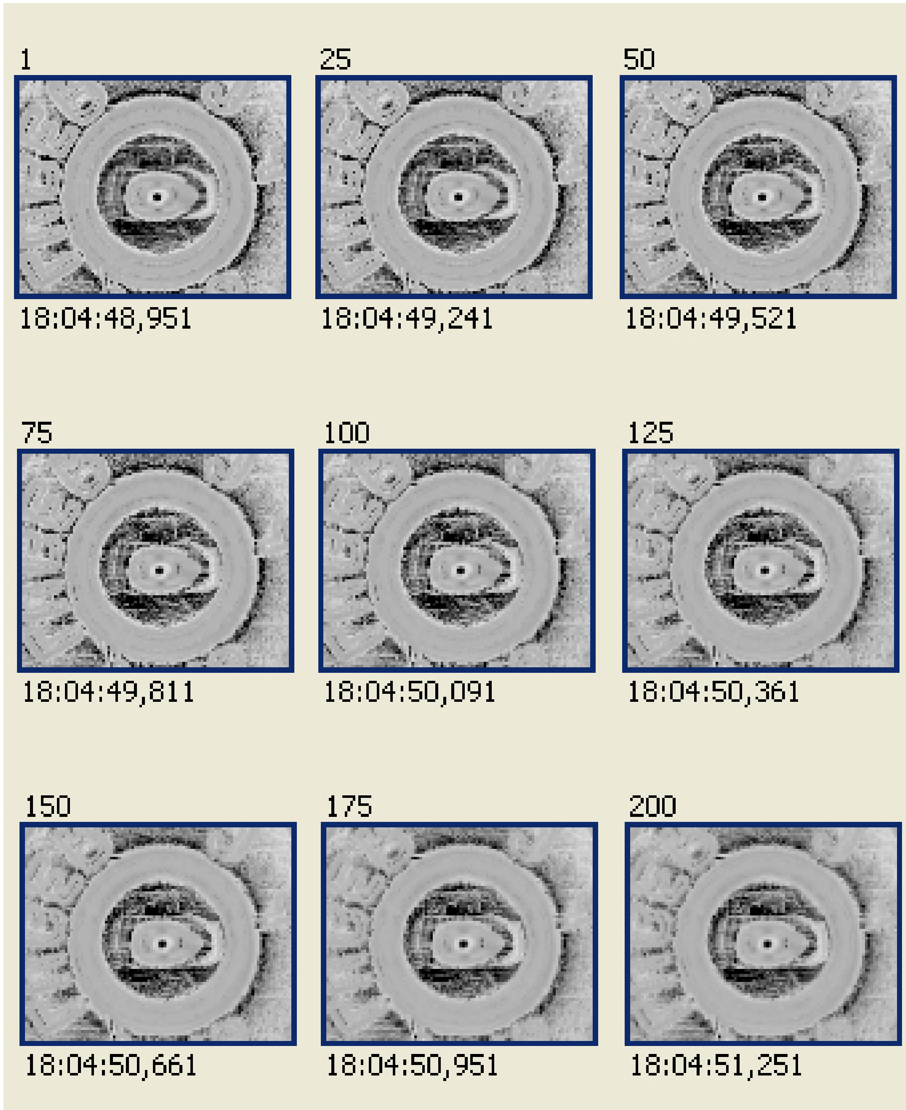


Once this imagery was acquired, FlashCorrelation® was applied to the surface topography data to generate high-probability associations. The procedure was tedious and resulted in the collection of a tremendous amount of ancillary images, further slowing the backup and storage of imagery, and increasing the rental costs for the infrared camera..

When the third set of cartridge cases became available, the FTW (Forensic Toolmark Workstation) was used. The Jim Hamby collection of 9mm Glock cartridge cases were imaged using a single infrared camera configuration of the FTW. Two rounds of imagings were performed with the 640x512 detector array camera; a 3X lens was used to image breech face and sheering marks. An extender was added to image firing pin indent details. Sample images were taken with a 320x256 detector array camera using the same lens and extender in order to evaluate the quality of images and matching performance as a function of spatial resolution of the camera. Due to field of view variations, that analysis requires additional effort outside the scope of this project.

Results of Cartridge Case Matching

Infrared image sequences were collected using a digital IR camera with 640x512 detector array and 14 bit output. For each cartridge case, a sequence of 200 frames was recorded at a rate of 50 frames per second. During the imaging time, the infrared camera was moved 0.01 inch along the camera axis to capture at least one frame in focus of breech face marks, Glock shearing marks, and the edge of the firing pin indent. Sample frames are below. Greyscale values along cutlines were automatically extracted and the resulting signatures used to find matching images in the database. Siblings were correctly identified in every case.



4. PROJECT ACCOMPLISHMENTS – **Toolmarks on Metal**

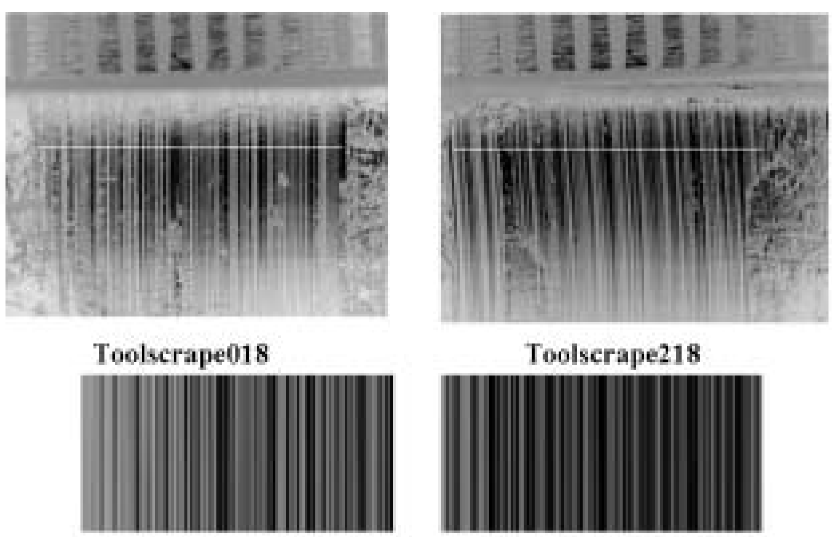
Project Goals Accomplished

Infrared imaging and matching of toolmarks created by screwdrivers was also considered under this project. A technique was demonstrated that produces a barcode representation of the toolmark that can be matched manually or automatically to barcodes of other marks. In a study of 100 tools (200 edges) the technique was shown effective in matching marks made by different people with the same tool.

Technology Basis for Accomplishments

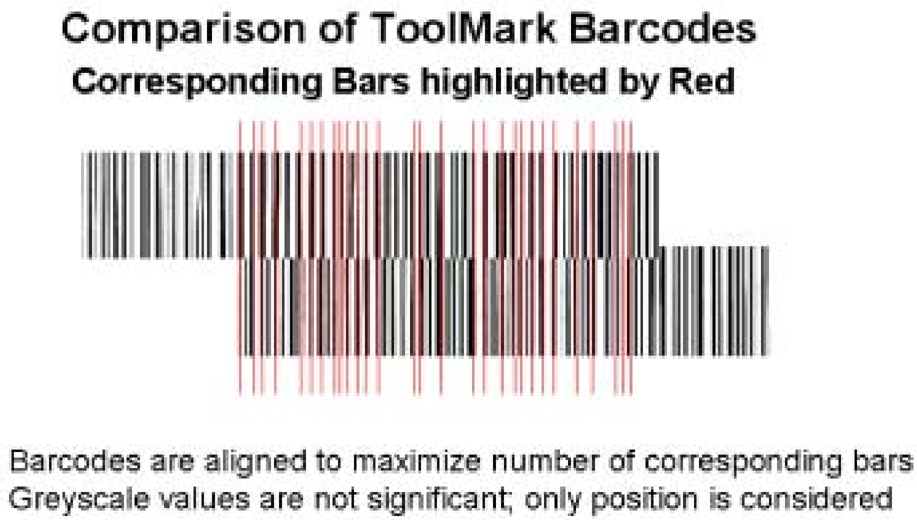
The FTW was not available at the time the toolmarks were imaged. Future consideration of toolmark imaging and comparison will take advantage of the automation features of the Workstation to systematically vary the focus distance and path location along the toolmark. In this project, the focus distance was constant as the camera moved along the toolmark. Use of the numerically-controlled FTW will allow variations in focus distance as the imager moves along the path of the toolmark.

