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Ballistics Matching Using 3D Images of Bullets and Cartridge Cases

Grant Number: 97-LB-VX-0008

Project Summary

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1. Introduction

Microscopic impressions (striations) found on the surface of fired bullets are routinely used as a means to associate a questioned bullet with a suspect weapon. Such association is possible because the striations found on the surface of fired bullets are imprinted on them by the microscopic imperfections found in the gun's barrel. Exhibit 1 shows the main components involved in the transference of barrel imperfections into the bullet's surface; namely the barrel and the fired bullet. The interior of the barrel (seen on the right side of Exhibit 1) is machined to have lands and grooves whose purpose is to force the bullet to rotate as it travels through it. These lands and grooves in turn imprint land impressions and groove impressions on the surface of the bullet (seen on the left side of Exhibit 1). Because all bullets fired by a given gun must travel through the same barrel, the striations found on bullets fired by the same gun will display significant similarities. We emphasize the expression "significant similarities," because even in the best of conditions, the striations found on two bullets fired by the same gun will not be the same. Usually, the most one can hope for are **regions** of similarity.

This very simple principle is the basis of the discipline practiced by firearms examiners. At the core of firearms examiners' discipline is their ability to compare the striations found on the surface of different bullets, and to determine whether these striations indicate that different bullets were fired by the same gun. It might be worth noting that making such determination requires significant experience and is by no means an easy task.

Until recently, such comparisons could only be made manually; i.e., by a firearms examiner inspecting a pair of bullets under a comparison microscope. The comparison microscope is an

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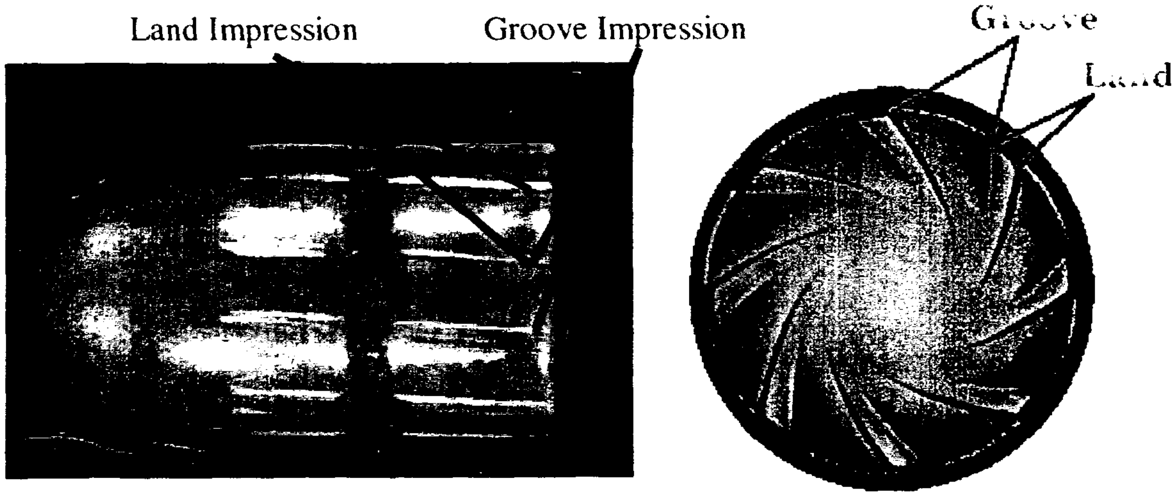

Bullet Impressions

Barrel Rifling

Exhibit 1: Generation of Striations on Bullets

optical instrument which allows the examiner to manipulate and "line up" images of two bullets in an attempt to identify coinciding striations. The left side of Exhibit 2 shows a common such comparison microscope. The right side shows a typical black and white image of a pair of matching land impressions as seen through a comparison microscope (the images that the firearms examiners actually see are in color). The image to the right might look like that of a single land impression. However, these are two land impressions from two different bullets, fired by the same gun, successfully lined up by the firearms examiner. It is worth noticing that this particular "match" is a remarkably clear one.

