Document Title: Ballistics Matching Using 3D Images of Bullets and Cartridge Cases: Final Report

Author(s): Benjamin Bachrach

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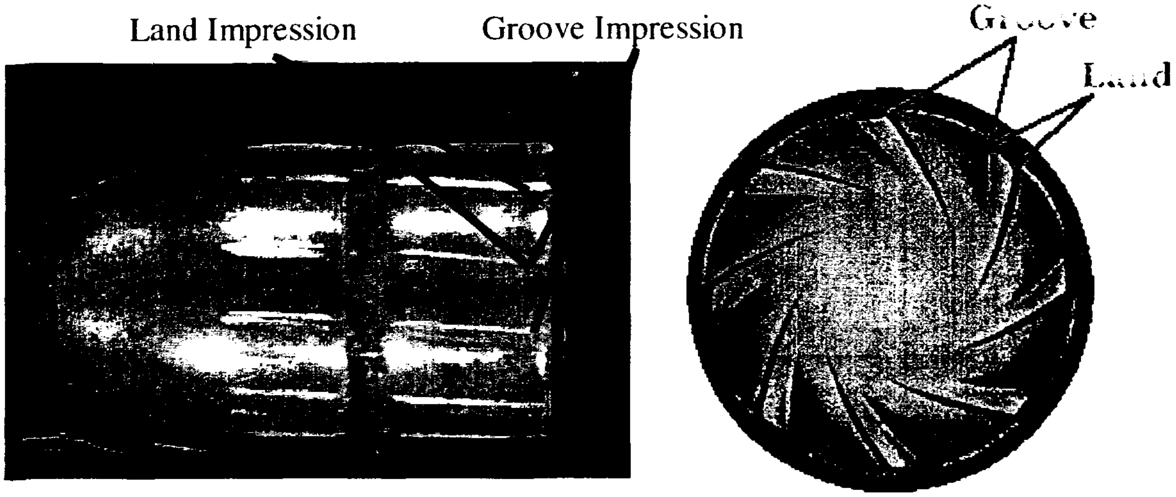
1. Executive Summary

1.1 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 (discounting guns with interchangeable barrels), 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.



Bullet Impressions Barrel Rifling

Exhibit 1: Generation of Striations on Bullets

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 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.

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 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).

Exhibit 2: Comparison Microscope and Typical Comparison Microscope Image

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:

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

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. It should be noted that these systems are not designed to substitute the firearms examiner, but only to assist in his task.

Currently, two such automated systems have a prominent place in United States forensic laboratories, namely, IBIS (Integrated Ballistics Identification System) [1] and DRUGFIRE [2]. Both IBIS and DRUGFIRE offer the capability of 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.

Exhibit 3 shows a typical image (corresponding to the already digitized data) of a single land impression as obtained by the DRUGFIRE system. Notice the similarity between this image and the comparison microscope image shown on the right side of Exhibit 2 (the image shown in Exhibit 2 is taken at a higher magnification than the one in Exhibit 3, but the similarity is still apparent). Among other technical factors, the fact that firearms examiners are used to this type of

Exhibit 3: DRUGFIRE Digitized Data of a Single Land Impression

images has been a motivation for the use of this type of captured data in existing automated search and retrieval systems.

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. In the following sub-sections we discuss in more precise terms what does it mean to capture 3D data of the bullet's surface, and why is the use of 3D captured data more effective than the use of 2D captured data.

1.2 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. So what does it mean to capture 3D data? Intuition suggests that 3D data capture should be associated with the depth of the striations. In this sub-section we make a more precise description of what is meant by 3D data capture.

Exhibit 4 shows a schematic view of a bullet "sectioned" at different levels along its longitudinal axis. By sectioned we mean that each of the planes shown defines a level at which information regarding the surface of the bullet will be captured. Exhibit 5 shows in a schematic format the content of the information captured at each level of the bullet.

As seen in Exhibit 5, a closed curve is defined at each section by the intersection of the sectioning plane and the bullet's surface. Each of these curves is of course a cross-section of the bullet, and it contains information of all land and groove impressions on the bullet's surface at the given level. In principle (and ignoring finite resolutions

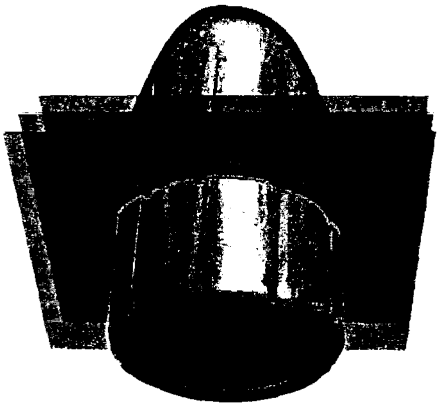


Exhibit 4: Sectioning of Bullet

and tolerances), a complete description of a bullet as a three dimensional object is possible if one takes enough of these cross-sections. Thus the term 3D data or 3D captured data.

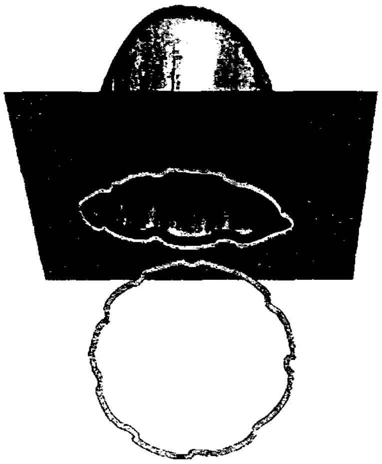


Exhibit 5: Bullet's Cross-section

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 5. From the point of view of the correlation algorithms and from the point of view of the user it is much more convenient to take a further step in the processing of the data acquired from each cross section. Exhibit 6 shows schematically how the cross-section closed curve is "cut" and "peeled" from the surface of the bullet. In practice, the "cutting and peeling" takes place at the hardware level, and it is a result of the methodology used to collect the data. The data gathering process will be discussed in the following sections. The "peeled" data thus corresponds to the digitized data, as described in Section 1.1.

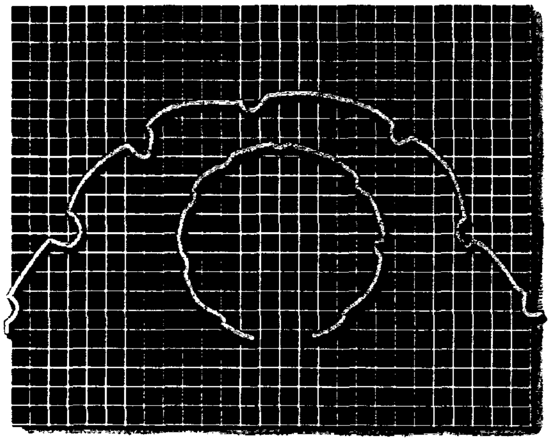


Exhibit 6: "Peeling" Surface of Bullet

The final component of the acquisition process is the generation of the normalized data. Exhibit 7

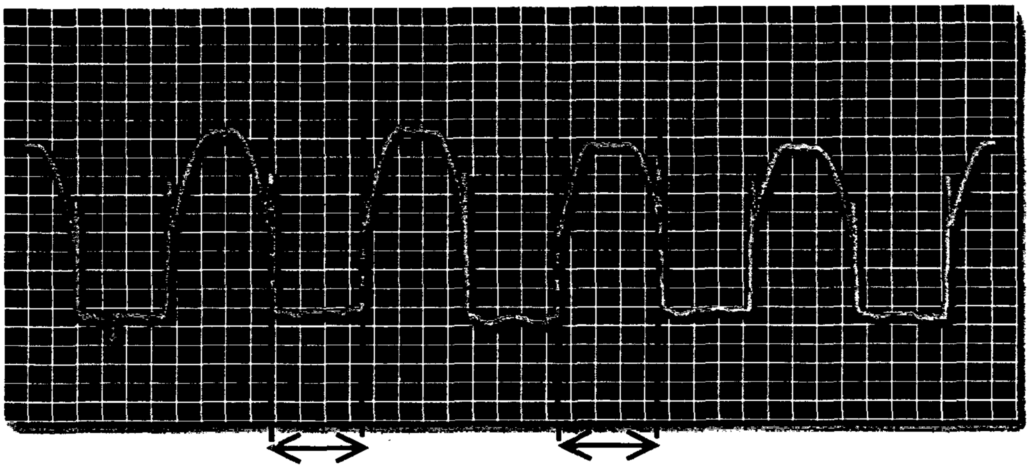


Exhibit 7: 3D Normalized Data

shows an example of what a normalized data set looks like. This 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. We will discuss the normalization aspect of the acquisition component in the following sections.

Once the data is normalized, the most significant features of the bullet emerge very clearly. As an example, let us consider the widths of the land and groove impressions. Land and groove impression width measurements are very effective in narrowing down the possible manufacturers of a gun. As seen in Exhibit 7 the transitions between land and groove impressions can be identified very accurately in the normalized 3D data. A more dramatic comparison of 3D vs. 2D data can be seen in Exhibit 8, where the 3D data has been superimposed on the 2D data for the same bullet (as acquired by the DRUGFIRE system). Notice the clear definition of the transitions

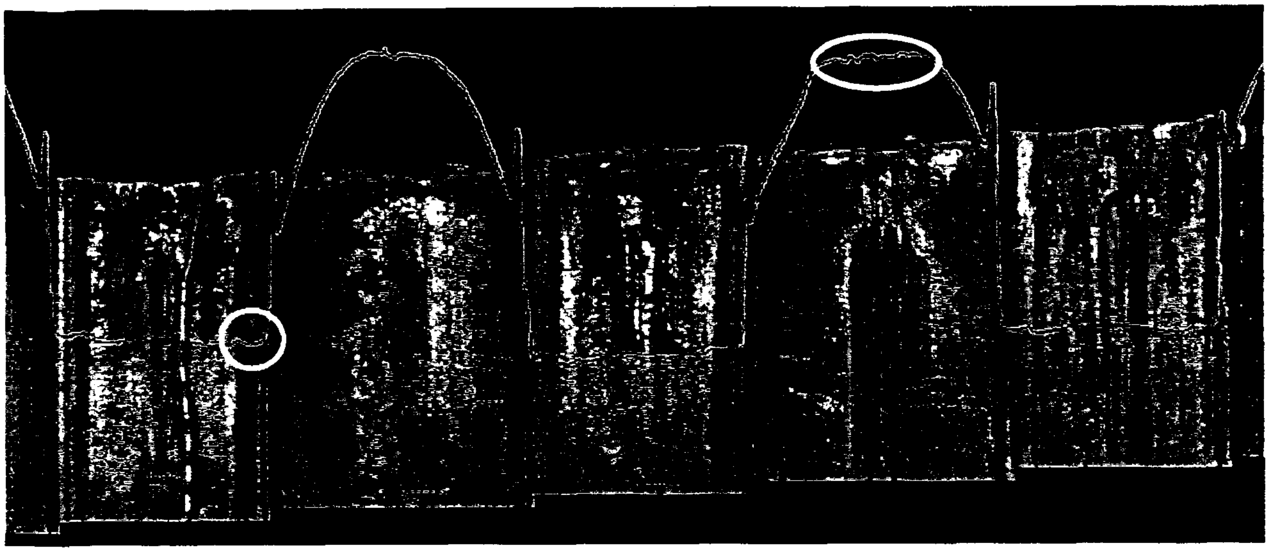


Exhibit 8: Superposition of 3D on 2D Data

between land and groove impressions in the 3D data, while the same boundary is not well determined by the 2D data. The bullet in question was scratched with a stylus as can be seen on the leftmost land impression. It is easy to see how significantly this scratch appears in the 3D data, while being a relatively minor feature in the 2D data.

