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Development of a 3D-based Automated Firearms Evidence Comparison System*

ABSTRACT: Since the early 1990's, the idea of automated systems for the comparison of microscopic firearms evidence has received considerable attention. The main objective of such systems is to enable the analysis of large amounts of evidence, therefore, transforming the comparison of firearms evidence from an evidence verification tool into a crime-fighting tool. Two such systems have been widely used in United States forensic laboratories; namely, the Integrated Ballistics Identification System (IBIS) (1) and DRUGFIRE (2). Both IBIS and DRUGFIRE have in common the fact that their characterization of a specimen is based on a two-dimensional (2D) representation of the specimen's surface.

Although these systems have provided satisfactory results in the identification of cartridge cases, their performance in the identification of bullets has not yet met firearms examiner's expectations. This project was motivated by the premise that a better characterizations of the bullet's surface should translate into better performance of automated identification systems. A three-dimensional (3D) characterization of the bullet's surface is proposed as an alternative to a 2D characterization. This paper discusses the development and preliminary results obtained with SciClops™, an automated microscopic comparison system based on the use of a 3D characterization of a bullet's surface.

KEYWORDS: forensic science, firearms identification, 3D forensic imaging, automated comparison of microscopic firearms evidence

Microscopic striations found on the surface of fired bullets (and cartridge cases) are routinely used as a means to associate an evidence bullet with a suspect weapon. Such association is possible because the striations found on the surface of a fired bullet are imprinted on it by imperfections found in the barrel through which it was fired. In practice, the association of an evidence bullet and a suspect gun is made by firing the suspect gun under controlled conditions (usually into a water tank) to obtain two or more "control" bullets, and comparing the striations found on the evidence bullet with those found on the control bullets. The ability to perform bullet-to-bullet comparisons based on microscopic surface features is therefore at the core of forensic firearms examinations. Until relatively recently, such comparisons could only be made manually; i.e., by a firearms examiner inspecting a pair of bullets under a comparison microscope. This is a very time-consuming process, and it requires highly trained and skilled personnel. For this reason, assuming that class characteristics matched, a microscopic examination of the evidence was only undertaken if there was a reasonable degree of confidence of associating a bullet found in a crime scene with a suspect gun.

Since the early 1990's, the idea of "automated search and retrieval" systems for the comparison of microscopic firearms evidence has received considerable attention. The rationale behind the development of these systems is to take advantage of the continuously improving performance of computers to provide a powerful screening tool for firearms examiners. The main objective of such systems is to enable the comparison of large amounts of evidence and control bullets, therefore, transforming forensic ballistic analysis from an evidence verification tool into a crime-fighting tool. Currently, two automated systems for the comparison of microscopic firearms evidence have a prominent place in United States forensic laboratories; namely, the Integrated Ballistics Identification System (IBIS) (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 comparisons between a given specimen and a user specified segment of an available database. These systems also have in common the fact that the characterization of the specimen is based on a 2D representation of the specimen's surface.

In this paper, a 3D characterization of the bullet's surface is proposed as an alternative to a 2D characterization. This approach goes back as far as 1958, when J. H. Davis (4) proposed the idea of the "Striagraph." However, the technology necessary to make depth measurement with the required accuracy was not available at the time. As recently as 1999, and in parallel to our research, the application of 3D methodologies for ballistics identification applications has been reported by J. De Kinder (5,6). The significance of 3D methodologies and their potential is explicitly recognized by the National Institute of Justice (NIJ) and the Office of Law Enforcement Standards (OLES) of The National Institute of Standards and Technology (NIST) (3).

This paper discusses the development and preliminary results obtained with SciClops™, an automated system for the comparison of microscopic firearms evidence developed at Intelligent Automation, Inc. based on the use of a 3D characterization of the bullet's surface (see Fig. 1). In Section 2, we provide a brief background on computer-aided comparison of microscopic firearms evidence in general, their main components, and a comparison of 2D versus 3D-based data acquisition techniques. Sections 3 and 4 present some of the principles applied, and results obtained using 3D-based data acquisition methodologies. Finally, the Results Section briefly reports some preliminary results related to

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FIG. 1—*SciClops*™ *acquisition platform.*

bullet classification achieved by the proposed methodology. The conclusion section includes a brief discussion of future work.

Computer Aided Comparison of Microscopic Firearms Evidence

The basic components of an automated system for comparison of microscopic firearms evidence are the acquisition and the correlation components. The acquisition component is responsible for acquiring the data from the bullet and processing 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 (digitize) 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."

The correlation component is responsible for comparing sets of normalized data and organizing the results for inspection by the user. In general, the correlation component includes all the software elements necessary to:

a) Evaluate the degree of similarity between two sets of normalized data.
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. A Graphical User Interface provides this function.

2D Characterization of a Bullet's Surface

Existing automated comparison systems use a 2D representation of the specimen's surface. The 2D data capture process is schematically shown on the left side of Fig. 2. 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. Notice, however, that for this acquisition methodology to be effective, the incident light angle and the camera view angle cannot be the same. In fact, these two angles must be significantly different. This is because in order to obtain a pattern of dark-and-bright reflections of the bullet's surface, the camera and light source cannot be positioned at the same angle with respect to the surface of the bullet (see Fig. 2). Side lighting is a common and well-established approach to examine microscopic firearm evidence as a 2D image (7). Figure 3 shows a typical image of a single land impression as captured by the DRUGFIRE system.

3D Characterization of a Bullet's Surface

In order to successfully acquire 3D features from a bullet's surface, the choice of sensor technology is crucial. For our system, a confocal type sensor was selected. Confocal sensors operate by projecting a laser beam through a lens onto the surface under measurement and detecting the reflection of the laser with the same lens. The sensor continuously displaces the lens in order to maintain the reflected laser beam focused at a given focal plane. By detecting the position of the lens, it is possible to accurately follow the surface under measurement (for more information regarding confocal sensor technology or confocal microscopes, see (8)). An important property of these sensors is that the angle of incidence and the angle of reflection of the laser beam are the same, so that the measurement can be made along a direction perpendicular to the surface. This process is schematically shown on the right side of Fig. 2. The data acquired using a confocal sensor is the distance between the surface features and an imaginary plane.