Cutlines Drawn on IR Images of Toolmarks with Ruler in FOV



Cutlines Converted to Barcodes
Expanded to Show Detail

Cutlines were drawn manually across toolmark swaths and used to generate barcodes in the same manner as was used for cartridge cases. Particularly when different people use the same tool, the depth and constancy of striations varies significantly along the swath. Multiple cutlines may be drawn to increase the chance of a match. The number of corresponding bars provides the strength of the match.



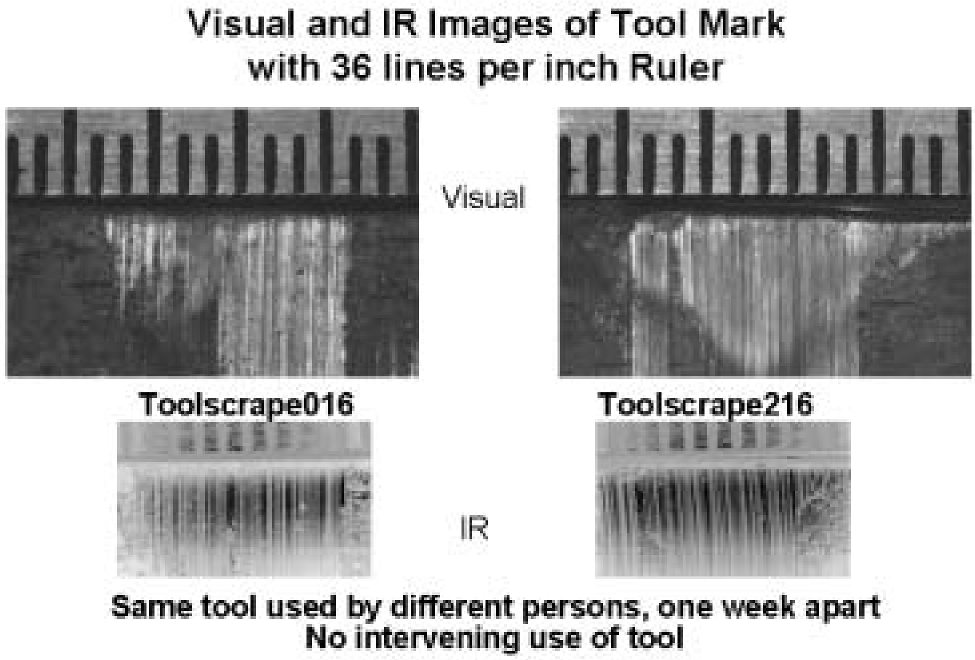
Method and Procedures Used

Screwdrivers are often the primary tools used to gain entry during burglaries and other property crimes. Therefore we chose to collect a series of striated marks made by 100 Brownell tips. All were the same type and size. Each tip was ground down on different grinding devices to remove any class characteristics, and so that each side of the tip would present a different identified mark. This allowed us to emulate 200 different tools. The collection of marks was made on lead sheets. A fixture was fabricated to hold the lead in place when the tip was placed in a holder and scraped across the lead at approximately a 45 degree angle. Care was taken to handle the lead and the shavings with gloves and breathing protection. In addition twenty tips were scraped a second time by a different person so that we could look to match tool characteristics alone.

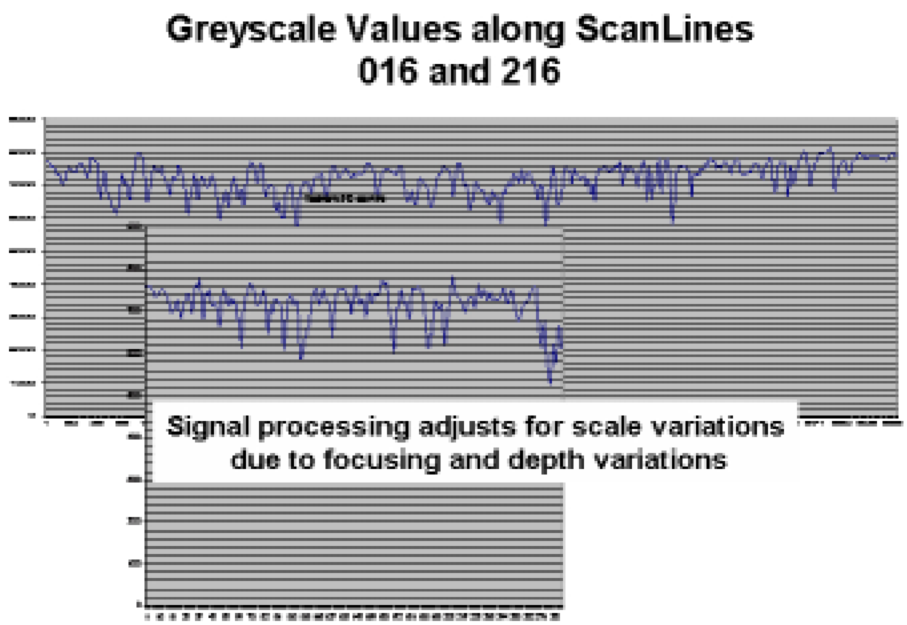
Goal was to demonstrate whether IR was superior to visible light imaging with respect to accuracy of match for the 20 toolmarks against the database of 200 marks. The method for matching striations was comparison of barcode representations of "cutlines" through the toolmark perpendicular to the direction of the mark.

Variables included: angle of tool with respect to lead substrate, pressure on tool, path and speed of marking. These produced variations in depth of mark, represented as grayscale changes in both visible light and infrared images. Focusing on the parallel marks made by tool edge irregularities creates scale differences between images being compared. Scale differences are greater for infrared images due to shallow depth of focus relative to visible light cameras. Visible light images require illumination which may produce reflections and shadows. Illumination is not required for infrared images and did not affect the infrared cutlines or resulting barcodes.

Resulting marks were imaged using an infrared camera with 640x512 detector array and 3X optics and also a visible light 2592x1944 CCD camera. The infrared images produced more consistent striations than the visible light images. As a result, each of the 20 infrared secondary marks was correctly matched to the primary mark made by the same tool by the first experimenter. Only 4 of the visible image marks were correctly matched to their primary marks.



As a second method of matching, a Tablet PC was used with the infrared camera to collect cutline data. The experimenter used the stylus to draw a cutline across the toolmark at a location that presented multiple striations. The experimenter could draw multiple cutlines and each was converted into a signal waveform and matched against the cumulative database of waveforms. Software produced signal waveforms with normalized amplitude values. Standard one-dimensional signal processing was used to match against the database. This approach requires additional research. Results obtained were not as consistent as the barcode results and did not achieve the same level of accuracy.



5. PROJECT ACCOMPLISHMENTS involving FOOTWEAR IMPRESSIONS

Project Goals Accomplished

Two-dimensional infrared imaging was demonstrated to produce images of footwear impressions under dim light and under total darkness conditions. It was also shown to produce detailed images of athletic shoe sole patterns without controlled lighting. Three-dimensional infrared imaging was demonstrated to produce dimensionally accurate 3D digital models of footwear and footwear impressions simply and fast. The primary advantage of infrared imaging over visible light imaging for footwear evidence is that it produces more consistent feature details under conditions of uncontrolled lighting. Feature contrast in infrared images can generally be enhanced by air flow over the features, which differentially heats or cools portions of the features.