During the 1990's, a number of automated "search and retrieval" systems emerged. The rational behind the development of these systems was to take advantage of the continuously improving performance (and decreasing cost) of today's computers to facilitate the task of the firearms examiner. The basic components of an automated search and retrieval system are the acquisition and the correlation components:

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Exhibit 2: Comparison Microscope and Typical Comparison Microscope Image

The acquisition component is responsible for acquiring the data from the sample (either bullet or cartridge case) and preparing it for analysis. In general, this component includes all hardware and software elements required to:

a) Capture data from the specimen. We will refer to this data as "captured data." The captured data is closely associated with the physical phenomenon employed to record the desired features of the sample's surface. In the case of a photograph, for example, the underlying physical phenomenon is the reflection of light on the object's surface, so the captured data corresponds to the different light intensities at different points on the sample's surface. This process is performed by specialized hardware (sensors).

b) Encode the data in a format that can be stored and manipulated by a computer. We will refer to this data as "digitized data." This process is also performed by specialized hardware.

c) Process the digitized data in preparation for analysis and comparison. This process usually requires a number of intermediate steps. We will refer to the final processed data

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set as "normalized data," and by extension we refer to the overall process as "data normalization." At the core of the data normalization process are the normalization algorithms.

The correlation component is responsible for comparing sets of normalized data, and organizing the results for inspection by the user. The name "correlation component" originates from the fact that correlation algorithms are very often used to compare normalized data sets. In general, the correlation component includes all the software elements necessary to:

a) Evaluate the degree of similarity between two sets of normalized data. At the core of this process are the correlation algorithms.
b) If more than two bullets are involved in the comparison, to organize the results of a set of comparisons in some convenient way (for example, to rank by degree of similarity).
c) To provide the user with tools to verify the results obtained by the correlation algorithms. At the core of this task is a Graphic User Interface (GUI).

With the help of the appropriate acquisition and correlation algorithms, automated search and retrieval systems can perform tasks ranging from preliminary classifications of bullets (by class characteristics, for example), up to ranking a database of bullets against a questioned bullet by degree of similarity. Moreover, computers can perform these tasks in a fraction of the time it would take a firearms examiner.

Currently, two such automated systems have a prominent place in United States forensic laboratories, namely, IBIS and DRUGFIRE. Both IBIS and DRUGFIRE offer the capability of

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acquiring data from both bullets and cartridge cases, storing such information in a database, and performing correlations between a given specimen and a user specified segment of the available database. These systems also have in common the fact that the captured data is a two-dimensional representation of the specimen's surface based on the variations of light intensity as it reflects on the surface of the specimen. In somewhat simplistic terms, the captured data is basically a "photograph" of the surface of the specimen. We refer to data captured under this methodology as 2D data.

Algorithms developed to correlate different specimens based on 2D captured data have provided satisfactory results in the case of cartridge cases, but rather disappointing results in the case of bullets. This project was motivated by the following question: Are there advantages to the use of 3D captured data as opposed to 2D captured data? In other words, if instead of using a "photograph" of the bullet's surface as the captured data we use a depth measurement of the surface, could we get better performance? This question is of considerable more interest in the case of bullets as opposed to cartridge cases because, as already mentioned, correlation algorithms based on 2D captured data have had reasonable performance in the case of cartridge cases, but rather disappointing performance in the case of bullets. **For this reason, we decided to focus throughout the project on the harder problem of bullets as opposed to cartridge cases.**

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2. What does 3D acquisition mean?

As discussed in the previous sub-section, capturing data in 2D can be thought of as taking a photograph of the surface of the specimen. As seen in Exhibit 3, each cross-section of the bullet contains information of all land and groove impressions on the bullet's surface at the given level.

