What are the Prospects of 3D Profiling Systems Applied to Firearms and Toolmark Identification?

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ABSTRACT

This paper details a comparative pilot study of 3D (three dimensional) imaging technologies for potential application in forensic firearms and toolmark identification; as such it reviews the most up-to-date profiling systems. In particular, the paper focuses on the application of 3D imaging and recording technology as applied to firearm identification, being a specialised field within the discipline of toolmark identification. Each technology under test employs a different technique or scientific principle to capture topographic data i.e. focus-variation microscopy, confocal microscopy, point laser profilometry and vertical scanning interferometry.

To qualitatively establish the capabilities and limitations of each technology investigated, standard reference samples were used and a set of specific operational criteria devised for successful application in this field. The reference standard crucially included and centred on was the National Institute of Standards and Technology (NIST) 'standard bullet'. This was to ensure that evaluation represented the practical examination of ballistic samples i.e. fired cartridge cases and bullets.

It is concluded that focus-variation microscopy has potentially the most promising approach for a forensic laboratory instrument, in terms of functionality and 3D imaging performance, and is worthy of further investigation.

Introduction

Firearms identification has been an accepted scientific discipline for over 100 years and aims, in its most simple terms, to identify whether a bullet has been fired from a particular weapon.

Hamby has extensively reviewed the history of firearms identification up to the present day with regard to identification methodologies, reliability, validity and its use in criminal cases [1-3], while Nichols has robustly responded to numerous criticisms from lawyers about its use in court [4-7]. A USA National Academy of Sciences (NAS) committee recently studied technologies associated with ballistics imaging and made three conclusions of concern to toolmark and firearm examiners [8]. These conclusions included comments relating to the uniqueness and reproducibility of toolmarks and the subjectivity of their interpretation, recommending additional studies should be performed to make the process of individualisation more precise and repeatable. The NAS report comments and recommendations were consequently addressed by an Association of Firearm and Toolmark Examiners (AFTE) committee [9]. An important concern is that such criticisms have been made by those who may not have the expertise required to fully understand the scientific theory behind methods of firearms identification.

Traditionally, the method of firearms identification has been undertaken using a relatively low powered microscope, such as a comparison macroscope. The appearance of 2D images, however, can vary, depending on the lighting conditions due to the shadows cast by the surface features [10]. Thus, similar but known non-match samples may appear to erroneously match due to relatively small variations in lighting conditions. Hence the need for suitably qualified, experienced and highly-skilled examiners to conduct the assessment, however there will always be the potential for claims of subjectivity with

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this approach.

Over the last decade, there has been a move from the use of traditional 2D (two dimensional) pattern matching techniques towards the incorporation of the third dimension of measurement; depth. It is self evident that 3D data could offer advantages over 2D data due to the extra information available for analysis. Also, 3D data is invariant against changes in illumination. However, while there has been research regarding the utility of 3D data, such data has not yet been put to rigorous and formal experimental test, including the impact of depth variations and reproducibility given various metal malleability in bullet construction, cartridge case material and engagement (obturation) of ballistic sample to tool (rifling). There are a number of important issues associated with acquiring, manipulating and developing analytical methods of assessment which require further work.

The generic term '3D imaging' implies the topographical quantification of the sample's surface. Bachrach details the difference between bullet surface characterisation using 2D and 3D techniques and also their associated advantages and disadvantages [11]. Brinck has also documented the improved capability of the Forensic Technology Inc. (FTI) Integrated Ballistic Identification System (IBIS) BulletTRAX-3D system to match samples over the FTI IBIS Heritage 2D system due to the combination of both 2D and 3D data acquired [12].

At present, there are a number of 3D technologies available that may be suitable for the application to ballistic samples. Some of these have already been reviewed in the literature, including the stylus profilometer [11, 13, 14], 3D virtual comparison microscope [15], atomic force microscope [11, 13], confocal microscopy [10, 11, 16], photometric stereo [17], laser profilometry [18, 19], laser triangulation [11] and white light interferometry [11]. However, there have been further technological developments since then, for example, improvements in the technical specifications of some reviewed technologies and development of the focus-variation technique. This paper therefore examines the comparative benefits and limitations of vertical scanning interferometry, point laser profilometry, confocal microscopy and focus-variation microscopy with specific application to firearms identification.