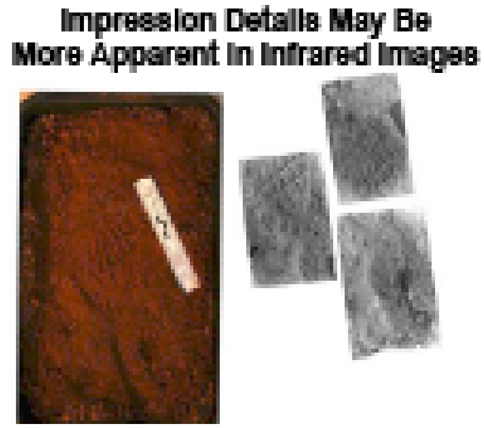
Technology Basis for IR Impression Imaging

2D/IR Locates Footware Imprints Without Lighting Artifacts

The composition, texture, color, moisture content, and uniformity of the impression material all contribute to determining its emissivity or percentage of heat radiated and seen by the infrared camera. Deep crevices in the soles of athletic shoes produce both concave and convex impressions in sufficiently soft footing. Along the impression feature boundaries, the surface of the impression material is generally at an angle other than perpendicular to the infrared camera axis. Therefore, only a portion of its heat emissions are directed toward the camera and so it appears to be cooler than surrounding areas that are flat. In the infrared (left) image flat areas outside the shoeprint appear hotter (whiter) than the feature details for that reason. In the visible light image on the right, flat areas outside the shoeprint appear darker than the shoeprint area and similar to the color of the dark features within the print. This is due to the fact that the shoeprint is being illuminated, and the hard packed areas of the print that are relatively smooth reflect more light back towards the visible light camera than does the more loosely packed surrounding material. Given that footprint sizes do not vary greatly simple filtering software on the output of a digital video infrared camera can provide realtime detection of footwear imprints from a handheld camera at distances of several meters.

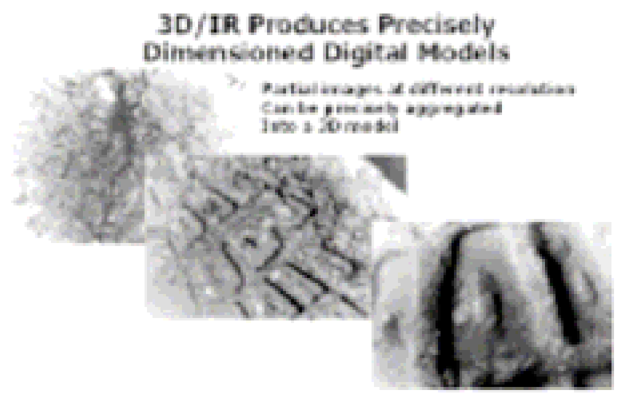
Visible Light Imaging of Footwear and Impressions May Both Produce Shadows

Using visible light imaging, matching images of suspected footwear to images of impression evidence from a crime scene presents several technical challenges. Both images may include shadows. The sole of the shoe is probably not flat and so it will appear to be a different size than the impression. Spacing between features may appear different in the two images because of different lighting angles. The effect of weight may change the aspect ratio of the impression to be different from that of the empty shoe.



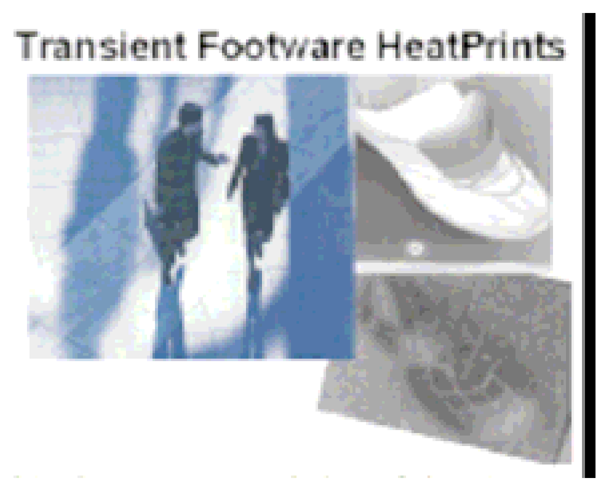
An impression of the suspect shoe may be made in a biofoam box to enable the test impression to be compared to the crime scene impression. Feature details may be more readily apparent in the infrared image of impressions made in biofoam or at the crime scene due to the color of the impression material as well as lighting effects.

Infrared cameras use different lenses just as visible light cameras do. The three images to the right are taken with 25mm, 50mm, and 100mm lenses on an infrared camera with 320x240 detector array. Due to the relatively small size of detector arrays in IR focal plane cameras, high resolution imaging of sizeable objects will often require several images. Areas with little detail or larger details can be captured with wider field of view lenses. Combining multiple images of an object to produce a single image for comparison purposes requires designation of corresponding points and control of camera aspect angle and distance for each component image.



3D/IR imaging systems were previously developed for biometric applications, and were used in this project to produce dimensionally accurate 3D models of footwear and impressions for comparison. We expect that 3D/Visible Light imaging will be developed for this application; perhaps using the near-infrared capability of many digital cameras.

Transient HeatPrints Also Considered



Although not in our proposal or contractual responsibilities, we performed a brief investigation of heatprints produced by walking across various flooring materials. Detailed patterns can be obtained whether persons are barefoot, wearing socks, or wearing shoes. Three applications are of current interest: First, security monitoring of the passage of specific persons through a set of checkpoints such as occurs at an airport. At some location, a correlation is established between a person's identity and his footware heatprint. This could be done automatically when a biometric sensor or ID card is used while the person is standing on a heatprint mat that is monitored by an infrared camera. Other heatprint mats would be located at checkpoints. Heatprints would be collected of each person crossing the mat. Persons could be tracked through a network of checkpoints by the uniqueness of their heatprints within the current population of the airport. Incorporating a weight sensor into the heatprint mat would provide additional discrimination.

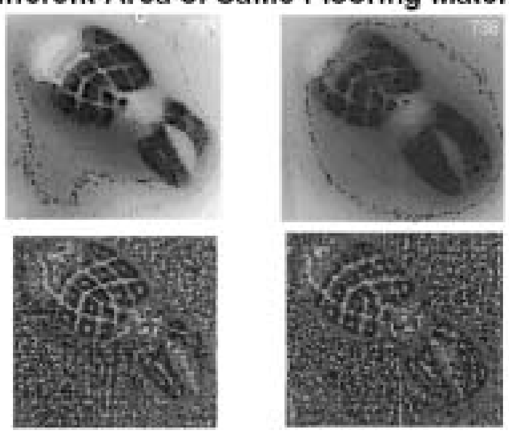
A major advantage to this method of tracking is its operational simplicity relative to the use of faces in the crowd tracking, which requires provisions for imaging different height persons, under various lighting conditions, changes in head pose relative to the cameras, and blocking of person's faces by taller persons in the line of sight. Heatprints are all collected at floor level and appropriate placement of mats can insure that all persons are tracked.

3D/IR Images Produce Contact Equivalent Prints

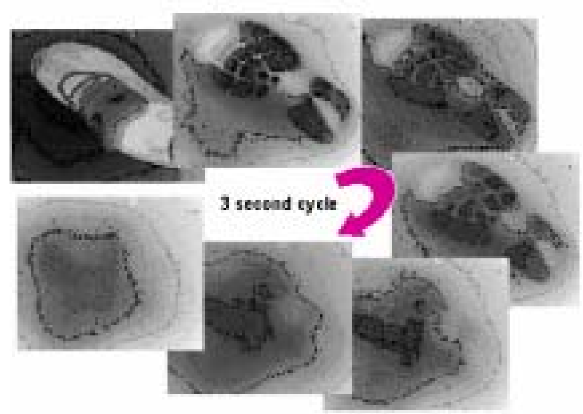
Second, persons who are barefoot or wearing thin socks provide highly detailed heatprints that could possibly be used as a biometric identification method at airport security when travels remove their shoes.

Depending on traffic level, flooring materials would be selected for heatprint mats according to the desired residual period. High traffic areas would require a material that quickly developed a well-defined print as viewed by the infrared camera, and then lost all trace of the print before the next person stepped on the mat. Low traffic areas could utilize a material with longer retention that would facilitate integration of multiple infrared images to enhance image feature characteristics.