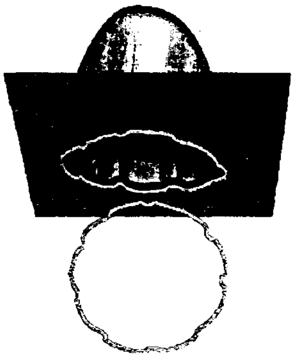

Exhibit 3: Cross-section

In practice, the 3D data captured from the different cross sections of the bullet's surface is neither obtained nor stored as the closed curve shown in Exhibit 3. Exhibit 4 shows schematically how the cross-section closed curve is "cut" and "peeled" from the surface of the bullet. The "peeled" data thus corresponds to the digitized data, as described earlier.

The final component of the acquisition process is the generation of the normalized data. The 3D normalized data set is the result of mathematically processing the digitized data to remove all systematic errors introduced during the capture process. The normalization of the digitized data is a crucial step towards obtaining consistent data for comparison. Exhibit 5 shows a superposition of the 3D normalized data set on top of the conventional 2D image for the same bullet.

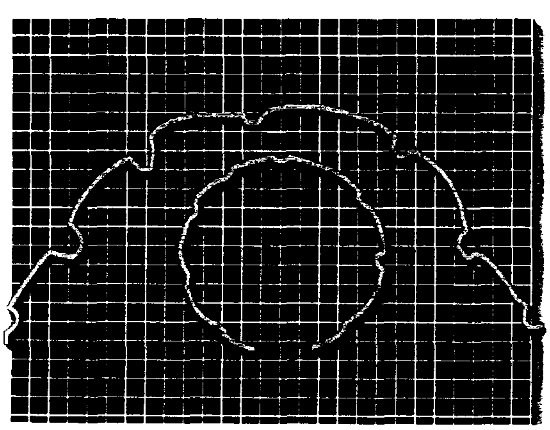

Exhibit 4: "Peeling" Surface of Bullet

Once the data is normalized, the most significant features of the bullet emerge very clearly. Notice

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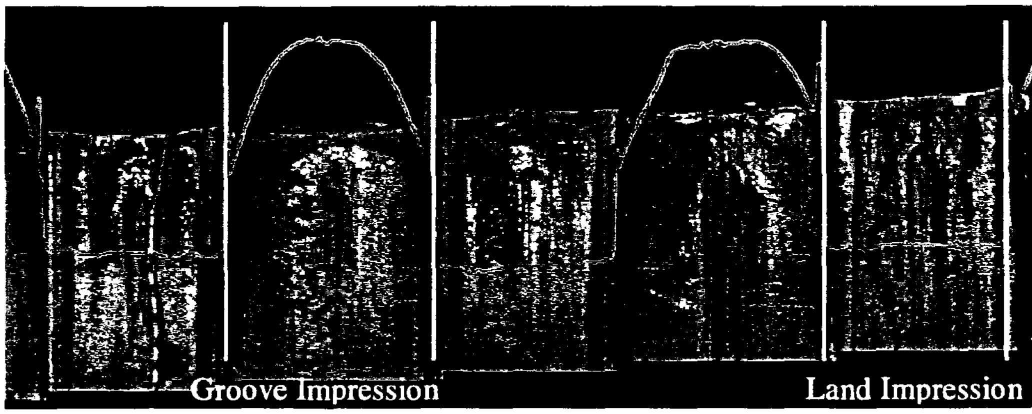

Exhibit 5: Superposition of 3D on 2D Data

in Exhibit 5 the clear definition of the transitions between land and groove impressions in the 3D data, while the same boundary is not well determined by the 2D data. Land and groove impression width measurements are very effective in narrowing down the possible manufacturers of a gun. The bullet in question was scratched with a stylus as can be seen on the leftmost land impression. Notice how significantly this scratch appears in the 3D data, while being a relatively minor feature in the 2D data.