3D Versus 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 indi-

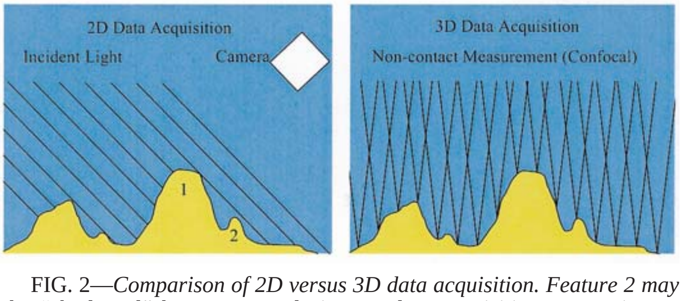

FIG. 2—*Comparison of 2D versus 3D data acquisition. Feature 2 may be "shadowed" by Feature 1 during 2D data acquisition, preventing an accurate characterization of the surface.*

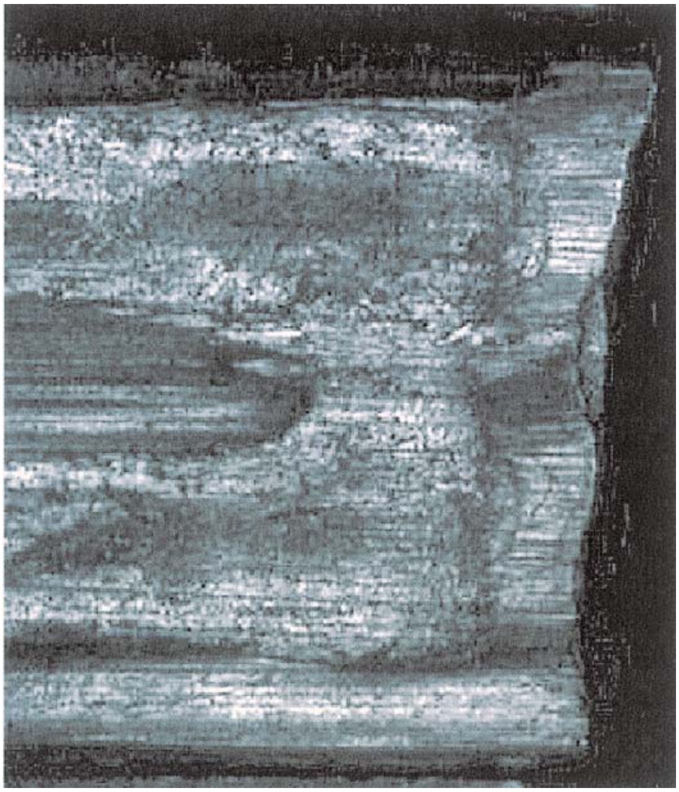

FIG. 3—*Bullet land impression as imaged by the DrugFire system.*

rect measurement of the bullet's surface features, while 3D data capture is for all practical purposes a direct measurement. In this section we discuss the advantages and disadvantage of each of these acquisition methodologies.

Robustness of Acquired Data—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 striations found on the bullet's surface, but also on a number of independent parameters such as the light incidence angle, the camera view angle, variations on the reflectivity of the bullet surface, light intensity, accurate bullet orientation, etc. This implies that the captured data are also dependent on these parameters. The amount of effort required to eliminate the effect of these parameters on the 2D captured data are similar to that required to reconstruct the 3D topography of the surface based on 2D data. Existing 2D-based systems do not make this kind of compensation.

Discontinuity of Acquired Data—Another significant problem associated with 2D data capture is the phenomenon of "shadowing." Take as an example a surface depicted on the left side of Fig. 2. Given an incident light source with the shown angle, some of the smaller surface features (see Feature 2) can be "shadowed" by the larger features (Feature 1). This implies that there may be regions of the surface where the captured data does not accurately reflect the surface features. Furthermore, this example also shows that 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 (the same problem applies to the angle of view of the camera). In mathematical terms, the transformation between the incident light and the reflected light is discontinuous with respect to the angle of incidence of the light (and angle of view of the camera).

Problems such as shadowing are not unique to 2D data capture techniques. As shown on the right side of Fig. 2, the laser beam used by confocal sensors to detect the depth of the surface under measurement occupies a conical region. The proper operation of the sensor requires this conical region to be unobstructed. Therefore, confocal sensors are limited with respect to the steepness of the surfaces they can measure. However, although steep surfaces can cause distortion on the measured depth, this distortion is not discontinuous with respect to the angle of incidence of the laser beam. This is significant because small variations in the angle of incidence cannot result in arbitrary large errors in the measured depth.

Acquisition Speed—Existing technology allows 2D data to be acquired significantly faster than 3D data. The fact that 2D data acquisition is so much faster than 3D data acquisition allows the user to inspect the 2D surface data and make decisions regarding which regions of the bullet to acquire for comparison. Furthermore, the fact that firearms examiners are used to this type of representation of a bullet's surface has been a motivation for the use of this type of data.

3D Based Acquisition Component

3D Data Acquisition Process

Figure 4 shows a schematic view of a bullet "sectioned" at different levels along its longitudinal axis. A closed curve is defined at each cross section by the intersection of the sectioning plane and the bullet's surface (see Fig. 5). Each of these curves contains information of all land and groove impressions on the bullet's surface at the given level. In principle, by taking a sufficient number of such cross sections, it is possible to obtain a complete description of a bullet as a three dimensional object (within finite tolerances).

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 Fig. 5. Figure 6 shows schematically how the cross-section closed curve is "unfolded." This unfolding takes place at the hardware level, and it is a consequence of the method-

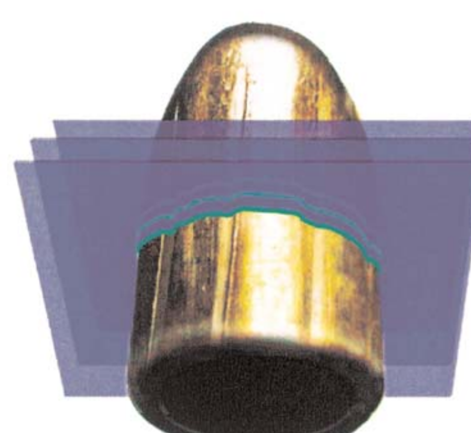

FIG. 4—*Schematic view of bullet sectioned at different levels along longitudinal axis.*

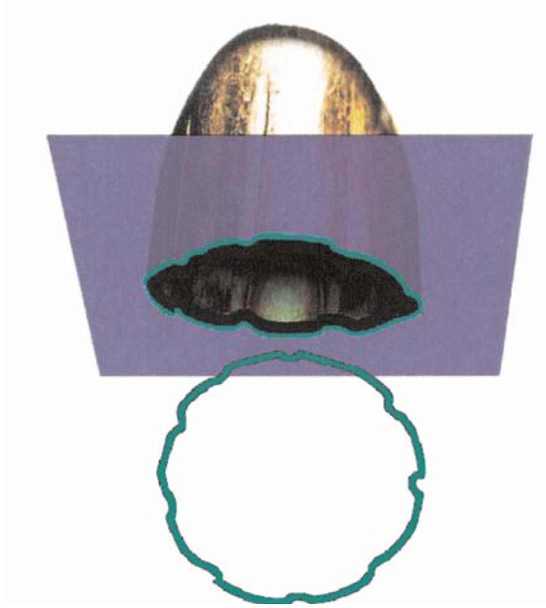

FIG. 5—*Each cross section defines a closed curve containing information of all land and groove impressions at a particular level along the longitudinal axis.*

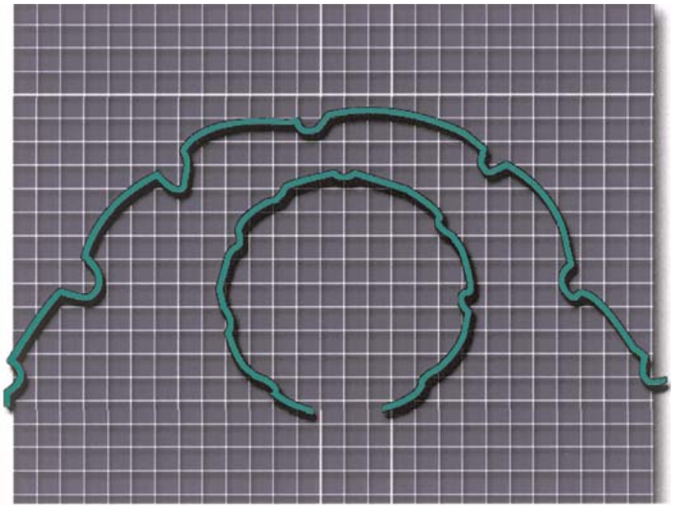

FIG. 6—*Schematic view of the "unfolding" of the bullet surface.*

ology used to capture the data. This data corresponds to the digitized data, as described in Section 2. The final component of the acquisition process is the generation of the normalized data. Figure 7 shows an example of a normalized data set. The normalized data results of mathematically processing the digitized data to remove all systematic errors introduced during the data capture process.