Standard Reference Materials

In 2006, Song et al. published a paper correlating topography measurements from four different techniques [20] using a standard reference sample manufactured by National Institute of Standards and Technology (NIST); Standard Reference Material (SRM) 2460 standard bullet. The 'standard bullet' is depicted in Fig. 1. The purpose of their study was to compare surface profiles obtained using an interferometric microscope, Nipkow disk confocal microscope, laser scanning confocal microscope and a stylus profilometer to a virtual standard reference profile of a master bullet obtained with the same stylus profilometer. After appropriate filtering of the data, the profiles compute a maximum cross-correlation function of higher than 90 %. This suggested that the reference standard could be used for 2D and 3D surface topography comparisons.

As a result, the main reference standard measured in this project was the NIST 'standard bullet' land impression number 5 (land engraved area, LEA 5). Fig. 1 illustrates the location of LEA 5. The systems investigated acquired data across the width of LEA 5, at an area close to the base of the bullet.

Tactile calibration standards with a very smooth surface finish were also used to test the capabilities of the test systems. These included step height standards from 1 μm to 500 μm, sinusoidal and sawtooth profiles. These results are not detailed within this paper as all systems appeared to be well calibrated. However, one example calibration result is depicted in Fig. 2; the 30 μm step height standard measured using a point laser profilometer with the curvature (the standard's surface is slightly domed) removed from the raw

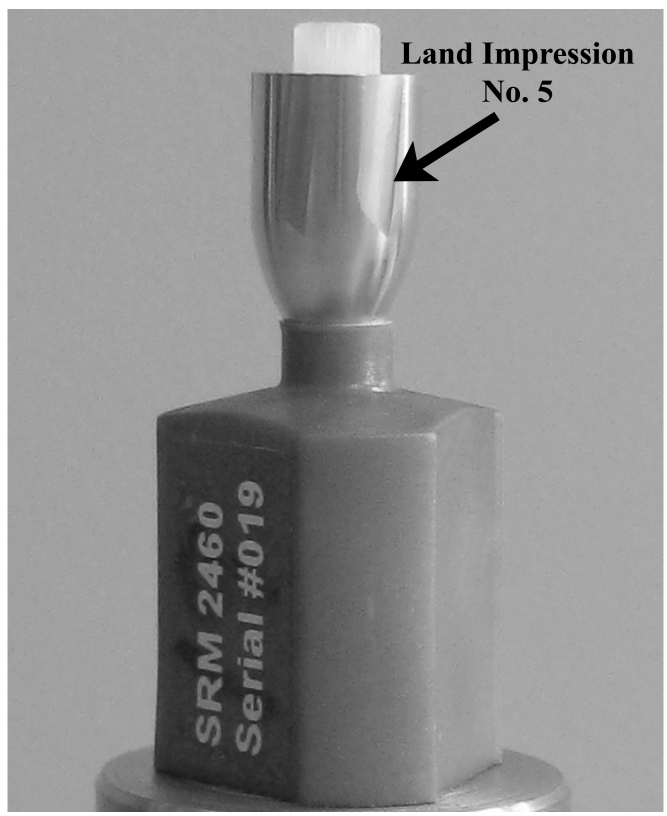


Figure 1: NIST 'standard bullet' indicating LEA 5

data. Fig. 2 also illustrates the production of artefacts by point laser profilometers that are not present in the true surface of the reference standard and are discussed further in the results and discussion section.

Comparison of 3D Measurement Techniques

This pilot study aims to determine the most appropriate 3D imaging technology for capturing raw topographic data from ballistic samples; and by hypothesis identify the optimum generic technique or principle for 3D surface interrogation and analysis. The study is bounded by the requirement to maintain evidence integrity and therefore concentrates on the use of non-destructive, optical, non-contact methods.