It is also interesting to notice that the regions where land impressions transition into groove impressions (see yellow circle in Exhibit 8) are seen to be qualitatively different to the regions at the center of the land impressions. These are regions where reliable striations (consistent between different bullets fired by the same gun) can usually be found. Although firearms examiners have long known that these regions usually contain reliable striations, a quantitative representation had never been obtained. Another region where reliable striations can usually be found is the center of the groove impressions (see yellow ellipse in Exhibit 8). Interestingly enough, these are regions that are often overlooked by firearms examiners, who usually rely much more in land impressions

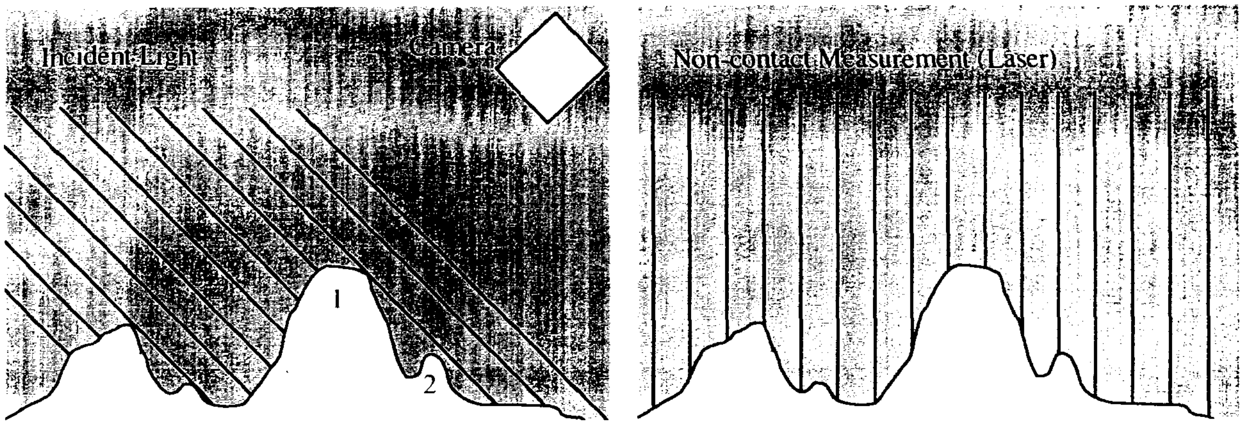


Exhibit 9: 3D Vs. 2D Data Capture

than groove impressions. Based on our measurements, it has been our experience that these regions often contain very significant and reliable data.

1.3 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 9. 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 Exhibit 9. 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 reflected light 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 9. Given an incident light source with the shown angle, some of the smaller surface 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

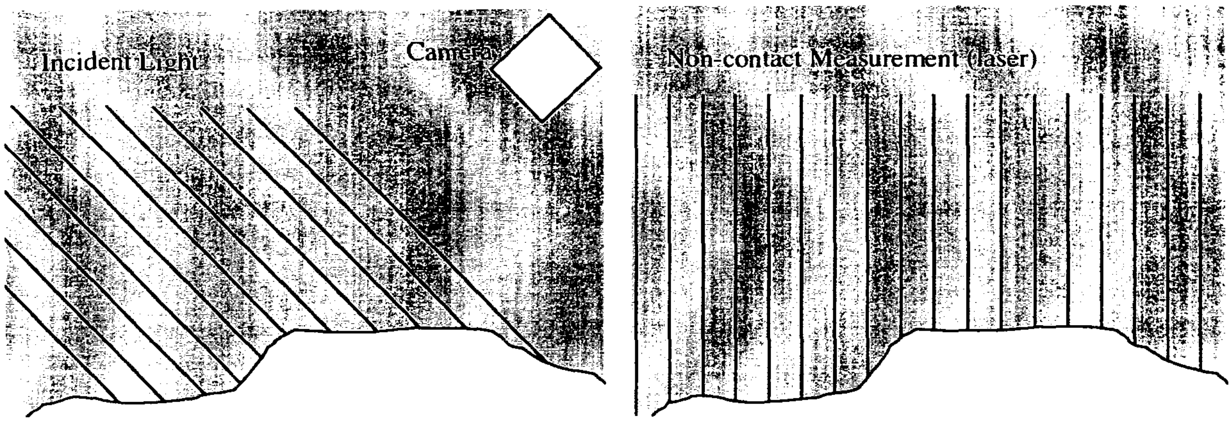


Exhibit 10: 3D Vs. 2D Data Capture

discontinuous with respect to the angle of incidence. An example of a similar problem is shown in Exhibit 10, where the surface consists of mostly flat sections. From the perspective of the camera, except for a transition between the two sections, there will be no way to retrieve the difference in the height of the sample's profile.

In summary, 2D data capture methodologies can be affected by extraneous variables which can be very difficult to control. Moreover, because these variables are not measured, their effects on the captured data cannot be compensated for. As a consequence, the normalized data resulting from such capture processes is also vulnerable to significant variability, or in other words, lack of repeatability. The performance of even the most sophisticated correlation algorithms will be degraded in the presence of non-repeatable data. Taking in consideration that the bullet matching problem is quite demanding to begin with, it is not surprising that ballistic matching methodologies based on 2D captured data have had significant difficulties delivering the expected performance.

By comparison, the capture of data in 3D is a direct measurement of the surface's profile. This implies that capturing the data in 3D does not suffer from the lack of robustness or indeterminacy which 2D data capture displays, and has considerable promise towards improving automated ballistic automated search and retrieval systems.

1.4 Experience Obtained/Results

The ultimate objective of this project was to determine whether 3D information from a bullet's surface can be successfully exploited to improve the matching rate of existing automated search and retrieval systems. To achieve this objective, it was required to develop and implement all the elements of an acquisition component as described in Section 1.1. Moreover, 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 2 types of independent evaluations.

Discrimination: The first such evaluation involved bullets fired by three different guns, whose barrels were manufactured consecutively. The challenge to the system was to group the different bullets correctly. Such evaluation not only tests whether the system is capable of identifying similar bullets, but due to the similarities between consecutively manufactured barrels, it also tests whether it can discriminate a true match from a very close false match. This set of bullets was used to "tune" the many parameters in the numerical algorithms of the system.

Identification: The second type of evaluation was meant to emulate a more "real life" situation. These evaluations involved so-called "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 (i.e., to match the questioned bullets with the control bullets). It is worth mentioning that in each of these tests the guns in question had the same class characteristics. We performed two sets of tests, the first with 6 guns and the second with 5 guns. In both cases the system was able to correctly identify which gun fired each of the questioned bullets.

2 Project Description

As mentioned in Section 1.4, the ultimate objective of this project is to determine whether 3D information from a bullet's surface can be successfully exploited to improve the matching rate of existing automated search and retrieval systems. To achieve this objective, it was required to develop all the hardware and software elements of an acquisition component as described in Section 1.1. Together with the acquisition component, in order to verify the usefulness of the 3D captured data, a preliminary version of a correlation component was also developed.

Together with these efforts, a number of evaluations were performed to determine the potential of the system. These evaluations are described in general terms in Section 1.4, and in detail in Section 4.

3. Scope and Methodology

The scope of this project was to validate the use of 3D captured surface data as a reliable methodology for ballistics analysis and matching. In order to achieve this goal, it was necessary to develop the main components of a basic search and retrieval system, and to evaluate its performance. Because at the core of this project is the premise of exploiting a new type of captured data, we focused most of our efforts in the acquisition component of the system; in other words, in the consistency and reliability of the acquisition procedures and algorithms. We have also invested a considerable amount of effort in the development of a correlation component. This correlation component has also proved to be quite successful.

3.1 Acquisition Component: Hardware

One of the most important steps for this project was to design, build and test a practical setup to measure the depth of bullet striations. This task involved two main decisions: the selection of a depth measuring device capable of performing the required measurements to the required specifications (for a reasonable cost), and the selection of a methodology and corresponding hardware setup to perform these measurements. We selected the measurement technology/device which best satisfies the requirements of this application. This was not a trivial task due to the stringent requirements inherent to the required measurements. We also conceived a methodology and assembled a prototype mechanism to enable us to make these measurements. This section describes in detail our considerations for the development of the hardware aspects of the acquisition component.