Once the data are normalized, the most significant features of the bullet emerge 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 the gun through which a bullet was fired. As seen in Fig. 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 Fig. 8, where the 3D data have been superimposed on the 2D data of the same bullet (as acquired by the DRUGFIRE system). Notice the clear definition of the transitions between land and groove impressions in the 3D data, while the same boundary is not well defined by the 2D data. The bullet in question was purposely scratched with a stylus as can be seen on the leftmost land impression.

Measurement Considerations and Requirements

The first challenge associated with the design of a 3D-based automated comparison system was to identify a suitable sensor technology to perform depth measurements of the required accuracy. In order to make such selection, it was necessary to determine the characteristics of the surface to be measured (how deep are the features of interest? how wide? how steep?). To this effect, a number of measurements were made using different instruments/technologies such as Stylus-based Profilometer, Atomic Force Microscope, Scanning Tunneling Microscope, Scanning Electron Microscope and White Light Interferometry. Figure 9 shows a small portion of a land impression as measured using white light interferometry. Although an ideal technology from the point of view of accuracy, white light interferometry is not a feasible solution to our data acquisition requirements due to its considerable cost.

Based on a number of measurements similar to that shown in Fig. 9, we concluded that in order to obtain significant information regarding the striations on a bullet's surface, the minimum requirements on the 3D sensor would be a depth resolution on the order of .1 μm and lateral resolution on the order of 1 μm. It was also determined that the depth differential between a land impression and

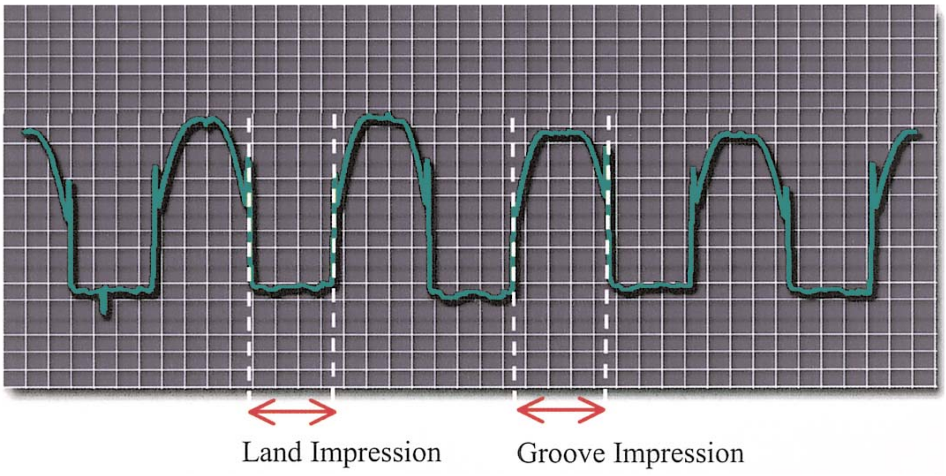

FIG. 7—*Normalized surface data. Notice clear definition of land and groove impressions.*

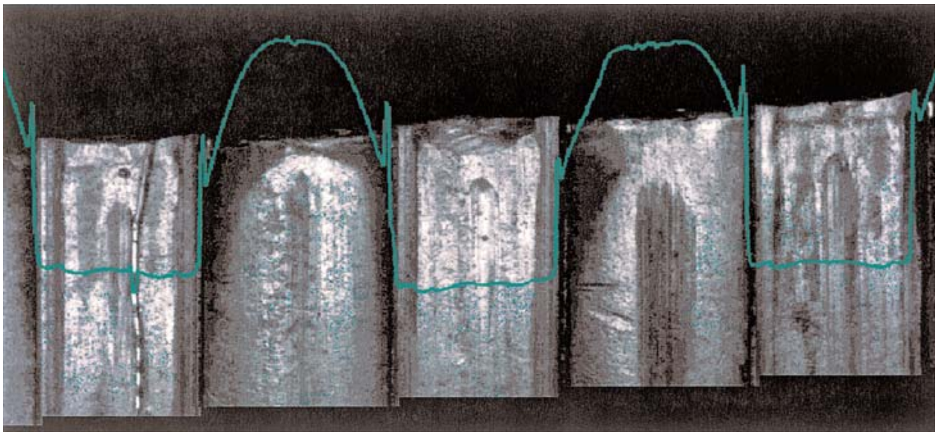

FIG. 8—*View of superimposed 3D normalized data and 2D surface data (acquired by the DrugFire system) of part of a bullet.*

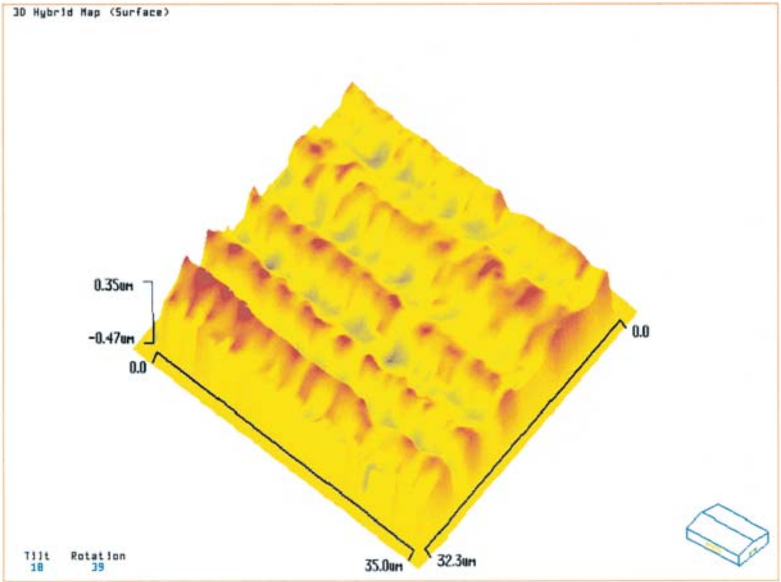

FIG. 9—*White Light Interferometry measurement of a portion of a land impression. Notice the characteristic dimensions of the striations.*