Subsequent HeatPrint from Same Shoe on Different Area of Same Flooring Material



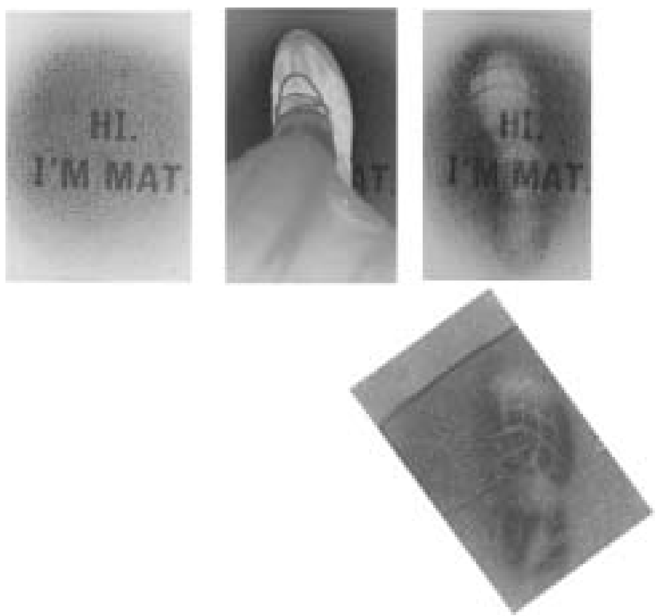
Transient HeatPrints Can be Obtained from Many Flooring Materials



A third application would arise when footwear impression evidence was found and there was reason to suspect the criminal would go to a specific location. Heatprint collections at that location could be used to identify possible suspects.

Further research is needed on potential for class and individual feature derivation.

Initial research found specific flooring materials with 3 second cycle and other materials with 20 second cycle. Further research may develop coatings to tailor flooring materials for a specific retention period.



6. Other PROJECT ACCOMPLISHMENTS

1. ATF Briefing: Of special note was the release of the National Academies Ballistic Imaging Study in March and the subsequent ATF sources sought looking for firms that could bring a significant plus up to the current NIBIN system. SED responded to the sources sought referencing the basic technology of Dr. Prokoski and the work being done under this DOJ grant. As a result we were able to brief the entire ATF NIBIN management team on the grant and where we are. There was a significant interest in following the progress of this grant and the results of the proof of concept analysis. Follow-on demonstrations are planned

2. Lab Briefings: During the March/April 2008 timeframe we made 7 visits to forensic labs to discuss the project and the preliminary analysis. During these visits we were able to gain feedback from approximately 40 current examiners or lab managers. These visits were critical to determining the utility of what we are developing and how to orient or continued development to make the results usable by examiners. Each examiner was asked to fill out a feedback sheet. The results were very useful with the examiners seeing the value of the technology where lighting is not an issue and how the amount of detail visible in IR images could aid in examiner analysis. A number of specific recommendations were made that have been incorporated into the grant development process. The examiners were from the following labs:

- ATF lab in Maryland
- Indiana State Police
- Indianapolis/Marion County
- Jim Hamby's International Training Lab
- Maryland State Police
- Virginia Labs in Richmond and Fairfax
- Baltimore City
- District of Columbia
- Delaware State Police

3. The Association of Firearms and Toolmark Examiners (AFTE) Annual Training Seminar in Hawaii: This was one of the key elements in disseminating information on the program, gain feedback from examiners, and show the progress to date. To accomplish this SED personnel made presentations and supported the effort with a booth.

- Two half hour presentations were made identifying the program, technology, concepts and status.

- The booth display demonstrated the information available to the user that is imbedded within an IR image and the capabilities of the FlashCorrelation© matching engine.

- We met with and briefed over 100 people at AFTE. Comments were uniformly positive and the examiners were amazed with the level of detail IR can give them without being concerned with the lighting. They are anxious to see a live full up working demonstration of the capability and show how it can improve the accuracy of potential matches from the NIBIN system.

4. **The International Association for Identification (IAI) Conference in Louisville, Kentucky:** This was a second meeting where lab managers and many forensic examiners attend. It is also where DOJ had a workshop showcasing the grants in progress that support forensic analysis. Our participation included the following:

- The SED president, Mr. Derr, made a presentation outlining the grant and status at the DOJ workgroup
- Dr. Prokoski and Mr. Bodziak made a joint presentation on the capability of the technology to enhance the analysis of shoe impressions.
- The booth display include a live proof of concept demonstration for ballistic cartridge case matching and the identification of information available to the user that is imbedded within an IR image and the capabilities of the FlashCorrelation© matching engine.
- Feedback was very positive and follow-on discussions are planned.

7. BACKGROUND ON INFRARED METROLOGY

Forensic and Industrial IR Metrology

Nationwide, more than 350,000 crime scene forensic evidence collections per year result in searches of image databases. That includes firearms, bullets and cartridge cases, tool marks on explosives devices and shrapnel, shoe and tire impressions, and latent fingerprints. More criminal proscecutions would benefit from such evidence processing if current backlogs could be eliminated and labor costs reduced through enhanced automation. Current imaging techniques utilize primarily visible light sensors. This project investigates the use of novel applications of infrared imaging to forensic analysis with significant benefits over current visible light imaging and surface metrology techniques.

Underlying Technologies

High-performance IR cameras produce image details resulting from combined thermal and emissivity properties of objects within the field of view. Even when the object being imaged is at a uniform temperature, striations, impressions, scratches, punctures, depressions, elevations, residue, debris, and deposits can be precisely seen in the IR image due to emissivity effects. While the same features may be apparent in visible light imagery, illumination-induced artifacts such as glare, glint, and shadows can affect detection and measurement of the features; particualrly when metal parts are viewed under a microscope with ring light or slant light illumination. IR imaging done in total darkness eliminates illumination-induced artifacts. When marks to be imaged are on irregularly shaped surfaces, simultaneous imaging with a calibrated range sensor produces 3D/IR imaging which provides precise metrology of the topography, including the length, width, and depth of surfaceanomalies, plus their relative positions in three dimensional space. Calibrating a visible light camera to the IR and range sensors allows selection of landmarks in visible light, thermal, or topographic bands, and enables automated position standardization, measurement, and comparison of features and images in three-dimensional space.

Matching detailed imagery against very large databases of images requires techniques for standardizing the imagery [as to scale, orientation, histogram, feature enhancement], determining which features have information content and which are to be ignored, and matching against millions of reference images per second. FlashCorrelation® matching and other novel techniques were adapted for this project.

The best results occur when IR images are matched against databases of IR images. However, even with adoption of IR imaging as standard, it will still be essential to utilize existing visible light image databases to link new crimes to old. Techniques for cross-spectral matching of forensic images and secure encoding of digital imagery to assure against undetected manipulation or forgery have been developed.

Forensic IR Metrology

The advantages of IR forensic imaging are especially apparent in the area of impression-type evidence which includes large volumes of physical evidence collected from many crime scene locations and matched against large databases of similar evidence collected from prior crime scenes.

The most common such evidence comes from marks caused by firearms on bullets and cartridge cases, toolmarks on explosive devices, shoe and tire impressions.

Current Methods

Current systems for automated comparison of impression evidence use visible light microscopes combined with high-energy illumination. The systems incorporate computers to assist in finding high probability associations between a cartridge case, toolmark or other impression evidence against databases of ones previously collected, selecting potential matching items for manual review by a forensic examiner. Achieving proper illumination for detailed imaging requires time and attention from the user. The metallic nature of the items causes glare and reflection to interfere with good imaging. Use of glancing light to highlight the relief structure interferes with distinguishing lands and grooves. Shadows create or mask features, and the depth of striations and indents cannot be determined. The automated analysis engines are computationally intensive and may be confused by manufacturing marks, shadow, glint, and focus. They may not distinguish between individual characteristics peculiar to the weapon, and manufacturing marks or incidental marks of no significance. The imagery and therefore the analysis are prone to variations due to differences in initial alignment, and to inconsistent lighting strength and direction from day to day and from laboratory to laboratory, and to differences in technique and visible light acuity from technician to technician.

Visible light images often include defects that cannot be overcome by image processing:

1. lost detail in dark areas such as firing pin indent
2. areas of focus blur
3. land/groove reversals
4. illumination-induced artifacts such as glare or shadow

Those occurrences can cause both false positive and false negative matches. When visible light forensic images are compared against other visible light images, the possibility of such defect in one or both images must be consdiered. Use of IR images minimizes the occurrence of image defects and resulting match errors.