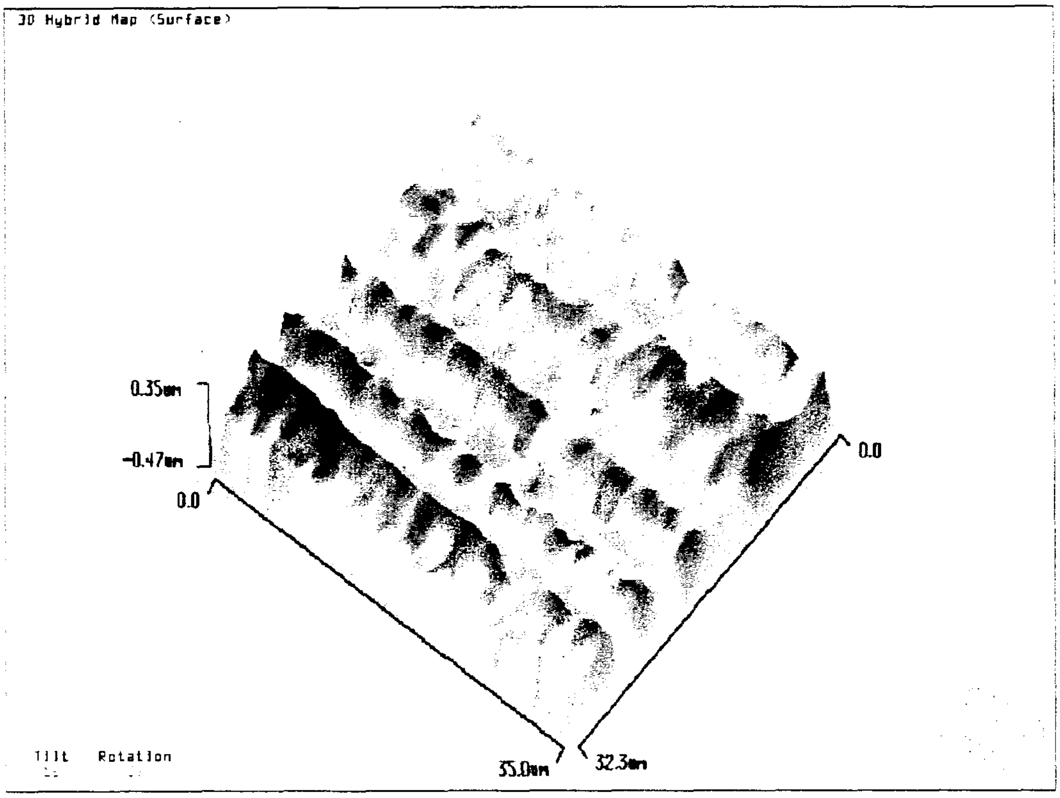


Exhibit 11: White Light Interferometry Bullet Surface Measurement

3.1.1 Measurement Considerations and Requirements

The first challenge of this project was to identify the best possible technology to perform the required depth measurements. Exhibit 11 shows the result of measuring a section of a land impression on a bullet's surface using white light interferometry. Although an ideal technology from the point of view of accuracy, due to its considerable cost, white light interferometry was not a feasible solution to our measurement needs. However, white light interfereometry was extremely useful to determine the characteristics of the bullet's surface, and by extension, the specifications of the depth sensor required to measure it.

Based on a number of these and a number of other measurements, we concluded that in order to obtain significant information regarding the striations on a bullet's surface, an instrument with depth resolution on the order of .1 microns and lateral resolution on the order of 1 micron would be optimal. Additional measurements helped us determine that the depth differential between a land impression and a groove impression on a bullet's surface is on the order of 100 microns.

Together with the depth sensor, it was necessary to identify a simple and cost effective methodology to perform the measurement in a consistent manner. By consistent we mean that the measurement methodology had to be such that different bullets would be measured under the same conditions and in the same manner. Due to the basically cylindrical shape of bullets, it was determined that the best measurement methodology would be to rotate the bullet in view of the depth sensor as opposed to performing a X-Y raster of the bullet's surface. By doing so, it is possible to take full advantage of the depth sensor range. The basic structure of the experimental setup is shown on the left side of Exhibit 12. The bullet under measurement is rotated in front of the depth sensor, while the depth sensor measures a cross section of the bullet.

Given that the depth difference between a land impression and a groove impression on a bullet's surface is on the order of 100 microns, in order to measure a complete cross section of a bullet (i.e., 360 degrees), the minimum required range for the depth sensor is in principle exactly 100 microns. However, because bullets are never perfectly round after being fired, and because there are always miss-alignment imperfections in the measurement process (the bullet under measurement could be improperly centered, or tilted, for example), a depth range of 600 microns was considered the minimum acceptable range for this application.

Finally, it was of critical importance for this application to identify a non-contacting measurement instrument (to prevent any possible damage to the bullets). Identifying a non-contacting depth sensor capable of satisfying the required lateral, depth resolution, and range parameters (together with reasonable measurement bandwidth) is not necessarily a very difficult task **for reasonably flat surfaces**. As an example, it is possible to find conventional triangulation-based sensor systems capable of satisfying these requirements for flat surfaces. However, after trying a couple of these, we found that such systems could not reliably measure the transitions (shoulders) between land and groove impressions. In fact, the output of such systems would saturate at these points, and whole sections of the bullet's surface would be lost. The reason triangulation-based sensors did not provide satisfactory performance for these regions is that the slope of the surface at these transition areas is too steep for these sensors.

Besides triangulation systems (which have the advantage of being cheap and widely available) we studied the feasibility of using other measurement methodologies. Among others, we considered Moire Interferometry, Shape from shading techniques, Photometric Stereo techniques, Scanning Electron Microscopy, Confocal Microscopy, and other Confocal sensors. Of all these techniques, we found that confocal based sensors offered a very good compromise between cost and performance. These were the only commercially available sensors capable of making measurements of the steep shoulders between land and groove impressions, while not being prohibitively expensive. Two commercially available confocal sensors were identified, one manufactured by Keyence Corporation, and the other manufactured by UBM Corporation. The sensor manufactured by UBM Corporation was selected based on cost and performance

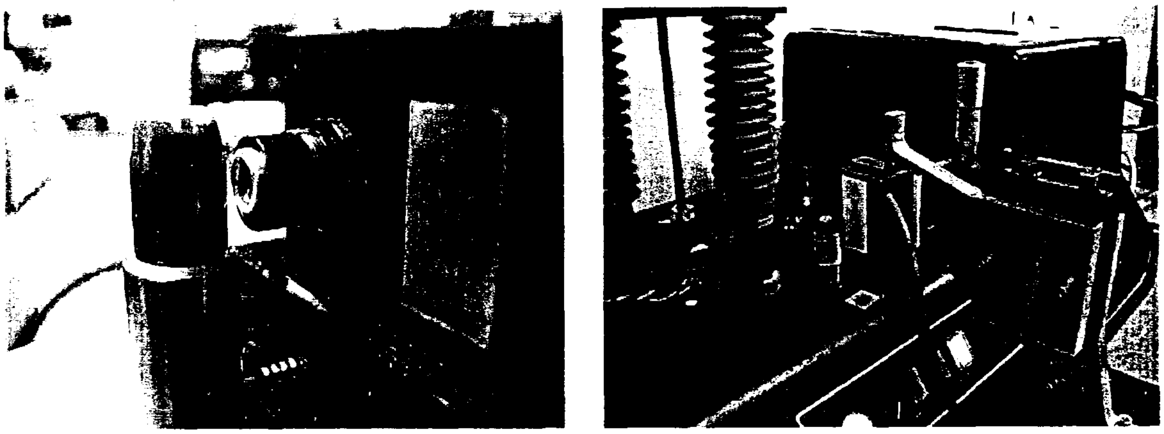


Exhibit 12: Measurement Setup

considerations. This sensor has a depth resolution of .5 microns over a range of 1000 microns, a lateral resolution of 1 micron and a bandwidth of 1.2KHz. The Keyence sensor has a lateral resolution on the order of 7 microns, and a bandwidth of 700Hz. The poor lateral resolution of the Keyence sensor excluded it from our application.

3.1.2 Experimental Measurement Setup

Exhibit 12 shows two hardware setups we used to evaluate the sensors (left), and to make actual measurements on bullets (right). The measurement arrangement to the right takes advantage of one of our RotoScan systems to hold and rotate the bullet to be measured by the depth sensor. A manually adjustable mechanism was configured to allow the operator to move the selected depth sensor along the longitudinal axis of the bullet, left and right with respect to the axis of rotation of the bullet, and in and out with respect to the same axis of rotation. Thus, we had all degrees of freedom necessary to position the sensor with respect to the rotating bullet. It should be noted that this setup does not include any type of vibration isolation structures to minimize the effect of all the different sources of vibration in the measurements. This setup was meant to be temporary, and we have already developed a considerably better measurement setup. It should also be noted the difference in depth between land and groove impressions is indeed in the order of 100 microns.

The depth resolution achieved with this measurement setup (show in the right side of Exhibit 12) was on the order of 2 microns (before processing). These limitations were introduced by vibration noise, and we have already improved our measurement environment to achieve a resolution of about 1 micron. For the measurements performed throughout this project, we improved on the hardware-limited resolution by taking repeated measurements and averaging. The final effective resolution achieved was about 0.25 microns.

Notice the sharp transitions between the land and groove impressions. As previously mentioned, these transitions cause considerable difficulty to most conventional depth measurement systems. Notice too that the overall shape of the bullet's surface seems to follow a sinusoidal function. This distortion of the bullet's surface is primarily due to the fact that the longitudinal axis of the bullet did not coincide with the axis about which the bullet was rotated. Errors in the acquired data are also introduced (but are less significant) by the bullet's longitudinal axis being tilted with respect to the axis of rotation. Because these errors relate to different kinds of misalignment between the bullet's longitudinal axis and the axis about which the bullet is rotated, we refer to all these measurement errors as coaxiality errors. Similarly, we refer to the numerical values of the parameters causing these errors (miss-alignment, tilt, etc.) as coaxiality parameters.

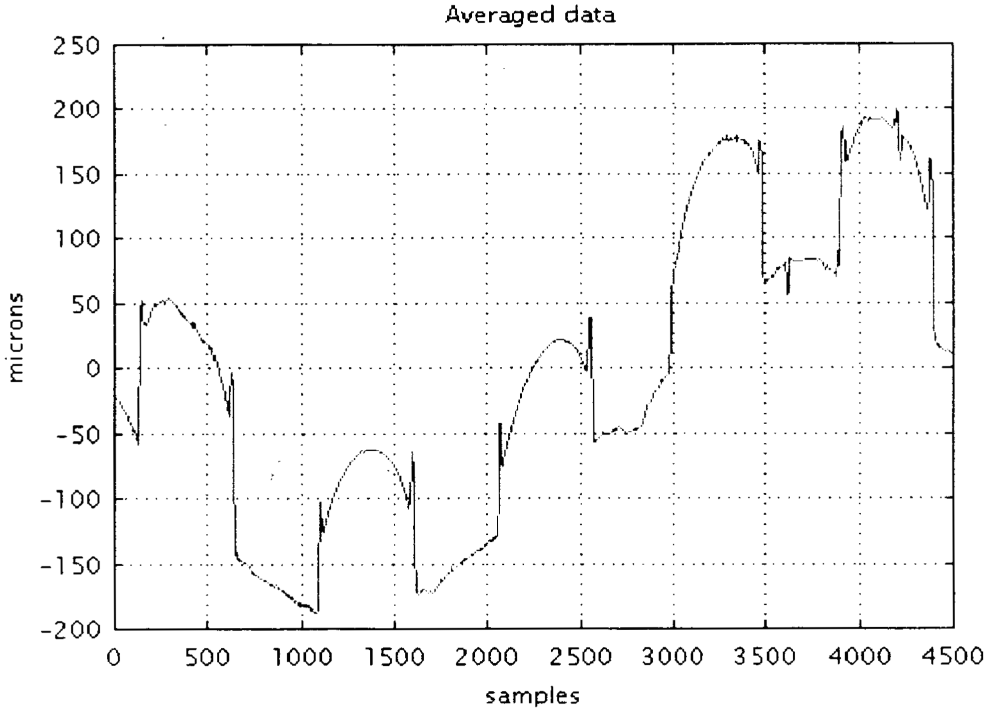


Exhibit 13: Characteristic Averaged Trace Measurement

that we used one of our RotoScan systems because it offered us the capability of inspecting the 2D image of the bullet. However, in no way is the methodology we developed dependant on this particular hardware component.