TABLE 1—*Sensor evaluations.*

Manufacturer	Model	Technology	Evaluation
Burleigh Instruments (Victor, NY)	Personal SPM	Atomic force microscope	Not suitable for steep slopes
Presicion Dynamics (Ontario, Canada)	PD-1000	Interferometry	Not suitable for steep slopes
Keyence Corporation (Woodcliff, NJ)	LC series	Laser triangulation	Not suitable for steep slopes
LMI Technologies, Inc. (Vancouver, BC, Canada)	LTS series	Laser twin triangulation	Not suitable for steep slopes
LMI Technologies, Inc. (Vancouver, BC, Canada)	LNS series	Confocal autofocus	Not suitable for low-reflectance surfaces
UBM Engineering (Sunnyvale, CA)	Microfocus	Confocal autofocus	Suitable, good lateral resolution
Keyence Corporation (Woodcliff, NJ)	LT series	Confocal autofocus	Suitable, sub-optimal lateral resolution

a groove impression on a bullet's surface is rarely greater than 150 μm (this conclusion was reached based on a limited number of bullet samples available, and it should not be interpreted as claiming that greater differentials can not be found). Therefore, the minimum required range for the depth sensor is in principle on the order of 150 μm. However, because bullets are never perfectly round after being fired, and because there are always miss-alignment imperfections in the measurement process, a depth range of 600 μm was considered the minimum acceptable range for this application. Finally, this particular application requires a non-contacting sensor.

Table 1 shows a summary of sensors that were tested in our facilities as candidates for the development of an experimental setup.

We limited our search to sensor that did not require extensive training or sample preparation, and which fell within the project's budget. Of all sensor technologies we evaluated, we determined that confocal-based sensors offered a very good compromise between cost and performance. These were the only commercially available sensors capable of operating while 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 (see Table 1).

Given that our search for a suitable sensor technology was constrained by cost considerations, one might wonder if the quality of the acquired data suffers from this limitation. The answer to such a question is beyond the scope of the work performed to date. However, based on measurements such as that shown in Fig. 9, it appears that a measurement resolution of .1 μm in depth and 1 μm in lateral resolution is sufficient to capture the most significant elements of the surface data. Moreover, it is questionable whether 3D features smaller than those detectable by the specified resolution would at all be repeatable between firings, although this assertion would have to be verified. The acquisition speed of the sensor, on the other hand, can limit the amount of data that can be acquired in a "reasonable" amount of time. Although a few hours may be considered a reasonable amount of time for the acquisition of data of a single bullet, such amount of time would be unacceptable in practical applications. More costly sensors are capable of acquiring 3D data faster than those considered in this project. Therefore, although cost constraints do not affect the achievable performance of the system in principle, they do have an impact in practice. As will be discussed, adding a complementary sensor technology, such as a 2D sensor, can mitigate this limitation.

Experimental Measurement Configurations

Together with the depth sensor, a simple and cost effective methodology to perform the desired surface measurements was developed. Due to the predominantly cylindrical shape of bullets, it was decided that the best measurement methodology would be to rotate the bullet within the sensor measurement range, 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 sensor's range. Figure 10 shows the evolution of the different measurement configurations used during this project (labeled A, B, C and D). Configuration A consists of a bullet glued to the shaft of a constant speed motor. This configuration was used to determine the ability of the sensor to make the required measurement (in particular, to handle the steep transitions between land and groove impressions). This configuration did not provide any degrees of freedom to adjust either the bullet or the sensor, and it was not used for the acquisition of surface data. Configuration B was used to make preliminary measurement of bullet samples. Notice that this configuration takes ad-

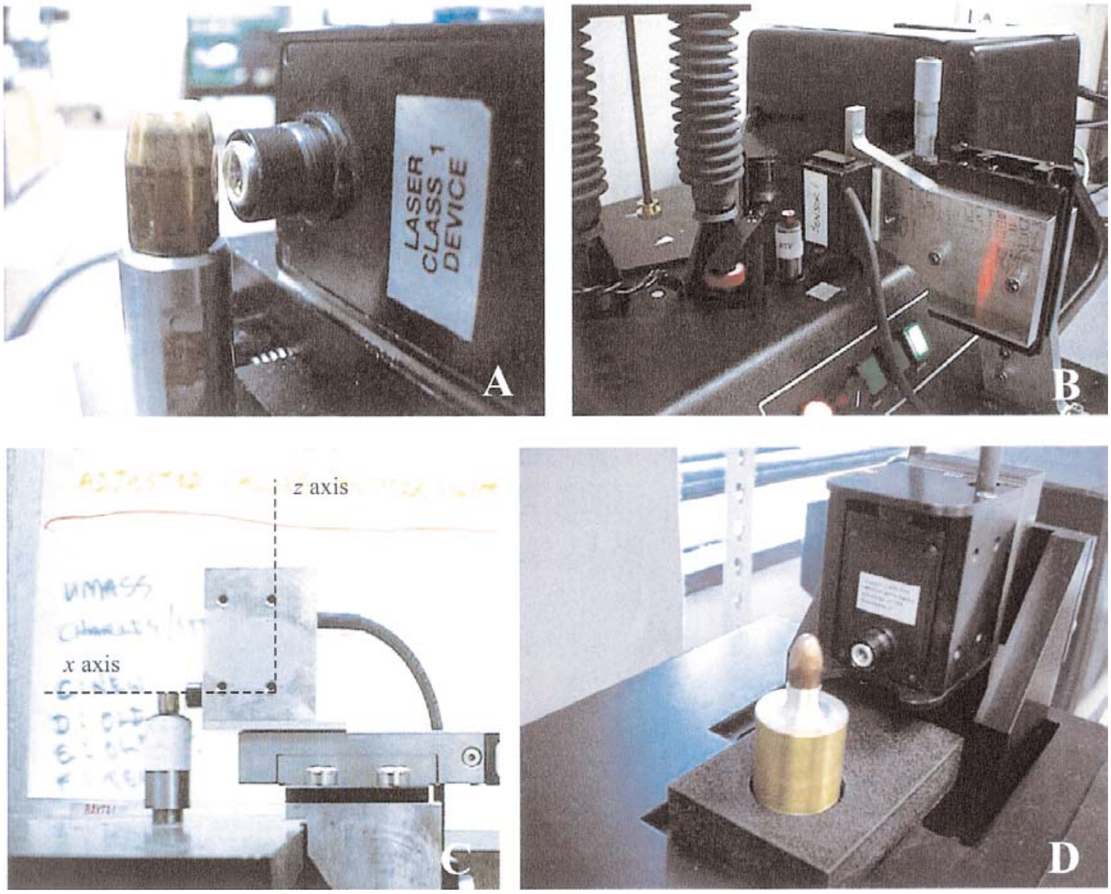

FIG. 10—*Evolution of data acquisition configurations. A) Bullet glued to constant velocity motor shaft, depth sensor (manufactured by UBM Corporation) is fixed. B) Bullet mounted on RotoScan unit, depth sensor can be manually adjusted along* x, y *and* z *axes. C) Bullet mounted (not glued) on constant velocity motor, depth sensor position is computer controlled along* x *and* z *axes. D) Bullet mounted on precision rotational stage, depth sensor position is computer controlled along* x *and* z *axes.*

vantage of the bullet component of the DRUGFIRE system (RotoScan, manufactured in our facilities) to enable the acquisition of both 2D and 3D data. This configuration included manual adjustment capabilities for the sensor. Configuration C consists of a constant speed motor to rotate the bullet, and includes computer controlled motion stages to displace the sensor. Based on our experience with configurations A, B, and C, the data acquisition component of the SciClops™ system was implemented (configuration D). This configuration includes computerized motion control of both the displacement of the sensor and the rotation of the bullet, as well as vibration isolation mechanisms.