Required Improvements

The intent of automated forensic matching systems is to find the best matches between a database of images and a current piece of evidence, and display the selected images to an examiner who makes the final determination as to whether a true match exists. The goal is to minimize the workload of the examiner without sacrificing accuracy. Currently, the only fully automated forensic matching systems are for cartridge cases. Bullet, shoe and tire matching systems require extensive interaction by technicians. The IBIS system for cartridge case matching often returns 5% or more of the database of images as a potential match for a particular caliber round. This requires detailed manual investigation by a firearms examiner of possibly dozens of images.

The need is for an evidence image collection and matching technology that is significantly faster and presents fewer candidate images to an examiner. The goal is to increase the capacity of the law enforcement community to identify increasing numbers of impression items, faster and with greater accuracy, and at minimum cost both in terms of manpower and system expenses. Systematic use of infrared imaging is expected to provide a generalized imaging capability leading to significant improvements in automated identification of forensic images.

In prior demonstrations, IR imaging and FlashCorrelation® matching has been demonstrated to identify illumination-induced artifacts such as glint and shadow, detect features such as additional striations hidden by shadows, and correct for apparent reversal of lands and grooves in visible images, resulting in 80% more correct matches.

Proposed Improvements

We have configured a new forensic imaging and matching system to obtain significantly enhanced images of impression evidence, while retaining the ability to match against existing visible light databases. Future production models should provide a standalone modular capability so that similar systems can be used to analyze different types of impression evidence at crime scenes or in forensics labs. Many crimes involve impression evidence that is first matched to commercially available data bases such as tire tread patterns that can be incorporated into the collection system. Other databases may require the security of matching within a government facility or over secure communication lines. Network features should be therefore incorporated into future system designs to allow matching against remote databases.

Tool marks made by pliers, screwdrivers, crowbars and other rigid items on metal or other materials can provide important clues. Marks include both impressions and striations that can vary significantly when a tool is used with different techniques by different users. Rust, corrosion, embrittlement, fracture, and wear can all affect the marks made by a tool. IR imaging can show the presence of rust and other residue, and can be used to assess the type and extent of changes in marks made by the tool as a result of multiple uses over time.

IR imaging can be performed directly on marks at a crime scene; matching them against marks at other scenes without having the tool available. Since no illumination is required to image tool marks in situ at a crime scene, consistent imagery is obtained at different locations and by different technicians. That consistency translates into higher correlation between images of marks from different scenes made with the same tool; including test marks made by the forensic technicians to match a tool to crime scene marks.

Shoe marks and footprints can be collected as residue on a hard surface (linoleum, wood, tile, stone), impressions on a soft surface (snow, earth, mud), or disturbance of texture (dust, freshly vacuumed carpet). Often these marks are latent, which means that they are not visible under standard conditions. To make the latent prints visible, current techniques include: side light, chemical spray (e.g., leuco crystal violet for blood stains), gelatin or electrostatic lift for dust prints. Those marks will persist until disturbed such as by the snow melting. Those three types of marks can be imaged directly in IR. In addition, temporary thermal prints can be collected if the footwear is a different temperature from the substrate. Thermal prints will decay as the print and substrate temperatures equalize. IR surveillance systems routinely image all four types of prints and may provide immediate detection and collection faster and cheaper than current techniques.

Impression evidence from footware will provide class characteristics of the make and model of shoe; but may also provide information about the wearer such as: stance and stride, weight estimate, pigeon-toed or bowlegged gait from considering multiple prints. Residue on the shoe may also provide useful information. IR imaging allows thresholding based on spectral filtering to highlight areas covered with particular residues. When the footware itself is imaged, IR images can be thresholded based on apparent temperature to automatically define sections made of different materials.

3D/IR imaging can be performed directly on footware and tires, as well as on impressions left at a crime scene, and used in conjunction with photographs and castings from the impressions. Resulting 3D digital models can be rotated within a computer to produce both a visualization and a precise volumetric measurement of how well the model of an item fits the model of an impression. Two impressions are compared digitally by separately coloring the two 3D models and then fitting one inside the other. The two colors combine to produce a third color where the models are the same; areas with original colors indicate differences. The computer calculates the volume of the areas of difference. When an impression is to be compared to a candidate shoe or tire, the two 3D models are again separately colored and rotated in the computer for best mating. Jury presentations using the 3D modeling technique are expected to improve visualization over current use of plaster casts.

The proposed use of 3D/IR digital models of footwear impressions is analogous to using NIBIN for initial comparison of a casing image against a database of images. A computer selects candidate matches which are then reviewed by an examiner.

Three-dimensional shoe print impressions in sand, clay, mud and snow are currently photographed and then cast with dental stone. 3D/IR images of the impression, the casting, and suspect shoes can be collected and compared digitally. The quality of the 3D/IR images can be immediately determined and additional images taken with no risk of disturbing the evidence. The 3D/IR digital models can be immediately and securely stored and transmitted to other locations with date/time/location annotation. Comparison of impression marks can be directly performed from the digital data without involving a physical model or casting.

A precise 3D physical be recreated on demand from the digital data at minimal cost if that becomes a requirement. Exact duplicate models can be recreated at other locations as desired, eliminating the cost and risk involved in storage and transport of castings.

Shoe prints found at crime scenes generally are not high quality, are partial prints, and contain debris. Therefore an automated classification system must accommodate those factors. Collection of multiple prints from a scene, if properly aggregated, can significantly improve quality of the print used for classification and match. While commercial software can be used to precisely combine 2D visible light images into 3D representations, the nature of footwear impressions reduces the quality of the results. 3D/IR imaging is expected to streamline collection and analysis of multiple prints.

Design of Forensic IR Systems

Available IR and range sensors are being used to collect sample imagery under the current DOJ project. Database analysis is being performed on separate PCs. Procedures for marking test items and naming data files were established for the current project and would need to be revised to suit future forensic market applications. Future systems designed for forensics use must consider requirements for field and laboratory use. Protocols and user manuals need to address, for example:

- Type and areas of articles to be imaged
- Selecting lenses and spectral filters
- Magnification range for imaging of each type article and each camera
- Determining position and orientation of article relative to cameras during imaging
- Relating filters to type of residue suspected
- Marking evidence items and data files
- Producing 2D images for reports and 3D models for jury presentations

Expected benefits from deployment of IR-based systems include speed, ease, and cost of image collection; reduced matching errors caused by illumination-induced artifacts and presence of debris; higher level of standardization of database imagery due to greater automation and removal of variables such as lighting; reduced cost of evidence storage and reduced expenses associated with maintaining a chain of custody for evidence presented at trial or shared with other jurisdictions.

Industry Applications

Three dimensional infrared imaging 3D/IR overlays precise temperature patterns onto concurrent topographic mappings and visible light images to create aligned, multilayered thermal, topographic, and color data for three dimensional surfaces. Current commercial IR imagers provide thermal sensitivity to 0.015^{o}C and spatial resolution to 1024x1024 arrays with a choice of optics. The level of overlay precision is determined from each sensor's optics, detector sensitivity and resolution.

IR imaging is already used in many industrial applications. Adding the metrology of range imaging to infrared imaging provides precise measurement and location of thermal anomalies and features seen in IR imaging, and specifies the 3D geometry of the surface relative to the IR camera, which affects apparent temperature. Furthermore, finely resolved topographic (range) images provide flatness and texture measurements that can be used to further refine emissivity corrections to apparent temperatures and confirm the detection of cracks, delamination, voids, bad welds, and other specific anomalies seen in IR images. The presence of debris such as oil, variations in surface geometry or texture, thinning or flow of walls, can create false appearance of temperature variations where none exist. Topographic imaging and analysis can eliminate false thermal anomalies.

Range imaging is already used in many industrial applications. Adding realtime infrared imaging to range imaging provides precise thermal measurement across 3D surfaces showing the effects of vibration, deflection, mechanical stress, and material composition. The combination of IR and topographic images can be used to better quantify tool alignment, sharpness, wear, corrosion, and embrittlement. Automated IR image analysis, combined with topographic imaging during manufacture, can detect inconsistencies in material composition, surface finishing, rigidity of structures, and other characteristics. Use of fast frame IR during vibration analysis offers very early detection of very small fractures in airfoils and turban blades, for example.