Using the described manual setup we made a number of measurements on different bullets. Exhibit 13 shows a characteristic averaged (more than one measurement were averaged) measurement of a cross section of a bullet. This data corresponds to the digitized data as defined in Section 1.1. The bullet in this measurement was a 9 mm, 5R, copper jacketed bullet. The horizontal scale shows sample points, while the vertical scale shows microns. Thus, the lateral resolution for this particular measurement was on the order of 6 microns. It can also be seen that

3.2.1 Coaxiality Errors Parameter Estimation:

As already mentioned, in order to compensate for the effect of coaxiality parameters, we first have to identify them. In order to identify all the required coaxiality parameters, we construct a mathematical model of the effect of the coaxiality parameters on the measured data. We then perform a least-squares estimation of these parameters based on the acquired data. In other words, we construct a cost function parameterized by the coaxiality parameters, and taking into account the acquired data. By minimizing this cost function, we obtain the best possible estimate of the true coaxiality parameters.

Exhibit 14 shows the different transformations taking place between the bullet's true surface data (on the left side of Exhibit 14) and the captured data (on the right side of Exhibit 14). Between these transformations, we define "reference systems," which enable us to discuss the changes in the data as certain specific transformations take place. We begin with the "Bullet System," which represents the true bullet's surface without the errors introduced by the measurement procedure. We parameterize the bullet's true surface in polar coordinates as $(\theta_b[i], r(\theta_b[i]))$, where $r(\theta_b[i])$ corresponds to the surface distance to the bullet's center at the angular position $\theta_b[i]$ in the bullet's system or reference frame.

The initial assumption in this analysis is that the geometric shape formed by the undamaged land impressions on the bullet's surface approximates a cylinder. This cylinder undergoes an initial transformation into the Deformed System. It is at this stage that extraneous parameters such as tilt, off centering, etc., have an effect on the bullet's surface data. This data is then transformed into the Spin Cup System, which corresponds to the mechanical setup where the bullet is

3.2 Acquisition Component: Software

In the previous section we described the hardware setup and equipment used to capture the 3D data. We also briefly mentioned the fact that imperfections in the measurement setup introduce errors in the 3D captured data. In other words, the 3D captured data depends on independent parameters (coaxiality parameters), just as the 2D captured data. If so, can we still argue that 3D captured data is more robust and reliable than 2D captured data? The answer is yes, and the reason for such answer is that as opposed to 2D captured data, **we can use the 3D captured data to estimate these independent parameters. Once these parameters are estimated, it is possible to compensate the captured data to eliminate their effect.** In this manner we will obtain the normalized data set as defined in Section 1.1.

One can also view this approach from a different perspective. In principle, all measurement errors could be eliminated if it were possible to align the longitudinal axis of the bullet with the axis about which the bullet is rotated. To do so would require very stringent tolerances in the hardware design and manufacture. Such a task is next to impossible, among other reasons, because bullets are not really cylindrical objects (specially if deformed), which implies that there may be no well-defined longitudinal axis at all. From this perspective, our approach is to compensate for measurement imperfections in software, instead of attempting to eliminate them in hardware. A welcome benefit of this approach (and a considerable cost benefit) is that the tolerance requirements on the acquisition hardware can be reduced considerably, since tolerance imperfections are corrected together with all other measurement errors.

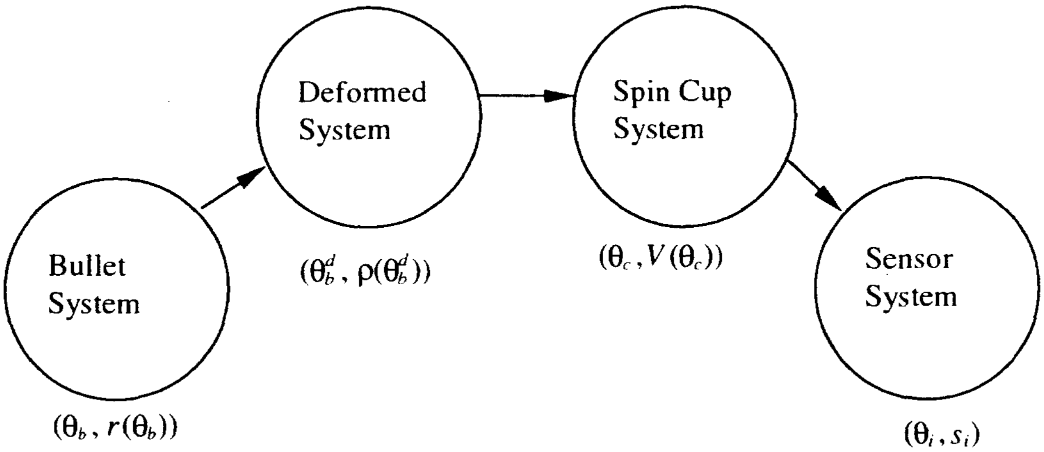


Exhibit 14: Schematic Description of Different Reference Frames

positioned for measurement. The final transformation between the Spin Cup System and the Sensor System corresponds to the transformation associated with the data capture process. We denote the data in the Sensor System by $(\theta_i[i], s_i(\theta_i[i]))$, where for each angular position $\theta_i[i]$ we assign a magnitude $s_i(\theta_i[i])$. This data corresponds to the digitized data as defined in Section 1.1, and this is the data available for analysis (see Exhibit 13).

The main objective of identifying the coaxiality parameters is to enable us to retrieve the true bullet data $(\theta_b[i], r(\theta_b[i]))$, based on our knowledge of the measurement setup, our knowledge of the coaxiality parameters, and the captured data $(\theta_i[i], s_i(\theta_i[i]))$. We are interested in the true bullet data $(\theta_b[i], r(\theta_b[i]))$ because this data amounts to the striations on the bullet's surface in their true magnitude and scale. The true bullet data $(\theta_b[i], r(\theta_b[i]))$ corresponds to the normalized data as defined in Section 1.1.

As already mentioned, the estimation of the coaxiality parameters is based on the solution of a least-squares estimation problem. We can formulate this problem based on at least two different approaches, which we have called the Forward Transformation approach and the Inverse Transformation Approach. As will be detailed in the following, in the Forward Transformation Approach the least-squares problem is formulated in the Sensor System, while in the Inverse Transformation Approach the least-squares problem is formulated in the Bullet System. It should be clear that we could also pick some "intermediate point" in the transformation to formulate the least-square problem. We discuss both approaches, and point out the advantages of the inverse approach with respect to the forward approach.

3.2.1.1 Forward Transformation Approach

In this approach, the least-squares problem is formulated as the solution of the following optimization problem:

$$\min_{\overline{p}} C_F(\overline{p}) \qquad (1)$$

Where the cost function $C_F(\overline{p})$ is defined by:

$$C_F(\overline{p}) = \sqrt{\frac{1}{N_p}\sum_{i=1}^{N_p}\left(s_i(\theta_i[i]) - \tilde{s}_i(\theta_i[i])\right)^2} \qquad (2)$$

The vector $\overline{p}$ corresponds to the coaxiality parameters, the vector $\tilde{s}_i(\theta_i[i])$ is the result of forward-transforming a cylinder of radius r according to the assumed values of the coaxiality parameters, and $s_i(\theta_i[i])$ is the portion of the captured data describing the surface defined by the land impressions. The difficulty in this approach is that we need to compute the forward transformation at the exact same phase angles at which we have data; in other words, at $\theta_i[i]$.

This would require a preliminary computation of the corresponding angles in the spin cup reference frame, and this complicates the procedure. The following inverse approach is much more convenient.

3.2.1.2 Inverse Transformation Approach

In this approach, the least-squares problem is formulated as the solution of the following optimization problem:

$$\min_{\bar{p}} C_I(\bar{p}) \tag{3}$$

Where the cost function $C_I(\bar{p})$ is defined by:

$$C_I(\bar{p}) = \sqrt{\frac{1}{N_p}\sum_{i=1}^{N_p}(r - r(\theta_b[i]))^2} \tag{4}$$

The value $r(\theta_b[i])$ is the result of inverse-transforming a point ($\theta_i[i]$, s_i) based on the assumed values of the vector of coaxiality parameters $\bar{p}$, and r is the radius of the cylinder describing the surface defined by the land impressions. Optimally, if the cost function equals zero, we will have found the coaxiality parameters generating the captured data ($\theta_i[i]$, s_i).

The optimization problems resulting from both the forward and the inverse approach are non-convex and offer no trivial solution. We have developed and implemented algorithms to solve both these optimization problems. Although fully functional and successful, these algorithms are still under research in order to improve reliability and speed.

3.2.2 Data Compensation Based on Estimated Coaxiality Errors:

Once the coaxiality parameters are estimated by solving either the Forward or Inverse least-square problem, it is relatively straight-forward to use these parameters to compensate the captured data (in fact, the digitized data). The compensated data becomes the normalized data as defined in Section 1.1. We have developed and implemented the algorithms required to perform the compensation. As a test of our parameter estimation/compensation programs, we performed a consistency evaluation. The objective of the consistency evaluation was to assess the consistency of the normalized data for a given bullet measured under different conditions. Such evaluation would challenge all our acquisition procedures and algorithms.

In order to perform this evaluation, we positioned a bullet in the measurement setup, and acquired data from 5 cross sections of the bullet on a 1mm ring (i.e. each cross section measurement was made 250 microns apart). The same bullet was then taken out of the measurement setup, repositioned in the same setup, and a similar measurement was made. By taking the bullet out of the setup and repositioning it, we inevitably modified the coaxiality parameters. In this manner we had data from the same bullet measured under different conditions; i.e., the captured data was distorted by different coaxiality parameters. We then proceeded to estimate the coaxiality parameters associated with each of the two data sets, and we compensated each data set according to their respective estimated coaxiality parameters.