3. 3D Vs. 2D Data Capture

The main difference between 3D data capture and 2D data capture lies in the fact that 2D data capture is fundamentally an indirect measurement of the bullet's surface features, while 3D data capture is a direct measurement. Let us consider the physical phenomenon involved in the 2D data capture. This process is schematically described in the left image shown in Exhibit 6. A source of light is directed at the bullet's surface, and a camera records the light as it is reflected by it. The data capture process is based on the fact that the light reflected by the bullet's surface is a function of the surface features. However, this is an indirect measurement, because it involves a transformation of the incident light into the light recorded by the camera. By comparison, the 3D acquisition process is schematically described in the right image shown in

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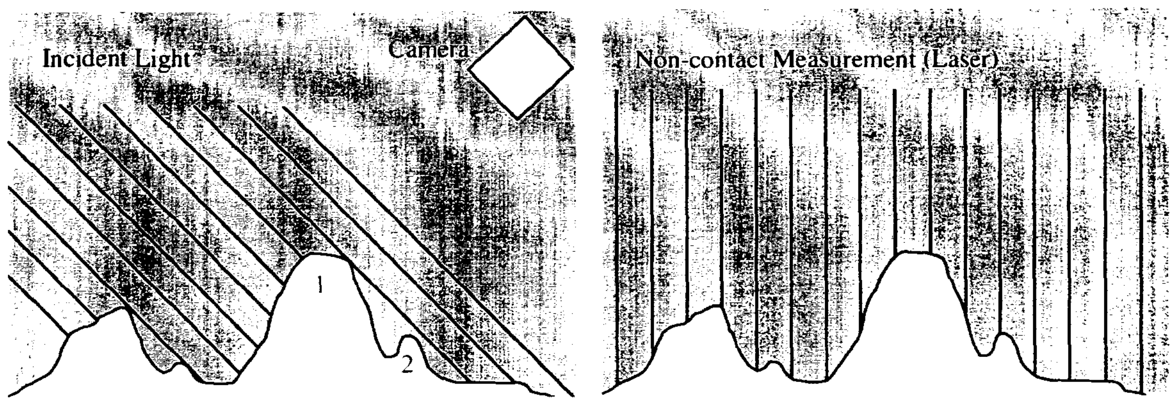

Exhibit 6: 2D Vs. 3D Data Capture

Exhibit 6. The data acquired in this manner is simply the distance between the surface features and an imaginary plane, and is thus a direct measurement. Let us consider the disadvantages associated with of the indirectness of the 2D data capture:

Robustness: A significant problem associated with 2D data capture lies in the fact that the transformation relating the light incident on the bullets surface and the light reflected by it depends not only on the features of the bullet's surface, but also on a number of independent parameters such as the angle of incidence of the light, the angle of view of the camera, variations on the reflectivity of the bullet surface, light intensity, etc. This implies that the captured data (the data recorded by the camera) is dependent on these parameters too. To attempt to eliminate the effect of these parameters on the captured data would be next to impossible (except possibly for light intensity). As a consequence, the 2D captured data is vulnerable to considerable variability, or in other terms, it is **non-robust**.

Indeterminate conditions: A different kind of problem associated with 2D data capture is the presence of indeterminate conditions in the data. Take as an example a surface as depicted in Exhibit 6. Given an incident light source with the shown angle, some of the smaller surface

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features (for example the feature labeled 2) can be "shadowed" by the larger features (feature 1). This implies that there will be regions of the surface where the captured data will not accurately reflect the surface features. In mathematical terms, the transformation between the incident light and the reflected light is **non-invertible**. Furthermore, this is an example where the angle of incidence of the light source can have a critical effect on the captured data, because arbitrarily small changes in the angle of incidence may determine whether feature 2 is detected or not. In mathematical terms, the transformation between the incident light and the reflected light is **discontinuous** with respect to the angle of incidence.

In summary, 2D data capture methodologies can be affected by extraneous variables that can be very difficult to control. Moreover, because these variables are not measured, their effects on the captured data cannot be compensated. As a consequence, the normalized data resulting from such capture processes is also vulnerable to significant variability, or in other words, lack of robustness. By comparison, the capture of data in 3D is a direct measurement of the surface's profile.