The combination of IR and topographic image analysis can distinguish between surface irregularities such as from incomplete polishing and changes in composition of material such as from incomplete mixing. It can also distinguish between apparent thermal variations and changes in surface geometry or distance relative to the IR camera. It can also determine whether areas of local thermal and texture anomaly are elevated or depressed. It also provides a true metric mapping of all thermal features relative to the imaging system coordinate system as well as to imaged item-centric coordinates.

Current industrial applications of thermal imaging that could benefit from the use of 3D/IR include:

- *Locate and Measure area and depth of refractory block defects inside a kiln, boiler, or furnace*
- *Map voids and delaminations during inspection of concrete bridge decks and other paved surfaces; distinguish texture variations from composition changes*
- *Create 3D maps of pipes and conduit viewed in an IR image to determine interconnections and layout geometry; also distinguish apparent anomalous thermal areas created by overlaps*
- *Determine surface cleanliness by measuring the material removal needed to achieve a given thermal emissivity on a portion of an article surface*
- *Detect and map deformations (blisters and depressions) in roadway and airport pavements in areas with anomalous thermal properties; Particularly when surfaces are covered with dirt, dust, and oil, and areas involved are large, calibrated topographic imaging can help distinguish incipient pot holes and other voids through calibrated mapping*
- *Similar imaging of concrete floors during construction of tall buildings can detect poor workmanship leading to potential sagging and collapse through detecting a combination of thermal and topographic variations related to water content, location of reinforcements, curing and cracking behavior*

Markets for IR Metrology Products and Services

Forensic

Successful commercialization of IR Metrology will provide the following capabilities to forensic examiners and law enforcement.

- Increased accuracy, speed, cost effectiveness, and ease of exploiting impression evidence
- Elimination of illumination-induced artifacts
- Greater degree of automation to reduce personnel workload
- Consistent, standardized imagery from all technicians at all facilities
- Potential for image collection at crime scene

Tool mark image collection and identification is an international forensic process performed by military police and intelligence agencies as well as local and federal law enforcement. The same techniques used to match cartridge cases from one drug-related gang shooting to another can be used in analysis of shrapnel from IEDs and other explosive devices to link terrorist events. The ability to match tool marks on portions of explosive devices found at different target locations provides a linkage between them. Separately, the ability to match the tool marks to tools found at suspects' locations provides evidence linking occupants to the events. Both mark-to-mark and mark-to-tool matching provide important assistance to counter-terrorism agents attempting to assign responsibility for terrorist attacks.

17,000 US local law enforcement agencies plus federal and international law enforcement, military, and private crime analysis organizations amount to a potential 20,000 organizations collecting crime scene evidence. Of those, approximately 400 laboratories are currently processing tool marks. While tool mark analysis makes up on average 7% of the caseload at forensic labs; it accounts for 30% or more of the technician's time. Depending on the device's capabilities, the level of training required and the system price, current market for an automated tool mark identification imager designed with interchangeable optics would be 300-5,000 systems in the US and equivalent number of foreign sales.

Industrial Metrology Systems and Services

A few system configurations would address many industrial applications. Mikron's RT software could be the starting point to add range mapping and very quickly develop a marketable product. We have developed 3D/IR calibration targets, procedure, and software that we could make available immediately. In addition to Konica-Minolta's Vivid range mapper, we have several other 3D imaging devices available to address sub-mm through large scale object imaging. We selected the Vivid due to our requirement for eye-safe range mapping on human subjects. Significantly cheaper range imaging systems are available for imaging objects given proper laser safety procedures are used.

We have not developed a market estimate for industrial uses, but we are confident it is significantly larger than the forensics market. Our guess is that at least 10% of industrial users of IR would be potential customers for 3D/IR and at least 20% of industrial users of surface metrology would be potential customers for 3D/IR.

Forensic Sciences Background

Physical Evidence Principles of Forensic Science

The process which links forensic examiners of all disciplines is that of performing comparisons, specifically comparisons of evidence items (questioned items) versus standards (known items) of some type. As examples, this would include examinations such as:

- Gross and microscopic comparison of fired cartridge cases recovered from a crime scene with cartridge case standards personally fired from an evidence firearm by a forensic firearms examiner in a laboratory setting. In this scenario, the examiner attempts to identify or eliminate a cartridge case as having been fired in a particular firearm.
- Gross and microscopic comparison of a toolmark recovered from a high value industrial burglary with toolmark standards produced by a toolmark examiner in the forensic laboratory. In this scenario the examiner seeks to determine whether or not the toolmark was made by the seized tool.
- Comparison of a recovered shoe print lift versus standards produced by an examiner in the laboratory. In this scenario the examiner compares the unique detail produced by random wear on the sole of a shoe versus known impressions produced in the laboratory from the evidence items.

- Inter-comparisons of evidence items (questioned items) recovered from one or more locations. As examples, this would include such examinations as:
  - Inter-comparison of fired evidence cartridge cases from multiple crime scenes in an effort to link the scenes to a single firearm, an especially valuable technique when no firearm has been recovered and serial shootings are suspected.
  - Inter-comparison of toolmarks recovered from multiple burglary scenes when no tools have been recovered.
  - Inter-comparison of shoe print lifts from multiple crime scenes when no footwear has been recovered.

These comparisons by nature involve the use of:

- Class characteristics, which are common to a large population of items, such as millions of firearms, cartridge cases and bullets, tools, and footwear items.
- Individual characteristics, which are unique to a particular item and no other, such as the unique marks left by a firearm on fired cartridge cases and bullets, toolmarks left by conventional and improvised tools, and 2- and 3-dimensional impressions left by shoes subjected to random wear and abuse

Class characteristics of physical evidence are natural screening devices, in that rapid exclusions can often be made on the basis of a comparison of obvious gross class characteristic differences. Normally, inconsistencies of class characteristics are quickly observed by examiners. As an example, for firearms examiners this would include differences in caliber or the direction of the twist of rifling impressions in a fired bullet. Complete consistency of class characteristics between two evidence items will dictate a more detailed comparison of any unique, individual characteristics that may be present.

Individual characteristics are typically much more difficult and time-consuming for an examiner to observe, assess and evaluate. Any enhancement to existing technology which can lead to a more efficient use of individual characteristics will have a number of direct results:

- Improvement in examiner efficiency
- An increase in case completion and output
- Lower turn-around times
- Reduced individual caseload
- Enhanced case/incident linkage

Current Technology for Evidence Linkage

Firearms Identification automated systems were initiated in the early 1990s. An evolutionary process began which culminated in the application of the science to firearms identification. This ultimately resulted in a gradual shaking out process and the worldwide predominance of IBIS™ (Integrated Ballistics Identification System™). This system has evolved over time and can now be configured with improved front end imaging (BulletTRAX-3D™) and back end image correlation (MatchPoint Plus™).

A number of experienced firearms examiners have indicated that this pioneering system should be improved so as to result in fewer false positives during the comparison of fired ammunition components. This is important in that any high probability association indicated by such a system needs to be addressed by the human examiner using comparison light microscopy. There are instances in which algorithms generate candidate images which are eliminated at a glance by human examiners. The key to attaining the goal of minimizing the number of false positives would be through better imaging, better algorithms and better correlation techniques.

Toolmark Identification is the forensic discipline which has at its heart the identification of unique toolmarks as having been made by a particular tool. In reality, firearms identification is just one subspecialty of toolmark identification. To date, few or no forensic examiners have brought computer-driven pattern recognition technology to bear of the general field of toolmark identification. No data bases of this type of evidence are currently known to exist. Since the pattern recognition technology applied to firearms identification applies equally as well to toolmarks (striated marks or impressed marks), the application of pattern matching technology appears to be a goal which would assist many toolmark examiners.

Shoe Print Lifts The use of any type of computer-driven pattern recognition system for class or individual characteristic comparisons of shoe print lifts is not currently known to the participants in this project. The application of this approach to shoe print evidence would appear to an innovation from which that forensic discipline could reap great benefit.

Ballistic Item Identification

In the case of firearm-related evidence, fingerprints on an unfired cartridge or a fired cartridge case may indicate a specific person loaded the gun. Firearm mechanism marks may indicate that a cartridge was fired in or extracted and ejected by a particular firearm. Residue such as cocaine or grease may provide additional useful investigative leads. All three types of data (fingerprints, firearm-related marks, and residue) can be imaged using infrared cameras with integral spectral filters.