The depth resolution achieved with the final configuration of the acquisition unit was on the order of 1 μm. This limitation was introduced by both sensor and mechanical vibration noise. We improved the hardware-limited resolution of the system by averaging 64 measurements for each data point, decreasing the noise level by a factor of 8 (assuming white noise). The final effective depth resolution achieved was 0.125 μm. The lateral resolution of the system was dictated by the lateral resolution of the confocal sensor to 1 μm. Thus, the lateral resolution satisfies the requirements specified in Section 3.2, while the depth resolution is reasonably close.

Figure 11 shows a characteristic averaged measurement of a cross section of a bullet. This averaged measurement was the result of averaging data from 5 cross sections. The first of these measurements was taken 1 mm from the base of the bullet, while the subsequent measurements were taken at intervals of 250 μm each (covering a ring 1 mm wide). This data corresponds to the digitized data as defined in Section 2. The bullet in this measurement was a 9 mm copper jacketed bullet. The horizontal scale shows sample points, while the vertical scale shows micrometers. The lateral resolution for this measurement was approximately 6 μm. It can also be seen that the difference in depth between land and groove impressions is in the order of 100 μm. Notice the sharp transitions between the land and groove impressions. 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 (see measurement configurations in Fig. 10). 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 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 and tilt) as coaxiality parameters.

Data Normalization Process

The objective of the data normalization process is to estimate the true profile of the microscopic impressions made by the barrel on the bullet's surface; i.e., the profile that would be measured if the bullet had not been deformed and/or if there had been no coaxiality errors during the acquisition procedure. In this section, we limit our discussion to the normalization process associated with pristine bullets, i.e., only the effect of coaxiality errors is considered. Normalization algorithms for damaged bullets are currently under development.

Figure 12 shows a cross-section of a pristine bullet, where the regions corresponding to the land impressions and groove impressions have been isolated. An enlarged detail of this image is shown in Fig. 13. As expected, the geometric region defined by the cross section of the bullet is approximately circular (or elliptical, if tilt is taken in consideration). This is particularly true of the regions corresponding to land impressions. For pristine bullets, such a-priori knowledge of the expected shape of the acquired data can be used to estimate extraneous measurement parameters such as coaxiality errors. Conceptually, the normalization process for pristine bullets consists of two steps: a) the estimation of the ellipse defined by the geometric location of the land impressions identified in the acquired data (i.e. estimation the coaxiality parameters), and b) the projection of the acquired data onto the estimated ellipse (i.e. compensation of coaxiality parameters).