Exhibit 15 shows the results of our evaluation. As can be seen, the normalized data from the two independent measurements looks very consistent indicating that the coaxiality parameters were reliably estimated, and that the data was accurately normalized. To get an idea of the magnitude

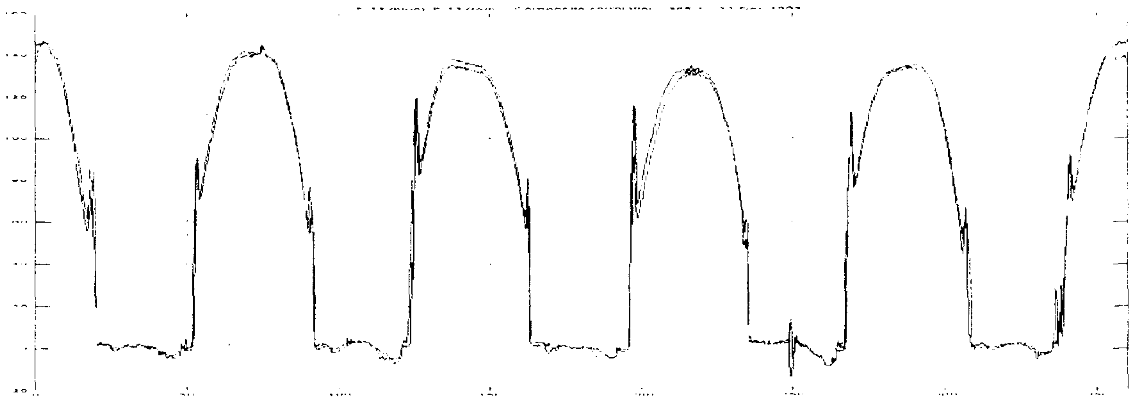


Exhibit 15: Consistency Test

of the difference between pre-normalized and post-normalized data, Exhibit 13 shows the captured data for this same test; i.e., the pre-compensated data (for one of the measured traces). Comparing this data with the data displayed in Exhibit 15, it is clear that the compensation algorithms have made a significant difference.

Notice that there are some minor differences between the two normalized data sets shown in Exhibit 15. In particular, notice how the last groove impression displays a significant valley in the normalized data shown in blue. This phenomenon can be explained by the fact that we made no attempt to capture the data at the same distance from the base of the bullet (relative to the longitudinal axis of the bullet). For this reason, there are minor differences. On the other hand, notice that not only the major features of the bullet coincide, but also the minor features repeat themselves in both measurements. These observations bring up the issue of consistency within the bullet itself; i.e., how sensitive is the captured data with respect to the location along its longitudinal axis. This is a topic that should be further researched.

The importance of an accurate compensation in the normalization process cannot be sufficiently emphasized. The effect of the coaxiality errors manifests itself not only in the form of a vertical displacement of the data, but it also produces a deformation along the horizontal axis (shrinking/stretching). Accurate compensation of the captured data is essential for the satisfactory performance of the correlation algorithms. It is for this reason that we take the trouble of estimating and compensating for the coaxiality parameters as opposed to simply filtering out their effects. The simpler idea of high pass filtering the captured data (to eliminate the predominantly low frequency coaxiality errors) would not compensate in any way the deformation of the bullet along the horizontal axis (shrinking/stretching).

3.3 Correlation Component

So far we have shown the feasibility of making reliable measures and obtaining consistent data from a bullet's surface. The question remains as to whether this information can be used to enhance the performance of existing ballistic analysis systems. To this effect, we developed a preliminary version of a correlation component. This software is still under development, but preliminary results have been extremely encouraging. At its core, the correlation component receives as an input the normalized data of two bullets (say for bullets a and b), and returns as an output the relative orientation at which these two bullets are most similar, and a similarity measure (denoted $s(a,b)$). The similarity measure is a function of different correlation values obtained from the data of the bullets under comparison. It was this software that was used to align the two signatures shown in Exhibit 15.

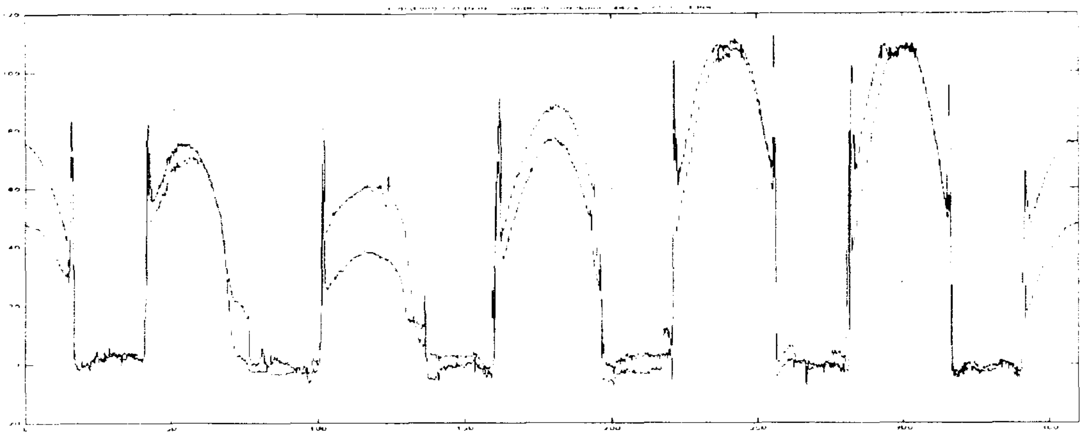


Exhibit 16: Normalized Data of Two Bullets Fired by the Same Gun

3.3.1 Testing and Evaluation

In order to evaluate the capabilities of the system to match bullets fired by the same gun, we captured data belonging to two bullets fired by the same gun. Exhibit 16 shows the results of comparing the normalized data of these two bullets. As can be seen, the major features of these bullets seem to be very similar. However, they would provably be so for any pair of bullets of similar material fired by a gun of the same manufacture. Notice too that although there are significant similarities, there are also considerable differences. This did not come as a surprise to trained firearms examiners to which we showed our results. As mentioned earlier, the most that can be expected from bullets fired by the same gun is regions of similarity; i.e., discrete portions of the surface where the bullets display similarities. Thus, in order to assess whether two bullets were fired by the same gun, it is necessary to inspect the details corresponding to the striations in the land and groove impressions. To this effect, our correlation software makes comparisons not only of the major features of a bullet pair, but also of the smaller details found within the land and groove impressions. Exhibit 17 shows a comparison of a high pass filtered version of the land

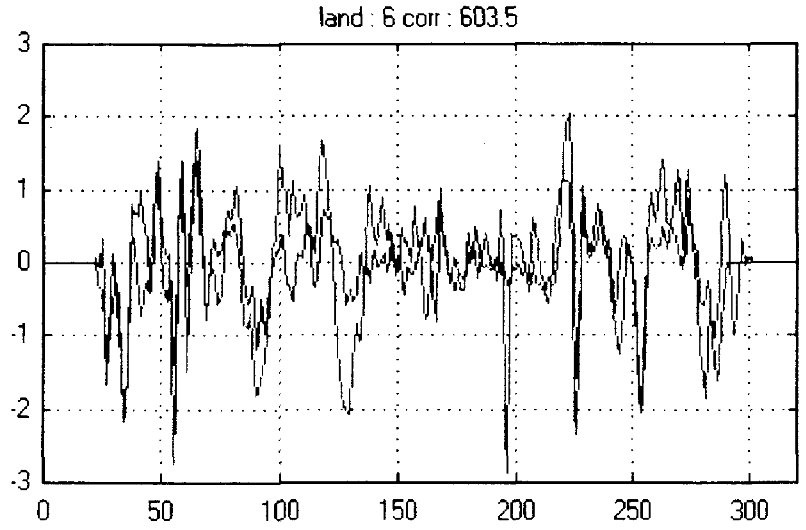


Exhibit 17: Comparison of Land 6

impressions in position 6 (the rightmost pair of land impressions in Exhibit 16), together with a numerical assessment of their similarity (correlation).

Given the considerable variations in the conditions under which bullets are fired, one should not expect the impressions made by the barrel on the bullet to necessarily have the same depth in every firing. Some of the main sources of variation in impression depth are the material of the bullet, and the temperature of the barrel, and any debris left by a previously fired bullet. The material of the bullet has significant influence on the way the barrel imperfections are imprinted on it. Similarly, the temperature of the barrel has an effect on its expansion, causing again some variation in the depth of the impressions. Finally, any debris left by a previously fired bullet, such as burnt powder, could cause striations that are not repeatable. Therefore, while inspecting these results, it is important to keep in mind that we are not necessarily looking for a perfect overlap of the surface features of the two bullets to conclude a high degree of similarity. What we are really looking for is a coincidence of sections or regions between the two surfaces.

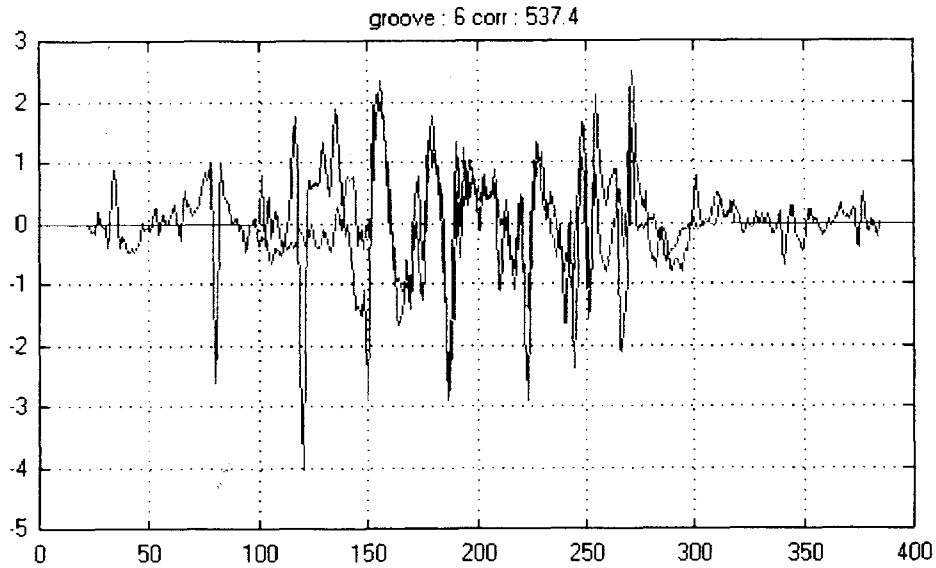


Exhibit 18: Comparison of Groove 6

Having said that, the similarities between the two land impressions shown in Exhibit 17 are the more impressive, since we do see some overlap on some regions. Notice that the regions to the sides of this pair of land impressions display the most significant similarities, while the region in the middle of the same impressions shows relatively little in common. This phenomenon was mentioned earlier, while discussing the advantages of 3D data capture over 2D data capture. The explanation for this phenomenon is that the sides of land impressions make better contact with the barrel than the center of the land impressions. For this reason, the resulting impressions are more consistent from bullet to bullet.