Firearms identification developed as the first forensic use of tool marks. The marks made on fired bullets and cartridge cases are only a special subset of the overall category of toolmarks in which the "hard object" is a firearm producing unique and identifiable toolmarks on the softer metals of fired bullets and cartridge cases. Generally these types of marks are easier for an examiner to work on, in that the tool (a firearm), unlike other tools, happens to always remain in the same physical relationship to the marked objects (bullets and cartridge cases). This makes them easy to reproduce, simply by firing a weapon. The types of marks that may be found on the surface of fired cartridge cases and shotshell casings include:

Name	Description
Firing pin impressions	Indentation of the primer of a centerfire cartridge case or the rim of a rimfire cartridge case when struck by the firing pin.
Firing pin drag marks	Striated toolmarks produced when a projecting firing pin contacts a cartridge or shotshell during extraction and ejection.
Breech face marks	Negative impression of the breech face of the firearm found on the head of the cartridge case and/or primer after firing.
Primer shearing marks	Striated toolmarks caused by the rough margins of a firing pin hole (aperture) scraping the primer metal during unlocking of the breech of a firearm.
Chamber marks	Individual microscopic marks placed on a cartridge case by the

	chamber wall as a result of chambering, expansion during firing, or extraction.
Extractor marks	Striated toolmarks produced on a cartridge or cartridge case from the operation of an extractor (usually found on or just ahead of the rim).
Ejector marks	Toolmarks produced on the head of a cartridge case, from contact with the ejector (generally at or near the rim)
Anvil marks	Microscopic marks impressed on the forward face of the rim of a rimfire cartridge case as it is forced or compressed against the breech end of the chamber by the firing pin.
Ejection port marks	Striated marks produced by hard contact between the ejection port of a firearm and a rapidly moving ejected cartridge case.
Magazine marks	Striated marks produced on the periphery of a cartridge as it moves from the lips of a magazine towards the chamber during feeding.

Class characteristics called general rifling characteristics (GRCs) in the form of gross impressions visible to the naked eye are made in the surface of bullets while in hard contact with the bore of the barrel. The clockwise or counterclockwise grooves inside a barrel result in groove impressions (higher areas) on the surface of a fired bullet. The areas between the grooves inside a barrel (lands) result in land impressions (lower areas) on the surface of a fired bullet. These gross impressions can be associated with a number of brands and models of firearms of certain classes. Although GRCs cannot identify a specific firearm, they are a useful investigative tool. They can provide invaluable lead information to investigators concerning the type of firearm.

Individual characteristics in the form of unique striated marks within the land and groove impressions caused by the passage of a bullet through the barrel of a firearm.

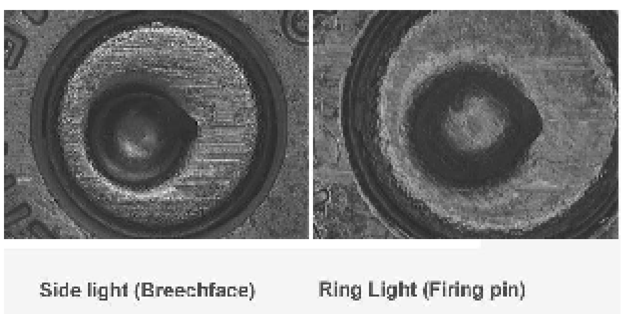
Of all of the marks left on fired ammunition components, the most productive marks of value for relating shooting incidents are the breech face marks (true 3-dimensional impressions) found on the base of fired cartridge cases. This type of mark is generally most attractive to firearms examiners:

- They tend to bear the most detail and minutia useful in the human process of pattern recognition as compared to other types of marks.
- When an identification is made of a fired cartridge case with a firearm there is no doubt that it was fired in the firearm.
- Many more cartridge cases are typically recovered at a crime scene than fired bullets which are most often subjected to mutilation, deformation and fragmentation.

Matching of shell casings has fewer variables than other types of impression evidence: tool mark striations can vary in dept, angle, and direction. Bullets proceed in only one direction but can be deformed as they pass through multiple materials. Matching of shell casings should be simpler than other tool mark and impression matching. However, comparing the use of 2D and 3D Infrared imaging against current systems for shell case matching faces the obstacle that current systems use proprietary technology for matching. We therefore cannot generate an assessment of the improvement offered by replacing the sensor in current systems with IR sensors.

Wavelet transforms can be used to deconstruct a visible light image into component images that represent properties at different scales (from coarse to fine) in the image. They are computationally efficient and they allow exact reconstruction of the original image. Previous studies have applied a wavelet transform that works on discrete data known as à trous (with holes) algorithm. Scale 1 of the à trous algorithm gives the finest details plus noise in the image. Higher scales represent coarser details. Matching one or more scales may provide faster comparisons less vulnerable to noise variations. We will try the wavelet transforms with the IR images and evaluate resulting speed and accuracy effects.

Rotational variations greater than 5^o have been shown to create significant matching errors. Even slight variation in lighting or positioning of preprocessed images requires extensive iterative processing for comparison of visible light images. For small database comparisons, the time required may be acceptable, but for sizable databases the processing time can become unacceptable. When rotational variation is a problem, as with shell casings, comparison based on log polar transforms offers a better solution. The log-polar transform of the Fourier magnitude removes the effect of rotation. However, it too requires extensive processing time and then provided only a rank ordering with the correct match within the top 10% in prior tests with visible light images. Better results are obtained faster if the log polar transform is performed after the third scale of the à trous wavelet transform. Final selection of matching algorithms to be used with IR images should be further considered to obtain the highest accuracy and speed. Continual improvement in algorithm development is expected to occur after systems are available to the forensic community.



Visible light Images

Both breechface and firing pin indents are generally imaged; the firing pin at higher magnification and different focus.

Tool Marks

Toolmarks result from the action of a harder object on a softer object, typically employed to gain a mechanical advantage. Due to the manufacturing processes that produced the tool, class characteristics as well as unique and identifiable microscopic marks from the operating surface of the tool can be left on a marked object. The term "tool" can also include items not necessarily marketed as a task-specific conventional tool, such as an improvised hard object used as a tool in order to gain a temporary mechanical advantage. Class and individual characteristics are defined as follows:

Class characteristics are measurable features of a tool that indicate a limited group source, although that group may number in the millions of similar items. They result from design factors and are therefore determined prior to manufacture (e.g., width length, shape, etc.). Common examples would be the width of the tip of a screwdriver, the width of the jaw of a gripping tool, or the kind of action employed by a tool.

Individual characteristics are marks on an object produced by the random imperfections or irregularities on the surfaces of the tools used to manufacture the object. These marks are produced incidental to the manufacturing process, are typically at the microscopic level, and are not planned for by the manufacturer. Individual characteristics can also be produced on an object by use, abuse, and the effects of random corrosion.

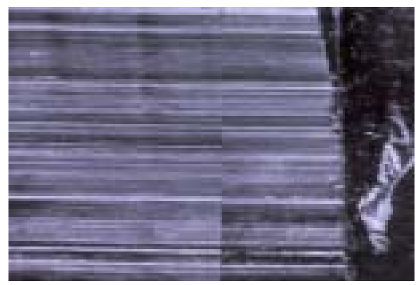
Striated or impressed marks may be produced by tools based on the types of actions performed.

- Striated toolmarks (also called striae, friction marks, abrasion marks, or scratch marks) are produced when a tool is placed against another object and moved parallel to and across the object with pressure applied to produce surface contour variations.
- Impressed toolmarks (also called compression marks) are produced when a tool is placed against another object and sufficient force is applied to the tool to leave an impression or contour variations on the surface of the object.

Both striated marks and 3-dimensional impressions are produced by the scraping action typically employed by a screwdriver. Toolmarks often, but not always, relate to a property crime in a lower priority investigation. Exceptions can occur when a break-in producing a toolmark leads to a personal crime, or when toolmarks such as striated knife marks are found on bone or cartilage. Tools may leave a variety of combinations of striated and impressed toolmarks, depending on the precise orientation of a tool to the marked item and the action employed.