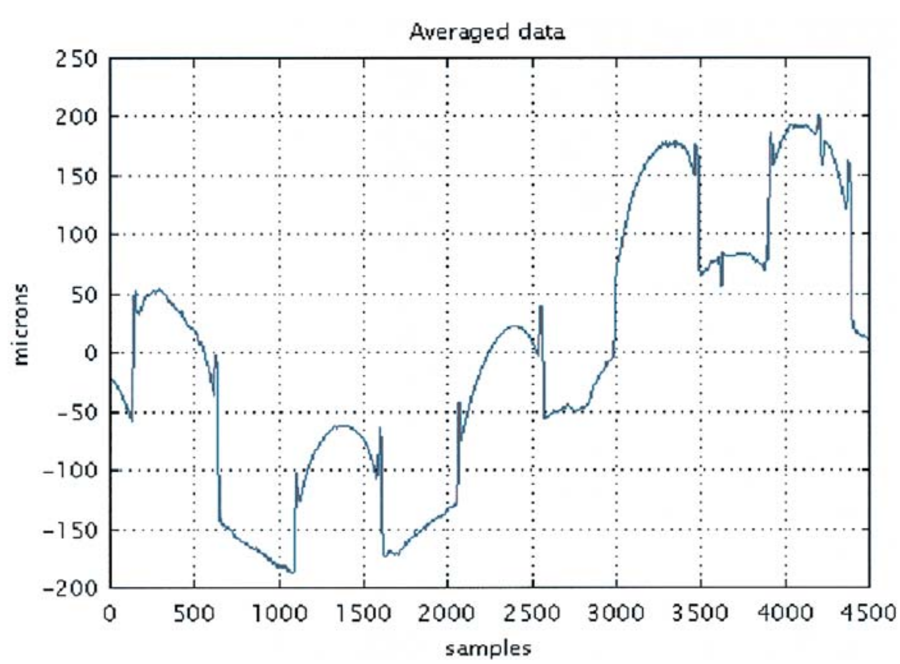

FIG. 11—*Characteristic averaged trace measurement.*

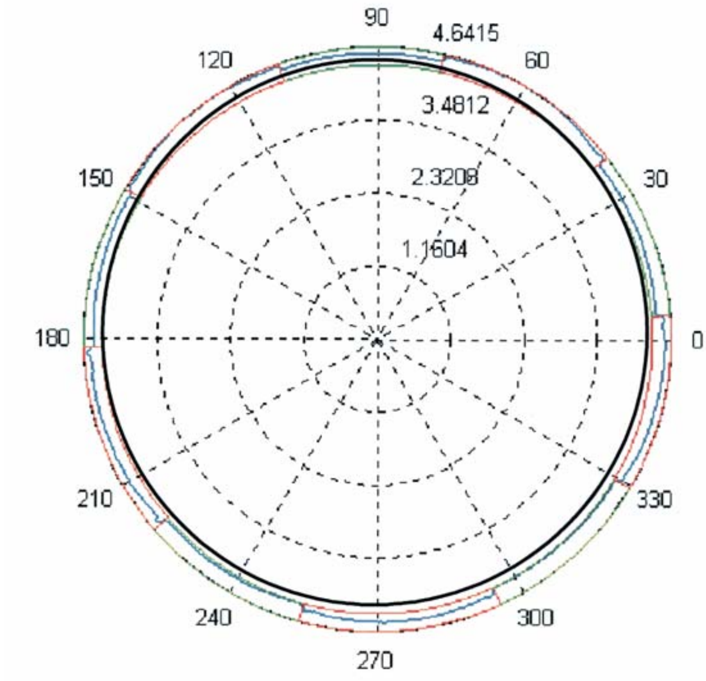

FIG. 12—*Cross section of pristine bullet.*

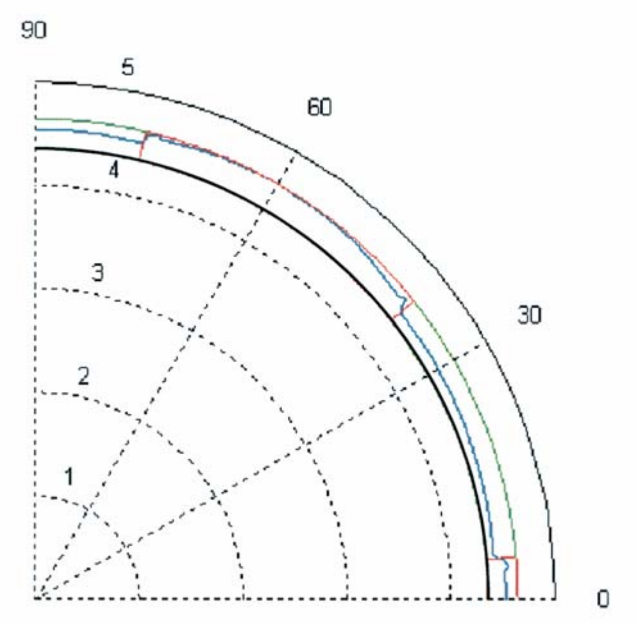

FIG. 13—*Detail of cross section of pristine bullet.*

The importance of an accurate compensation in the normalization process cannot be sufficiently emphasized. The effect of coaxiality errors manifests itself not only in the amplitude of the striations (see Fig. 11), but it also produces shrinking/stretching deformation along the horizontal axis. Accurate compensation of the captured data is essential for the satisfactory performance of the correlation algorithms. High pass filtering the captured data (to eliminate the predominantly low frequency effect of coaxiality errors) would not compensate for the deformation of the bullet along the horizontal axis.

Evaluation

As a test of the normalization algorithms, we performed a consistency evaluation. The objective of this evaluation was to assess the consistency of the normalized data for a given bullet measured under different conditions. The methodology followed to perform this evaluation was the following: we positioned a bullet in the measurement setup, and acquired data from 5 cross sections of the bullet on a 1 mm ring (i.e., each cross section measurement was made 250 μm apart). The first cross section was taken at approximately 500 μm from the base of the bullet, the second at 750 μm, etc. The bullet was then dismounted from the measurement setup, repositioned, and a similar measurement was made. By dismounting the bullet from the setup and repositioning it, we inevitably modified the coaxiality parameters (off-centeredness and tilt). In this manner, data from the same bullet was acquired 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 two data sets and we normalized each data set according to their respective estimated coaxiality parameters. The same procedure was repeated for five copper jacketed bullets of the same caliber (9 mm).

The results of one such evaluation can be seen in Fig. 14, where two sets of normalized data belonging to the same bullet (but measured under different conditions) have been aligned and superimposed. The normalized data from the two independent measurements looks almost identical, indicating that the coaxiality parameters were reliably estimated, and the acquired data sets correctly normalized. Figure 11 shows the digitized data (pre-normalization) corresponding to one of the normalized data sets shown in Fig. 14. The difference between this data set and the sets shown in Fig. 14 (normalized) gives an indication of the impact made by the normalization process.

Notice that there are some minor differences between the two normalized data sets shown in Fig. 14. In particular, the groove impression labeled GEA 1 (which is broken in two sections) displays a significant valley in one of the normalized data sets and not in the other. This phenomenon can be explained by the fact that while making the two sets of measurements, no attempt was made to capture the data at exactly the same distance from the base of the bullet (along the longitudinal axis). For this reason, there are differences between the two sets of captured data. On the other hand, notice that not only the major features of the bullet coincide, but also most of the minor features repeat themselves. 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 of future study.

3D Based Correlation Component

The correlation component receives as an input the normalized data of two bullets (bullets *a* and *b*), and returns as an output the following information:

a) The relative orientation at which the two bullets are most similar.
b) A similarity measure (denoted $s(a, b)$). The similarity measure is a normalized quantification of the degree of similarity between bullets *a* and *b* (in this context, the term "normalized" indicates that the similarity measure assumes a maximum value of 1). A similarity measure of 0 indicates no similarity between the normalized data of bullets *a* and *b*, while a similarity measure of 1 indicates that the normalized data sets of bullets *a* and *b* are identical in a sense to be further defined.

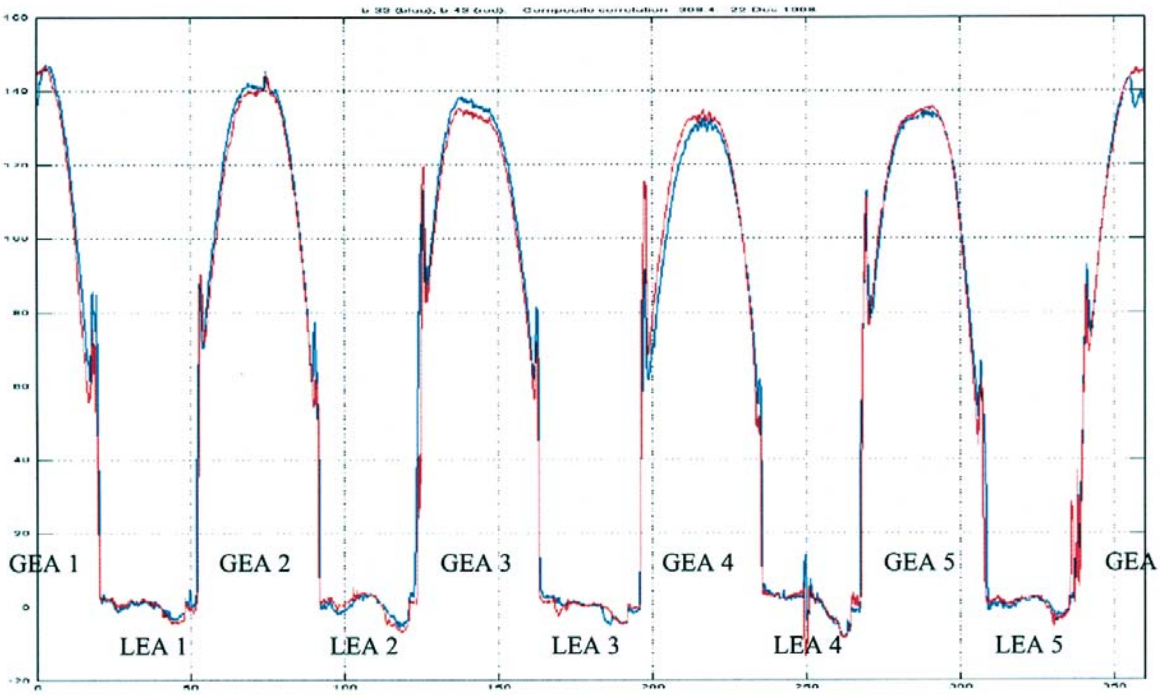

FIG. 14—*Superposition of two independent sets of normalized data of the same bullet acquired under different conditions (different coaxiality errors).*

Correlation Process

Given two sets of data (in the form of one-dimensional vectors), there are a variety of approaches to obtain a normalized measure of similarity between them. Perhaps, the most widely used measure of similarity between two data sets is the correlation function, defined as follows:

$$Corr(a_{norm}, b_{norm}) = \frac{(a_{norm})^T *(b_{norm})}{\sqrt{(a_{norm})^T *(a_{norm})}\sqrt{(b_{norm})^T *(b_{norm})}} \quad (1)$$

where a_{norm}, b_{norm} denote vectors of normalized data associated with bullets a and b, respectively, and the superscript T indicates the transpose operator. The correlation function as defined in Eq 1 corresponds to the cosine of angle between the n-dimensional vectors a_{norm} and b_{norm}. Therefore, its value is bounded between -1 and 1, where a value of 1 is obtained if and only if $a_{norm} = \alpha * b_{norm}$, where $\alpha > 0$. In other words, a correlation of 1 is obtained if one of the data sets is a positive linear multiple of the other. The use of Eq 1 for the comparison of two impressions (or surfaces in general) is complicated by the fact that the relative position (or "shift") where the impressions under consideration are most similar is not accurately known. This implies that whenever two surfaces are compared, Eq 1 is evaluated for a number of relative positions between the two surfaces. Similarly, minor corrections to Eq 1 are necessary due to the fact that often the length of the impressions under comparison is not the same. For ease of presentation, and because these details do not add to the overall understanding of this paper, they are omitted in our discussion.