Exhibit 18 shows a comparison of a high pass filtered version of the groove impressions in position 6 (the rightmost pair of complete groove impressions in Exhibit 16). Notice that in contrast to the results seen in the case of land impressions, the region of similarity is at the center of the groove impressions. Notice too that there is considerable overlap between the two normalized sets. The phenomenon that explains these results is the fact that the center of the groove impressions makes better contact with the gun's barrel, just as the sides of the land impressions. This phenomenon can be easily seen in Exhibit 16. Notice how the groove impressions have an almost rounded shape. It can easily be seen that mostly the middle region of the groove impressions display striations consistent with having contacted the barrel. The rounded sections, which do not seem to have been in contact with the barrel, do not contain consistent striations. Moreover, notice that some of the groove impressions do not show any signs of having contacted the barrel at all.

Based on conversations with firearms examiners, it seems that groove impressions are often ignored in the comparison of bullets, or are often given secondary importance compared to land impressions. A possible explanation is that, as discussed in the previous paragraph, groove impressions do not always make contact with the barrel's surface, and thus may have no consistent striations. Although this phenomenon has been understood for a long time, the development of a 3D acquisition component has enabled for the first time to observe and quantify this phenomenon. Moreover, as seen in Exhibit 16, the information obtained with this new methodology allows the examiner to detect which groove impressions contain significant information and which do not. It has been our experience that groove impressions often contain extremely valuable data, and it is our assessment that the potential for improvement of existing search and retrieve systems by incorporating groove impression's data is very significant.

4. Detailed Findings

The ultimate objective of this project was to determine whether 3D information from a bullet's surface can be successfully exploited to improve the matching rate of existing automated search and retrieval systems. To achieve this objective, we developed and implement all the elements of both an acquisition and a correlation component as described in Section 1.1. So far, we have described the results of our research in mostly qualitative terms. These results within themselves show that the application of 3D techniques has considerable potential in the ballistics analysis arena. However, in order to evaluate the feasibility of improving existing automated search and retrieval systems it is important to make some quantitative evaluations of the system's performance. The complete automated search and retrieval system was tested through 2 types of independent evaluations: a discrimination evaluation and an identification evaluation. Following is a discussion of the results of these evaluations.

4.1 Discrimination:

This evaluation involved bullets fired by three different guns whose barrels were manufactured consecutively. The challenge to the system was to group the different bullets correctly. The fact that the bullets used for this evaluation originated from guns with consecutively manufactured barrels implies that the impressions on these bullets were quite similar. Thus, this evaluation not only tests whether the system is capable of identifying similar bullets, but due to the similarities between consecutively manufactured barrels, it also tests whether it can discriminate a true match from a very close false match. This set of bullets was used to "tune" the many parameters in the numerical algorithms of the system.

		Gun 1		Gun 2		Gun 3	
		r-10	r-11	r-20	r-21	r-30	r-31
Gun 1	r-10	100.00	[illegible]	22.70	27.96	30.86	24.36
	r-11	[illegible]	100.00	22.29	23.69	24.50	23.65
Gun 2	r-20	22.70	22.29	100.00	[illegible]	27.24	22.04
	r-21	27.96	23.69	[illegible]	100.00	24.76	23.08
Gun 3	r-30	30.86	24.50	27.24	24.76	100.00	[illegible]
	r-31	24.36	23.65	22.04	23.08	[illegible]	100.00

Exhibit 19: Discrimination Evaluation

We used 6 bullets in this evaluation, 2 from each gun. The numerical results of this evaluation are tabulated in Exhibit 19. Each entry in the table corresponds to the similarity measure $s(a,b)$ between the two bullets found in the corresponding column and row as obtained by our correlation program. As a reminder, this similarity measure is based on correlation computations on the striations found on both bullets. The highest attainable similarity value is 100. The cells marked in red indicate the correct matches (i.e., bullets r-10 with r-11, r-20 with r-21, etc.). The purpose of this test was to determine whether the system is not only capable of pairing up similar bullets, but also whether it is able to discriminate a true match from a close false match. As seen in Exhibit 19, the system was able to identify the correct matching pair for each of the bullets. This can be concluded by the fact that after comparing each bullet with all the other bullets, the highest similarity measure is achieved with the second bullet fired by the same gun (discounting the comparison of each bullet against itself, which as expected gives the maximum similarity of 100). For example, for bullet r-10 the highest attained similarity measure was $s(r-10, r-11) = 35.20$, while the similarity measure between bullet r-10 and all other bullets is lower than this value. This is a correct match, because both r-10 and r-11 were fired by the same gun.

Consecutively Manufactured Barrels

	min	max	avg
d(x)	0.54	0.88	0.70

Exhibit 20: Discrimination Measure

For this evaluation, it was desired to assess the degree of discrimination of the correlation algorithm. To this effect, we defined the discrimination ratio $d(x)$ to represent the relative difference between a false match and a true match. In more precise terms:

$$d(x) = \frac{\max\limits_{y \notin G(x)} s(x,y)}{\min\limits_{y \in G(x),\, y \neq x} s(x,y)} \qquad (5)$$

where $G(x)$ denotes the gun which fired bullet x and $y \in G(x)$ denotes all bullets y fired by the same gun which fired bullet x, and $y \notin G(x)$ denotes those bullets not fired by the same gun which fired bullet x. This discrimination measure is thus **the ratio of the highest correlation value computed for a false match divided by the lowest correlation value computed for a true match**.

Exhibit 20 shows the minimum, the maximum and the average discrimination ratio for each of the bullets in question. In general, discrimination ratios indicate how close a false match can be to a true match. The lower the discrimination ratio is, the better discrimination between true and false matches has been achieved. This indicates that for this set of bullets, in the worst possible case, the discrimination ratio reached a value of 0.88, or in other words, that a false match can reach, al lest, a numerical value 88% of the numerical value of a true match. In our view, if this margin can be maintained for large number of bullets, it is indeed a very promising starting point.

	Gun 1		Gun 2		Gun 3		Gun 4		Gun 5		Gun 6	
	T1-01	**T1-02**	**T1-03**	**T1-04**	**T1-05**	**T1-06**	**T1-07**	**T1-08**	**T1-09**	**T1-10**	**T1-11**	**T1-12**
T1-a	36.71	34.46			43.67	43.38	57.75	57.18	37.33	31.83	40.07	40.69
T1-b	30.59	34.19	57.00	49.70	42.08	45.87			28.55	33.20	39.79	37.91
T1-c			39.20	37.33	32.41	27.68	36.62	32.00	29.17	26.56	37.90	38.36
T1-d	34.76	30.37	41.85	40.16	30.04	34.70	37.77	36.16			36.68	37.13
T1-e	28.29	28.05	44.57	47.87	41.31		47.72	44.21	30.59	31.39	47.01	38.79
T1-f	35.19	37.84	36.71	42.26	30.89	26.62	35.73	42.42	39.45	39.27		

Exhibit 21: Results of Blind Test

4.2 Identification:

The second type of evaluation was meant to emulate a more "real life" situation. These evaluations involved so-called "blind tests". We were provided with control bullets from different guns (i.e., we were told which gun 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 (i.e., to match the questioned bullets with the control bullets). It is worth mentioning that in each of these tests the guns in question had the same class characteristics (same caliber, number of rifling marks, etc.). We performed two sets of tests, the first with 6 guns and the second with 5 guns. In both cases the system was able to correctly identify which gun fired each of the questioned bullets. In this section we report the results of the first such test. The results of the second test were very similar.

The results of the first blind test are summarized in Exhibit 21. The control bullets were labeled T1-01 through T1-12 and these bullets are tabulated in the horizontal axis. As seen, bullets T1-01 and T1-02 were fired by Gun 1, bullets T1-03 and T1-04 were fired by Gun 2, and so on. The questioned bullets were labeled T1-a through T1-f, and these bullets were tabulated in the vertical axis.

For all questioned bullets except T1-e, the entries marked in red correspond to the two control bullets for which the correlation algorithm computed the highest similarity measure. As can be seen, for all these bullets the highest similarity measures were always obtained when compared with control bullets corresponding to the same weapon. It was thus assessed that these bullets were most likely to have been fired by such weapon (for example, T1-a was linked to Gun 2, T1-b was linked to Gun 4, etc.). As already mentioned, bullet T1-e was an exception, because the first and second highest scores did not correspond to the same gun. Nevertheless, we assessed that this T1-e should be paired with the gun whose control bullet gave the highest similarity measure, i.e., Gun 3. The reasoning behind such decision was based on the fact that bullets T1-05 and T1-06 were not very similar between themselves either ($s(T1-05, T1-06) = 44.03$). Thus, we concluded that although bullets T1-05, T1-06, and T1-e were fired by the same gun, bullet T1-05 was for some reason somewhat different than T1-06 and T1-e. When, after making our assessment, we verified our results with the firearms examiners who provided the bullets, they confirmed that we had correctly paired **all** the questioned bullets with their respective guns, including bullet T1-e.

It should be said that we learned a considerable amount from questioned bullet T1-e. The main lesson was that even two bullets fired by the same gun can be considerably different. As already mentioned, when we compared bullets T1-05 against T1-06 (which we knew came from the same gun, since they were both control bullets) we obtained a surprisingly low similarity measure ($s(T1-05, T1-06) = 44.03$). Upon commenting our experience with the firearms examiners who provided us the bullets, they confirmed that this is not an uncommon occurrence. Based on their experience, it is not uncommon to obtain rather different looking bullets form the same gun. The importance of this result cannot be sufficiently emphasized, since it implies that multiple bullets should always be used when trying to confirm whether a questioned bullet was fired by suspect gun.