Typical screwdriver shaft

Machined screwdriver tip



Visible light Matched striated marks made by a scraping action

In the case of tools such as pliers, screwdrivers, and crowbars, marks can vary significantly when employing different actions by different users. Rust, corrosion, embrittlement, fracture, and wear can all affect the marks made by a tool. IR imaging can show the presence of rust and other residue, and can be used to assess the type and extent of changes in marks made by the tool as a result of multiple uses over time.

IR imaging can be performed directly on marks at a crime scene; comparing them against marks at other scenes without having the tool available. Algorithms for processing 2D and 3D infrared images must allow comparison of toolmarks even with differences in tool, user, force, and residue.

Action	Description	Example
Scraping	A flat-bladed tool held at 90° to a surface and drawn across that surface.	A screwdriver or pry bar used on the surface of a door or window frame.
Pinching	An opposed blade cutting tool, such as a pair of bolt cutters or diagonal wire cutters.	Remains of explosive devices
Shearing	Shear cutters, the blades of which are offset to pass by each other in the cutting process, such as tin snips or scissors.	Cut alarm or telephone wires
Slicing	A single-bladed tool, such as a knife or axe.	Tires, wires, and (rarely) bone and cartilage
Prying	A prying tool using leverage to force open a locked door or cover at one of its edges. May be a flat-bladed prying tool, (e.g. crowbar, screwdriver, tire iron, etc.)	Bank or store safe, or the strike plate of doors
Gripping	A gripping tool with opposing jaws, such as a pipe wrench, pliers, or a vise. Serrated jawed gripping tools add another dimension to the types of marks present.	Doorknobs
Crimping	An opposing jawed tool designed to press material together without cutting it.	Lead seals (e.g., bank money bags or containers for classified material)

3D Depth Images

3D images can provide a combination of topographic and visible light information to characterize surface characteristics and assist in comparing sections of three dimensional objects such as tool marks, shell casing, and footwear impressions. The 3D model can be rotated within a computer to achieve optimal alignment between corresponding sections of two items. 3D images can be obtained using structured or coded light in a few seconds with commercial off the shelf imagers. Depth precision and distance between camera and object is limited by the sensor chosen. Resolution and field of view (FOV) is determined by selected optics.

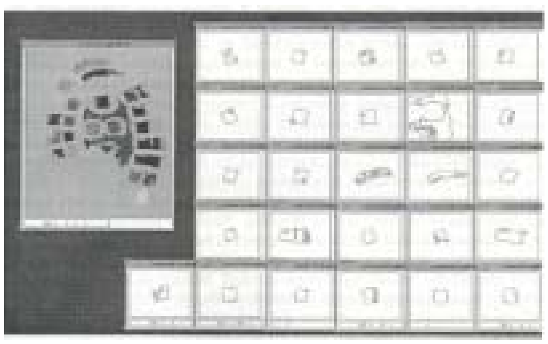
Coded light can be used to produce multiple images using a grid of switchable light or dark lines that are numbered from left to right. The numbers are encoded into a binary code in which adjacent lines differ by exactly one bit. Depth information is measured by a phase-shift at the edges of the object when illuminated by a special line projector. Knowing the angle of projection, the viewing angle and the geometric parameters of the set-up, the three coordinates of each object point are calculated to a precision of several microns. That level of magnification may be required for ballistic and other tool mark identification. Impression evidence may require only millimeter-level precision which can be obtained using simpler structured light sensors such as the Konica-Minolta Vivid 910.

In three-dimensional imaging, gray values are replaced by depth values z. Illumination artifacts may be reduced by the selection of depth sensor. Some techniques such as structured light utilize white light that returns incorrect depth information from highly reflective surfaces. Laser range finders suffer from dispersal of the laser beam by rough surfaces, resulting in imprecise measurement. Selection of a depth imaging technique must therefore consider the various substrates expected and whether or not a spray-on coating would be permitted. In some cases, the use of a fine powder, sputter coating, or magnesium smoke may improve the precision of the depth measurement without permanent change to the evidence.

Shoe and Tire Impressions

Footwear impressions may contain both class and individual characteristics. Typical class characteristics are size, shape and proprietary tread design features. While these class characteristics may be found on millions of shoes, each one will immediately begin to accumulate unique wear patterns during use. These individual characteristics can be transferred to hard floor, wall and door surfaces in the form of dust prints that can be recovered at a crime scene using gelatin and electrostatic dust print lifters. Both transfer a dust print to a surface which can be preserved for possible future comparisons with seized evidence shoes. Identifications of the crime scene lifts with a particular evidence shoe are based on the random marks borne by shoes as they are worn, abused and randomly damaged in use. Tire impressions are similarly processed.

Reference databases of footwear impressions and tire impressions are organized by segmenting the image(s), identifying and labeling shapes within each segment. Current methods for print labeling, classification, and matching generally use grayscale images to which thresholds are applied to define characterizing shapes as well as areas of wear. The grayscale image from visible light cameras is produced by side lighting with 2D visible light cameras. IR images will produce different features with different parameters. Matching of IR features to those obtained from visible light imagers will take advantage of reference databases of new tire and shoe tread patterns by manufacturer and model.



Segment labeling of shoe prints

8. PROPOSED CONTINUATION

The recent NIBIN report from the National Academies states a requirement for additional research on the nature of ballistic toolmarks:

"If firearms identification is to rest on firmer scientific ground, more research would need to assess the fundamental assumption that toolmarks are unique and remain recognizable over time, despite repeated firings. Such research should include a program of experiments covering a full range of factors that may degrade a gun's toolmarks, as well as factors that might cause different guns to generate similar toolmarks. Intensive work is also needed on the underlying physics, engineering, and metallurgy of firearms, in order to better understand the mechanisms that form toolmarks as a weapon is fired."

Use of IR imaging for toolmark comparison removes a major cause of image variations, providing a more consistent basis for comparisons. We propose a three part continuation to our Project involving ammunition components, plus further work in the areas of toolmarks and footwear impressions.

Ammunition Components

Part One would be the creation of a dualband database by imaging 10,000 cartridge cases using the Forensic Toolmark Workstation with both IR and visible light cameras. This would consist of 1000 handguns firing 5 types of ammunition, 2 rounds each. Each cc would receive an inserted plug with 2D barcode identifier to remove errors caused by typing errors. Assuming 100 cc's would be fired, recovered, plugged, imaged, and added to the database each day, the 10,000 cc database would be constructed within four months. Analyses on the constructed database would include: (1) Separate searches of the visible light feature map and IR feature map databases to locate siblings would be performed and the results compared. (2) IR image would be used to automatically align the cc for its visible light image and IR feature maps would be used to remove illumination anomalies from the corresponding visible light feature maps prior to searches of the visible light feature map database. Results would be compared against the original search to quantify the benefit of using IR to filter illumination artifacts. (3) IR feature maps would be used to search the visible light feature map database to quantify the potential benefit from cross-spectral searches.

Part Two would initiate involvement by universities in developing image matching algorithms, similarity indices, classification schemes, alignment methods, and feature encodings to accelerate directed searches; also to study the metallurgy and metrology of the items imaged in infrared. The goals would be to develop a scientific foundation for toolmark analysis and configure an open architecture enterprise network around the Forensic Toolmark Workstation which will serve as a dualband testbed. A committee and working group will be established to organize participation and contributions from the universities.

Part Three would analyze how the barcode/cutline approach presented in this report could support the consecutive matching striae (CMS) technique. Comparison of results from both methods could further improve NIBIN performance.

Future efforts to apply 3D/IR and 2D/IR imaging to collection and analysis of toolmarks and footwear impressions need to consider real world conditions at crime scenes. Within the scope of the current effort, only artificially contrived marks were considered in our laboratory. In both applications, the most important use of IR imaging may be finding the evidence under conditions of poor illumination and restricted access. Small size, weight, and power requirements of the IR systems lend themselves to remote-controlled survey use at a crime scene. A small teleoperated robot could quickly scan for footprints and casings before human staff walk onto the scene.

The second most important use could be rapid imaging of degrading evidence such as footwear impressions in loose material or when a storm is approaching. 3D/IR images could be collected faster than casting, and could be a backup in case the casting was not successful.