4. Experience Obtained/Results

To determine the feasibility of using 3D information from a bullet's surface to improve the matching rate of existing automated search and retrieval systems, it was required to develop and implement all the elements of an acquisition component as described in Section 1. Furthermore, this particular acquisition component would operate based on 3D captured data, as opposed to 2D captured data. Together with the acquisition component, a preliminary version of a correlation component was developed in order to verify the usefulness of the 3D captured data. The complete automated search and retrieval system was tested through a number of independent

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evaluations. Among these evaluations, we have performed a number of so-called "blind tests." For these blind tests, we were provided with control bullets from different guns (i.e., we were told which gun which fired each of the "control bullets"), and with questioned bullets. The task was to identify which gun fired each of the questioned bullets based on the data obtained from the control bullets. In all cases the system was able to perform in a very satisfactory manner, making very few mistakes in the identification of which gun fired each of the questioned bullets.

As a direct result of the research done under this project, and thanks to additional funding provided by the National Science Foundation (Contract No. DMI-9801361) and Nichols Research Corporation (Previously Mnemonic Systems Incorporated), we have developed a fully functional prototype of the 3D ballistic analysis system. This prototype system (named SciClops™, see Exhibit 7) made its public debut in the 1999 Conference of the Association of Firearms and Toolmarks Examiners (AFTE) that took place in July 1999 in Williamsburg, Virginia. During this conference, we gave a presentation of the system in the main conference hall to an audience of AFTE professionals. The debut of our system generated considerable interest, and a significant number of attendees inquired about the expected time frame for its release as a commercial product.

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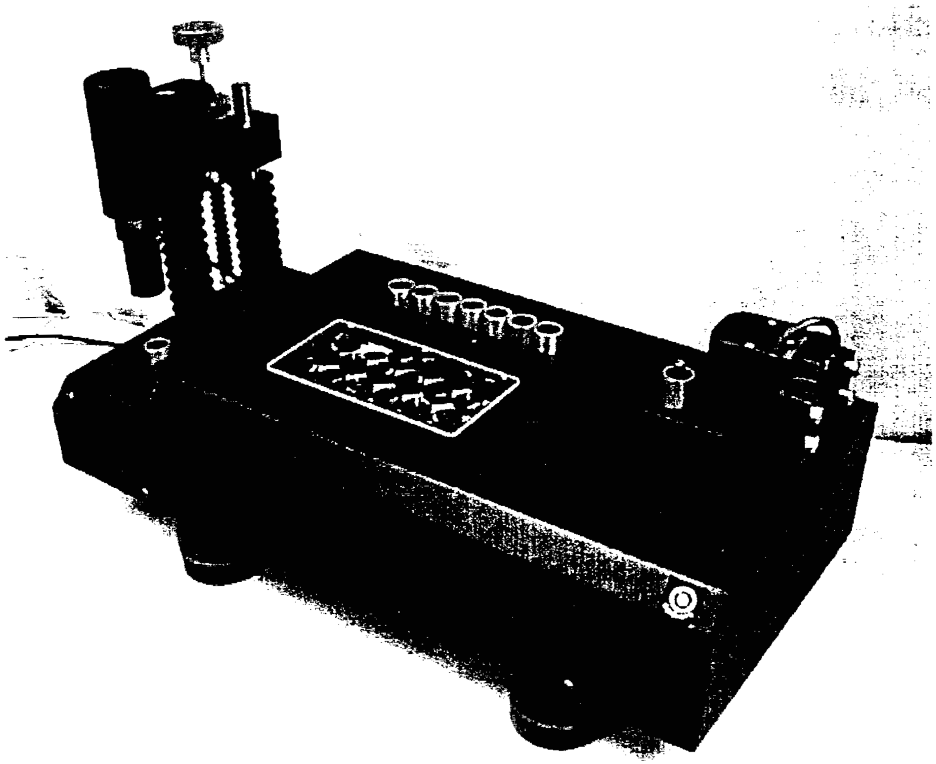

Exhibit 7: SciClops™ Ballistic Analysis System

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