Given a pair of bullets with n impressions, these bullets can be compared in n different relative orientations. For every possible relative orientation between bullets a and b, a measure of the similarity between the two bullets is obtained as a composition of two independently computed functions: the Macro Correlation function and the Micro Correlation function. The Macro Correlation is computed by applying Eq 1 to the pair of normalized data vectors a_{norm} and b_{norm}. The Macro Correlation function is a measure of the similarity of the major features of the two bullets, and is dominated by the land and groove widths (class characteristics) and their general shape. The Micro Correlation is computed by applying Eq 1 to pairs of high pass filtered versions of the portions a_{norm} and b_{norm} that correspond to individual impressions (land or groove), and then averaging the resulting values over all impressions. The Micro Correlation function is a measure of the similarity of the micro features or striations found in the land and groove impressions (individual characteristics). It is the Micro Correlation function that serves as the discriminator between a match and a non-match between bullets.

Once both the Macro Correlation and Micro Correlation functions are computed for a given orientation, the Composite Correlation function is computed. The Composite Correlation function is the geometric average of the Macro and Micro Correlation functions. The Composite Correlation function is an overall measure of similarity of the bullets under consideration, for the particular orientation under consideration. Once the Composite Correlation function is computed for all possible relative orientations between two bullets, the similarity measure is the maximum of all attained Composite Correlation values. Similarly, the relative orientation for which the largest Composite Correlation value is obtained is the orientation at which the two bullets are most similar.

Evaluation

In order to evaluate the ability of the system to match bullets fired by the same gun, data from two bullets fired by the same gun was acquired, normalized and compared. Figure 15 shows the results of comparing the normalized data of these two bullets. As can

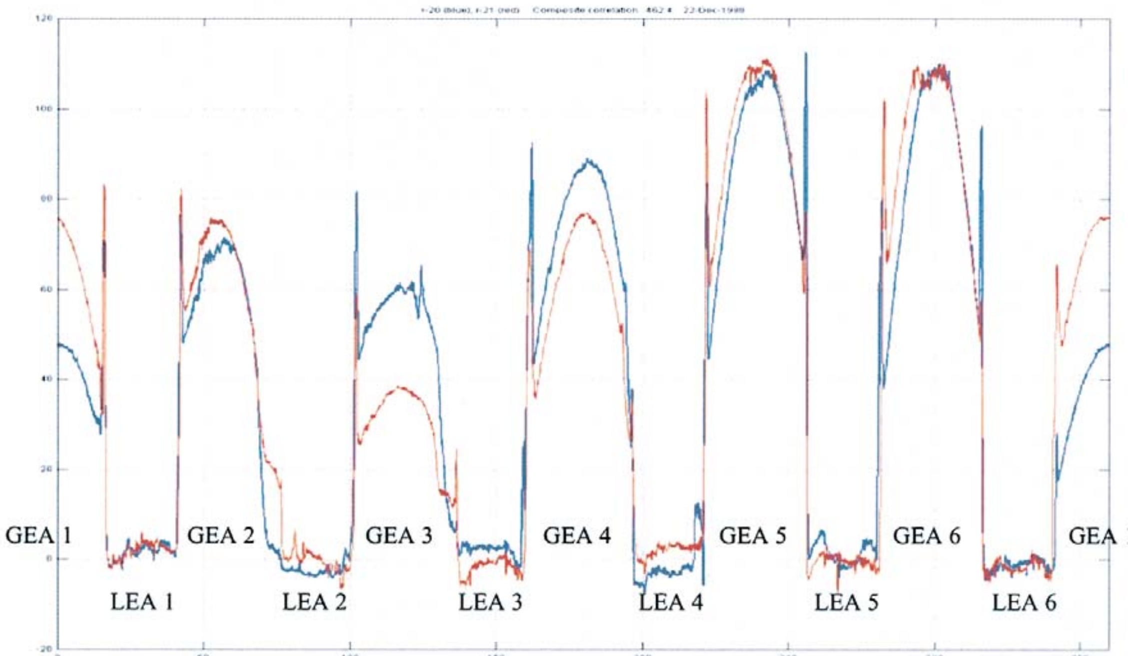

FIG. 15—*Superposition of two sets of normalized data of 2 bullets fired by the same gun.*

be seen, the class characteristics of these two bullets match. Moreover, the shapes of the major features of these bullets are very much alike.

As already discussed, the correlation software makes comparisons not only of the major features of a bullet pair (evaluated by the Macro Correlation function), but also of the microscopic details found within the land and groove impressions (evaluated by the Micro Correlation function). Figure 16 shows a comparison of a high pass filtered version of the pair of land impressions in the position labeled LEA 6 in Fig. 15. This is the data used by the Micro Correlation function. The similarity between these two land impressions is impressive. Notice that the regions to the sides of this pair of land impressions are very similar, while the middle region is not. This is because the sides of land impressions make better contact with the barrel than their middle. For this reason, the resulting impressions are more consistent from bullet to bullet. This phenomenon tends to be more pronounced as the data is acquired at a certain distance from the base, where skid marks begin to appear. Notice too that although there are significant similarities, there are also considerable differences. This is consistent with the experience of trained firearms examiners. Because of how a bullet travels through a barrel, only discrete portions of its surface display similarities.

Figure 17 shows a comparison of a high pass filtered version of the pair of groove impressions in the position labeled GEA 6 in Fig. 15. In contrast to the results seen in the case of land impressions, the region of similarity is at the center of the groove impressions. This is explained by the fact that the centers of the groove impressions make better contact with the gun's barrel, just as the sides of the land impressions. This phenomenon can be seen in Fig. 15. Notice how the groove impressions have an almost rounded shape, and 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.