As a result of our experience with the described evaluation, we were prompted to consider the case when more than one control bullet is available to the examiner. In many cases (very often when used as evidence in court) the firearms examiner is not required to determine whether two bullets were fired by the same gun, but whether a questioned bullet was fired by a suspect gun. If one assumes that the suspect gun is available (which is very often the case whenever ballistic evidence is presented in court), the possibility of multiple control bullets should be considered. For this reason, it is relevant to define a measure of similarity between **a bullet and a gun, as opposed to between two bullets**. This similarity measure would rely on the availability of more than one control bullet. Given a questioned bullet x and a gun G, we define the similarity measures $S_{avg}(x,G)$ and $S_{peak}(x,G)$ as follows:

$$S_{peak}(x,G) = \max_{y \in G,\ y \neq x} s(x,y) \qquad (6)$$

$$S_{avg}(x,G) = \underset{y \in G,\ y \neq x}{avg} \ s(x,y) \qquad (7)$$

where $y \in G$ denotes all bullets y fired by gun G. Thus, $S_{avg}(x,G)$ corresponds to an **averaged** measure of similarity between bullet x and **all** bullets fired by gun G (except itself, if x was fired by G), while $S_{peak}(x,G)$ corresponds to the **highest** similarity measure between bullet x and **all** bullets fired by gun G (except itself, if x was fired by G). These two similarity measures are a

	Gun 1 01-02	Gun 2 03-04	Gun 3 05-06	Gun 4 07-08	Gun 5 09-10	Gun 6 11-12
a	35.59		43.53	57.47	34.58	40.38
b	32.39	53.35	43.98		30.88	38.85
c		38.27	30.05	34.91	27.87	38.13
d	32.57	41.01	32.37	36.96		36.90
e	28.17	46.22		45.97	30.99	42.90
f	36.51	39.49	28.76	39.08	39.36	

	Gun 1 01-02	Gun 2 03-04	Gun 3 05-06	Gun 4 07-08	Gun 5 09-10	Gun 6 11-12
a	36.71		43.67	57.75	37.33	40.69
b	34.19	57.00	45.87		33.20	39.79
c		39.20	32.41	36.62	29.17	38.36
d	34.76	41.85	34.70	37.77		37.13
e	28.29	47.87		47.72	31.39	47.01
f	37.84	42.26	30.89	42.42	39.45	

Exhibit 22: Similarity Measure S_{avg} **Exhibit 23: Similarity Measure S_{peak}**

preliminary attempt to assess the similarity between a bullet and a weapon, as opposed to between two bullets. **An optimal definition of similarity between a bullet and gun is a topic of considerable interest.** We anticipate considerable research to identify the most promising such measure. Exhibit 22 and Exhibit 23 show the values of $S_{avg}(x,G)$ and $S_{peak}(x,G)$ attained for the test under consideration. Notice that using either of the new definitions of similarity between a bullet and a gun, bullet T1-e no longer displays any anomalies.

Based on this new measure of similarity (between a bullet and a gun, instead of between two bullets) we generalized the discrimination measure used in our discrimination test. The purpose of doing so is to assess the degree of discrimination achieved by this alternative similarity measure. For each questioned bullet we defined the discrimination ratios $d(x)$, $d_{avg}(x)$ and $d_{peak}(x)$ as follows:

$$d(x) = \frac{\max\limits_{y \notin G(x)} s(x,y)}{\min\limits_{y \in G(x),\, y \neq x} s(x,y)} \qquad (8)$$

where $G(x)$ denotes the gun which fired bullet x, and $y \in G(x)$ denotes all bullets y fired by the same gun which fired bullet x,

$$d_{avg}(x) = \frac{\max_{H \neq G(x)} S_{avg}(x, H)}{S_{avg}(x, G(x))} \qquad (9)$$

and

$$d_{peak}(x) = \frac{\max_{H \neq G(x)} S_{peak}(x, H)}{S_{peak}(x, G(x))} \qquad (10)$$

The different discrimination ratios fulfill two purposes. On one hand, they allow us to evaluate the validity of our comparison algorithm and the calculated similarity measures. Second, they allow us to evaluate which is the best similarity measure when it comes to comparing a bullet against a weapon as opposed to a bullet against another bullet.

Exhibit 24 summarizes the resulting similarity rations for the test in consideration. As shown in this table, we obtained a discrimination ratio $d(x)$ between .77 and 1.16. Bullet T1-e was the only questioned bullet for which the discrimination ratio was greater than 1. Exhibit 24 shows that the discrimination ratio improved as we considered an averaged discrimination measure $d_{avg}(x)$. In particular, it becomes lower that one for all bullets (between 0.71 and 0.97). Further improvement seems to be achieved by considering the peak discrimination measure $d_{peak}(x)$, which decreases the maximum discrimination ratio to 0.91. Although less than satisfactory (even a gap of 9% is not significant enough), these results are rather encouraging, and open the question of how to best make use of multiple control bullets when available.

It is not surprising that the averaged discrimination measure $d_{avg}(x)$ displays better results than $d(x)$, since by definition $d(x)$ considers the worst possible combination of false and true matches. It is interesting; however, that the peak discrimination measure $d_{peak}(x)$ displays better

Test Case I

	min	max	avg
d(x)	0.77	1.16	0.94
davg(x)	0.71	0.97	0.86
dpeak(x)	0.68	0.91	0.86

Exhibit 24: Discrimination Ratios

discrimination than the averaged discrimination measure $d_{avg}(x)$. This can be explained by the fact that, in general, two bullets from the same gun do not necessarily have high similarity. In general, even when dealing with a single pair of bullets, it seems more important to determine whether there are regions of the two bullets which display significant similarity, as opposed to the whole surface of both bullets being similar. In other words, due to the amount of random striations created during the firing of a bullet, is seems to be much more significant to find regions of similar features than to expect the whole surface to be similar. The same kind of reasoning seems to translate to multiple bullets fired by the same gun. It seems more significant to find **one** very similar bullet than to expect **all** bullets to be similar.

5. Analysis and Discussion

A number of important lessons can be learned from the results of our research effort. First and foremost, that ballistics matching using 3D information from the surface of bullets is a feasible methodology to improve the matching ratios of currently 2D based ballistic matching systems. The main reason for such improvement lies in the fact that, properly processed, 3D acquired data is more robust and consistent than 2D acquired data. This additional robustness and consistency translates into better correlation results, and better overall performance. Together with this general conclusion, there are a number of other important lessons that derive from our research, and which might, in some cases, be of help to ballistic analysis in general, be it 2D based or 3D based.

1) Careful processing of the acquired data is crucial for the successful comparison of bullet's surface information. In particular, it is critical to "normalize" the acquired data so that the conditions under which the data was taken have as little as possible influence on the data used for the actual comparison. In this fashion, the data used in the comparison does not depend on the particular operator that entered the data, the particular piece of hardware used to obtain the data, etc. This is another point where 3D methodologies have an upper hand over 2D methodologies, because the parameters which influence the acquired data (coaxiality errors, in our discussion) can be estimated and compensated for from 3D data, while the same is next to impossible to achieve with 2D data.

2) It has been our experience that groove impressions often contain extremely valuable data, and it is our assessment that the potential for improvement of existing search and retrieval systems by incorporating groove impression's data is very significant.

3) An important conclusion of our research is that whenever possible (whenever a suspect gun is available) it is very important to use multiple control bullets to compare against the evidence bullet. The importance of this result cannot be sufficiently emphasized, since it implies that multiple bullets should always be used when trying to confirm whether a questioned bullet was fired by suspect gun.

6. Conclusions and Implications of Findings

Based on our research, there is little doubt that ballistics matching using 3D information of a bullet's surface is a powerful tool to improve automated search and retrieval ballistics analysis systems. Our research indicates that using the right measurement technology and processing techniques, it is possible to obtain reliable and consistent normalized data of a bullet surface. Moreover, the information found is often sufficient to identify the gun by which a bullet has been fired.

Our research focused on the bullet identification and matching problem, instead of the cartridge cases matching problem. We did so not because we believe that a 3D imaging approach would not work for cartridge matching, but because computer-aided identification and matching methodologies are considerably more mature for cartridges cases than for bullets, and we felt it would be more beneficial to focus in the harder problem. That computer-aided bullet matching is more difficult than their cartridge counterparts is not surprising. To begin with, cartridges (when available) are usually retrieved in better condition than bullets. Furthermore, the processes that imprint a cartridge case are less "traumatic" than those that imprint a bullet. Finally, there are at least four different independent markings that are used to identify cartridges (breach face impression, pin impression, ejection marks and ejector mechanism impression), while there is only one fundamental process that imprints a bullet.

Until now, the creation of a national database of firearms based on either cartridge cases or bullets has been an elusive dream of the law enforcement community. In a recent New York Times article, the creation of such a database is stated as a specific goal (with the corresponding government support and funding) of the current administration [3]. Such database would be created by having all gun manufacturers test fire each weapon before it is sold to the public. At this stage, such database will be based on the use of cartridge cases as opposed to bullets. The main reason for such choice is past performance. As already mentioned, so far there has been considerable more success in the matching of cartridge cases as opposed to bullets. The reasons for such poor performance by the current 2D systems have already been discussed.

On the other hand, cartridge cases are not always available at a crime scene. This is because criminals are either becoming more sophisticated and are retrieving them, or because they are using revolver-type weapons, which do not eject the cartridge case as the weapon is fired. Bullets, on the other hand, are always left behind in a crime scene. For this reason, if at all possible, a computerized system capable of successfully matching bullets as opposed to cartridge cases would be much preferred for the creation of such database.

After a demonstration of its capabilities, Frank J. Sauer, Program Manager of the NIBIN/DRUGFIRE, FBI Laboratory, and Robert W. Sibert, Chief Firearms and Toolmarks Unit, FBI Laboratory, expressed their believe that 3D based ballistic identification could improve bullet-based automated ballistic analysis systems to the point of making it possible to establish a practical national database of firearms based on bullet signatures. The implications of creating a bullet-based database of firearms in addition to a cartridge case-based database would be significant, since such database would improve the ability of law enforcement officials to identify the weapons used in a crime.