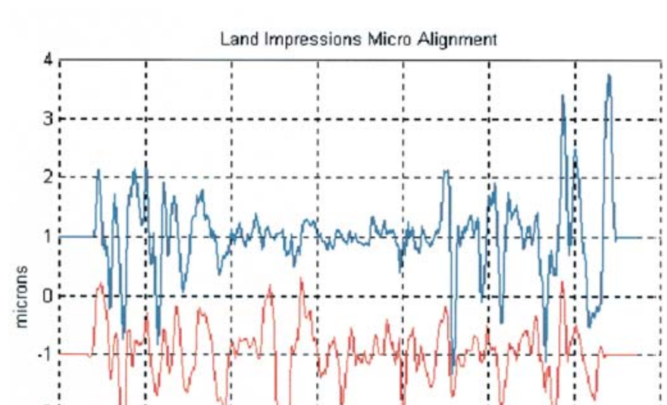

FIG. 16—*Superposition of high pass filtered land impression pair (LEA 6 in Fig. 15).*

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 relative 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 it. Moreover, as seen in Fig. 15,

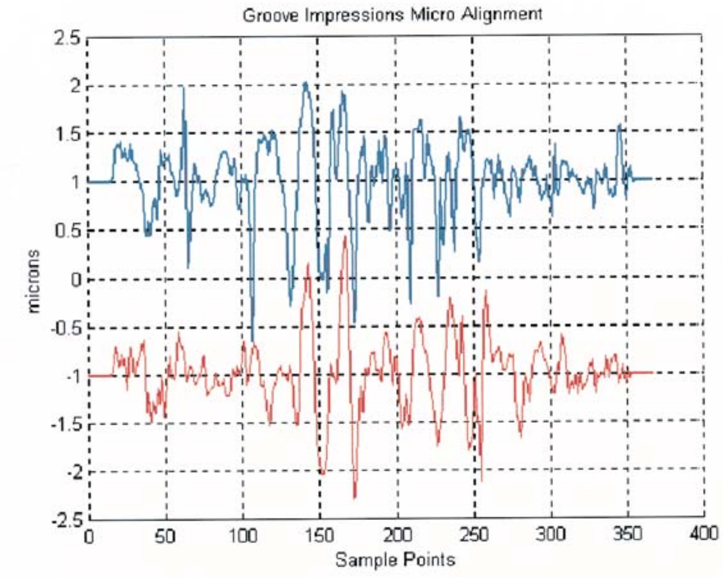

FIG. 17—*Superposition of high pass filtered groove impression pair (GEA 6 in Fig. 15).*

TABLE 2—*Discrimination evaluation.*

	Gun 1		Gun 2		Gun 3	
	r-10	r-11	r-20	r-21	r-30	r-31
Gun 1						
r-10	100.00	*35.20*	22.70	27.96	30.86	24.36
r-11	*35.20*	100.00	22.29	23.69	24.50	23.65
Gun 2						
r-20	22.70	22.29	100.00	*50.67*	27.24	22.04
r-21	27.96	23.69	*50.67*	100.00	24.76	23.08
Gun 3						
r-30	30.86	24.50	27.24	24.76	100.00	*35.46*
r-31	24.36	23.65	22.04	23.08	*35.46*	100.00

TABLE 3—*Discrimination measure.*

	Consecutively Manufactured Barrels		
	min	max	avg
d(x)	0.54	0.88	0.70

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 can contain extremely valuable data, and it is our assessment that the potential for improvement of existing automated comparison systems by incorporating groove impression's data is significant.

Results

So far, it has been shown that using the proposed approach it is feasible to obtain reliable characterizations of a bullet surface (Section 3), and successfully identifying similarities between bullets fired by the same gun (Section 4). It has not yet been shown, however, that the proposed approach is capable of discriminating between a matching and a non-matching pair of bullets. A discrimination evaluation was performed to determine whether bullets fired by different guns of the same manufacture could be grouped correctly. The guns used in this evaluation were Beretta 92's, and their barrels were consecutively manufactured. The bullets were copper jacketed, of Remington manufacture.

We used six bullets in this evaluation, two from each gun. The numerical results of this evaluation are tabulated in Table 2. 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 the correlation algorithm (the similarity measures shown in Table 2 are multiplied by a factor of 100). The italicized cells indicate the correct matches (i.e., bullets r-10 with r-11, r-20 with r-21, etc.). As seen in Table 2, the system was able to identify the correct matching pair for each of the bullets. 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 below this value.

In order to assess the degree of discrimination of the correlation algorithm, we defined the discrimination ratio $d(x)$ to represent the relative difference between a false match and a true match:

$$d(x) = \frac{\max_{y \notin G(x)} s(x, y)}{\min_{y \in G(x),\, y \neq x} s(x, y)} \qquad (2)$$

where $G(x)$ denotes the gun which fired bullet x, $y \in G(x)$ 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 similarity measure computed for a false match divided by the lowest similarity measure computed for a true match.

Table 3 shows the minimum, the maximum, and the average discrimination ratio for the bullets in question. In general, discrimination ratios indicate how close the similarity measure of a false match can be to that of a true match. The lower the discrimination ratio, the better discrimination between true and false matches has been achieved. The results shown in Table 3 indicate 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 the maximum achievable similarity measure for a pair of non-matching bullets can be as much as 88% of the lowest similarity measure achieved by a pair of matching bullets. This is a fairly reasonable gap. It should be noted that this result applies only to the set of bullets under consideration.

This evaluation is preliminary, and the results only indicate the ability of the system to discriminate between a true match and a false one, but no indication should be inferred regarding its effectiveness. A more rigorous statistical evaluation of the system's performance requires a larger database of bullets, and is currently underway. The main objective of such evaluation is the estimation of the probability of obtaining a false match and the provability of missing a match, at least for a particular class of weapons.

Conclusions

In this study, 3D-based data capture methodologies are explored as a possible alternative to existing 2D-based methodologies for automated examination of microscopic ballistic evidence. Because some of the variables influencing 2D data capture methodologies are not measured by existing 2D-based automated microscopic examination systems, their effects on the captured data are not compensated, and the resulting normalized data are less robust than that attainable by using a 3D-based data capture methodologies. On the other hand, due to its acquisition speed, 2D data acquisition offers the advantage of allowing the user to visually identify (and select) the regions of the bullet's surface to be used for analysis. The integration of both 2D and 3D data acquisition offers the best of both worlds in terms of performance. The 2D image allows the firearms examiner to select the region of the bullet's surface to be used for comparison, while the highly reliable 3D acquired data is most useful to perform the comparisons of the microscopic data.

Preliminary evaluations indicate that a 3D-based system shows considerable potential. A number of important questions, however, remain unanswered. As noted earlier, the results presented are limited in the sense that only pristine bullets were used for our evaluations. Both acquisition and correlation algorithms for damaged bullets need to be developed, and their performance evaluated. Also, statistical methodologies to quantify the performance of automated systems are of significant interest. Given an evidence bullet and a group of possibly matching bullets, existing automated systems can assist the firearms examiner by indicating which of the bullets in the selected group is most likely to match the evidence bullet. However, existing systems are not capable of determining how likely is said bullet to have been fired by the same gun as the evidence bullet. Such information would be an important tool to the firearms examiner confronted with large amounts of evidence. Another important question is the location on the bullet's surface where data should be acquired (along the bullet's axis). It is a well-accepted fact in the forensic community that the base of the bullet usually contains the most reliable data for comparing two fired bullets. It has been our experience that this is indeed true for land impressions, but may not be so for groove impressions. If available, the most reliable groove impression data seems to be found some distance away from the base of the bullet (depending on the bullet manufacturer, as far away from the base as 1 mm). These and many other questions remain open for future study.

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