6.1 Future Research

The results obtained during this project have been very encouraging. We are at the point where a 3D computer-aided ballistic analysis system is feasible. However, there is considerable work to be done towards validating and improving such a system. In general, there is room for improvement in all aspects of this project (both hardware and software). The hardware setup can be improved considerably to decrease noise levels and increase the speed at which a bullet can be acquired. As far as software, both the acquisition algorithms and the correlation algorithms can also be improved in terms of effectiveness and speed. In particular, there is considerable more work to be done in the correlation algorithms. There are, however some specific topics that were not directly addressed in this study, and where considerable improvement to the current state of the art in computer-aided ballistic analysis is attainable:

Classification Algorithms: One of the most challenging problems of taking full advantage of a national database of bullets is the magnitude of such database. It is not difficult to anticipate that once such database is in place, correlation comparisons over thousands of bullets will become routine. Therefore, in order to make such database practical and efficient, it will be necessary to perform large correlation comparisons in a reasonable amount of time. Classification algorithms will decrease the time it takes to make a match by narrowing the number of candidate bullets whenever a large search is performed. Classification algorithms can be thought of as a pre-filter in the matching process. In fact, simple versions of such algorithms are implemented in the existing systems, where the user can specify certain parameters such as number of lands and grooves (there is no point in comparing bullets that do not have the same number of lands and grooves), land-width and groove-width dimensions, bullet material, etc. to narrow the number of candidate bullets. However, more sophisticated means of classifying a large universe of bullets will be necessary.

Gun-to-bullet Correlation: To date, all research in computerized ballistic analysis has focused on the comparison of one bullet against another bullet. Clearly, such comparisons are of fundamental interest, and constitute one of the building blocks of computerized ballistic analysis. However, whenever the suspect weapon is available to the examiner, there are a number of alternatives that have never been addressed, namely, the possibility of making gun-to-bullet comparisons. By gun to bullet comparisons we mean the comparison of an evidence bullet against a variety of control bullets. As we have learned through our research, in order to determine whether a given evidence bullet was fired by a suspect gun, it is important to compare the evidence bullet against as many control bullets as possible. The question is then how to best perform such comparison.

One could postulate a number of ways to perform such one-to-many bullet comparison. We consider two of them here. The first option involves the creation of a composite bullet based on the multiple control bullets, and using such synthetic bullet as a signature bullet that characterizes a weapon. The second option involves comparing the degree of similarity among the control bullets themselves to the degree of similarity between the evidence bullet and the control bullets. We briefly expand on these ideas in the following paragraphs.

The first approach would be to synthesize a composite bullet signature out of all available control bullets. Such composite signature would capture the most significant and consistent features of all the control bullets, and it could in principle eliminate the randomness of each individual bullet. Although this idea could be used to create a "gun signature," one should be careful in that bullets of different material (or even manufacture) can be imprinted in significantly different fashion. Thus, to completely characterize a gun, it might be necessary to create composite signatures of bullets of a number of different materials.

The second approach can be described as a two-step process. First, the control bullets are compared among themselves, and the statistical characteristics of such comparison would be recorded. Once such step is taken, the evidence bullet would be compared against the control bullets, and the statistical characteristics of such comparison would be compared against the statistical characteristics obtained between the control bullets. If the statistical characteristics of the comparison between the evidence bullet indicate a degree of similarity (we use this term very loosely in this context) higher or equal than that obtained between the control bullets themselves, then there is a high degree of confidence that the evidence bullet indeed originated from the same source as the control bullets. This approach also lends itself to the following area of research: Quantification of Results.

Quantification of Results: of all areas where further research is required, an objective methodology to quantify the provability of an evidence bullet being fired by a suspect gun is provably the most interesting and valuable one. Such tool, once accepted by the scientific and legal community, would eliminate the subjectivity that currently exists in the testimony of "expert witnesses" in court. One could imagine a time when ballistic analysis comparison results will have the same kind of scientific and legal acceptance as today's DNA analysis.

6.2 Current Status

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^{TM}, see Exhibit 25) 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 a large 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.

Another interesting development that took place during the AFTE 1999 conference was the degree of interest that our presentation generated among the developers of the IBIS system. The IBIS system is the ballistic identification system favored by ATF, and is the competition of DRUGFIRE, which is manufactured by our commercial partner Nichols Research. Although we have a business relationship with Nichols Research, they have no objection to the sale of our product to the IBIS manufacturer. This understanding opens the possibility for the sale of our system to both the DRUGFIRE and IBIS manufacturers. This is not only beneficial to IAI and the SBIR program, but would also contribute to the unification of these two systems. This was one of the main requirements and goals of this project, and we feel that we have satisfied it in the most successful manner.

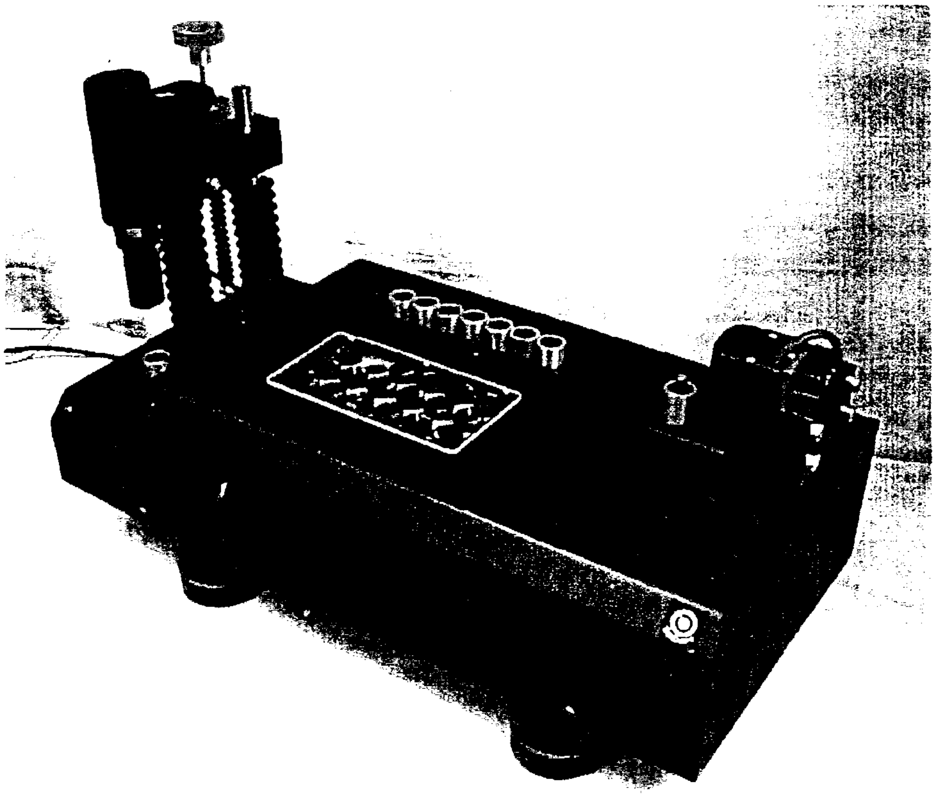


Exhibit 25: SCICLOPS^{TM} Ballistic Analysis System

As previously mentioned, the interest in the SCICLOPS^{TM} system has not been limited to commercial institutions. After a demonstration of its capabilities, Frank J. Sauer, Program Manager of the NIBIN/DRIGFIRE, FBI Laboratory, and Robert W. Sibert, Chief Firearms and Toolmarks Unit, FBI Laboratory, expressed their believe that 3D based ballistic identification could improve automated ballistic analysis systems to the point of making it possible to establish a practical national database of bullets.

7. Endnotes

This research was made possible thanks to the National Institute of Justice Grant Number 97-LB-VX-0008. This report was prepared by Benjamin Bachrach, PhD. Dr. Bachrach is a full time employee of Intelligent Automation, Inc., located at 2 Research Place, Suite 202, Rockville MD, 20850, Phone: (301) 590-3155. The Chief Executive Officer of Intelligent Automation is Joseph Schwartz, at same address.

7.1 References:

[1] Information regarding IBIS can be found at http://www.fti-ibis.com/.

[2] Information regarding DRUGFIRE can be found at http://www.firearmsid.com/A_drugfire.htm.

[3] New York Times article, National Report Section, published December 20, 1999, pg. A17.

- J. Paik, E. R. Canavan, B. Bachrach and H. J. Hauke, "Development of Superconducting Technology for Inertial Guidance, Gravity Survey and Fundamental Gravity Experiments", Report number TL-TR-94-2222 to Air Force, Phillips laboratory, Directorate of Geophysics.
- B. Bachrach, E. R. Canavan and W. S. Levine, "Diagonalizing Controller for a Superconducting Six-Axis Accelerometer", Proceedings of 29th Conference on Decision and Control, Hawaii 1990, Vol. 5, pg. 2785.

Benjamin Bachrach, Ph.D.

Education:

Ph.D.	Electrical Engineering	University of Maryland at College Park	May 1997
M.S.	Electrical Engineering	University of Maryland at College Park	May 1990
B.S.	Electrical Engineering	Tel Aviv University, Tel Aviv, Israel.	May 1987

Professional Experience: Senior Scientist. Intelligent Automation Inc. April 1997 - Date

3D Ballistic Analysis: Developed and implemented data acquisition and correlation algorithms for ballistics matching based on topological (3D) information. Responsible for all design and implementation aspects of the SCICLOPS^{TM} system, IAI's fully operational ballistic analysis system.

Image Capture Device: Responsible for design and implementation of electronic control systems. In particular, lighting and motion control systems. The Image Capture Device (ICD) is an image acquisiton device to be used by the Drug Enforcement Administration for identification of drugs and drug related paraphernalia.

Multipurpose, Multiaxial, Isokinetic Dynamometer: Developed overall system architecture and detailed control algorithms for exercise applications of the Multipurpose, Multiaxial, Isokinetic Dynamometer (MMID). The MMID is a candidate exercise system for the international space station.

X-33 technology demonstrator: Designed an implemented an adaptive control algorithm for the $X-33$, the advanced technology demonstrator for the Reusable Launch Vehicle under construction at Lockheed Martin's Skunk Works.

Research Experience: Sept 1994 - May 1997

Developed an algorithm and synthesis program for the design of fixed-structure robust performance controllers based on the use of μ synthesis theory. The program implements a branch and bound algorithm to solve a non-convex bilinear matrix inequality problem. Developed an algorithm for the synthesis of minimum order filtered inverses for FDLTI systems. This algorithm was used to develop a MATLAB program for the design of 2-degree-of-freedom decoupling controllers.

Graduate Research Assistant: Feb 1989 - Sept 1994

Developed dynamic model of the Superconducting Six-Axis Accelerometer (SSA) using Mathematica, which made it possible to understand complicated aspects of the SSA (such as coupling between axes). Designed a robust multi-input, multi-output decoupling controller for the SSA using Rosenbrock's INA and singular value decomposition techniques. The controller succeeded on improving the linearity and dynamic range of the instrument.

Selected Publications :