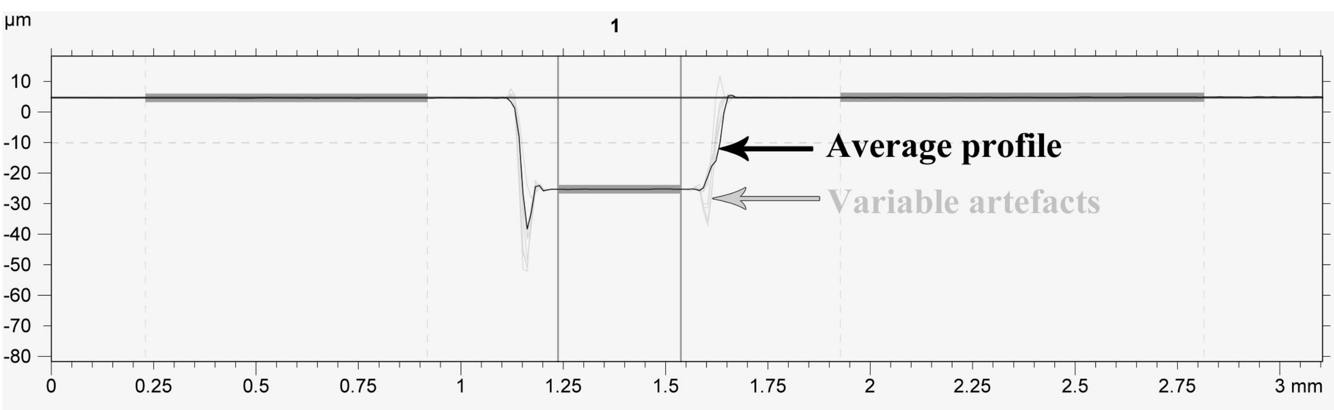
For some of the techniques, more than one system was evaluated as detailed in Table 1. The principle of operation of each technique is briefly detailed within the following sub-sections and Table 2 provides an overview of the relevant details for the systems. The figures provided in Table 2 are all quoted from manufacturers' technical specifications and therefore, do not show consistent accuracies due to the necessary grouping of systems within the scientific principles and the comparative nature of the study.

Table 2 also compares other important aspects of imaging and measurement technologies considered for application to firearms identification. Three of the five aspects have been expanded upon. The first aspect concerns the working distance of the objective lenses relative to the sample surface; if this distance does not exceed the depth of the feature imaged, collision with the sample is highly likely especially with an automated system. As can be appreciated, with higher magnifications the working distance reduces; for example, less than 1 mm, would be unacceptable when imaging a firing pin impression.

The second aspect concerns the system's vertical and lateral resolution; this determines the size of smallest surface feature that can be measured. For example, a 30 µm lateral resolution is insufficient to distinguish individual striations on a fired bullet sample that are typically between 1 and 10 µm wide. A lateral resolution less than 1 µm would be required.

The third being the maximum angle of the sample surface relative to the sensor head; surface features positioned such that they exceed this angle can lead to noise (illustrated in Fig. 4 and 5), gaps in the data acquisition (illustrated in Fig. 5 and 6) and/or artefacts being generated in the raw data (previously illustrated in Fig. 2), which are not true features of the sample surface. This reduces the reliability and validity of profile and subsequent measurements. Furthermore, as the magnification of the objective lens increases, the capability to image the maximum surface angle is increased, mainly due to improvement in lens numerical aperture. As previously explained the maximum surface angle figures provided in Table 2 were obtained from the manufacturers' technical specifications and not determined through experimental testing.

Although speed of acquisition is another important aspect of each system, the manufacturers do not always quote this in the technical specifications. This is largely due to acquisition variables such as the method of 3D imaging, height of the



Step#	Parameters	Mean	Std dev	Min	Max
1	Maximum depth	30 µm	0.039 µm	29.9 µm	30.1 µm
	Mean depth	29.9 µm	0.0352 µm	29.9 µm	30 µm
	Width	0.297 mm	0.00485 mm	0.29 mm	0.3 mm

Figure 2: Average of eight measurements for 30 µm step height standard using a confocal point laser profilometer

Scientific Principle	Number of Systems Evaluated	Systems Specification Comments
Vertical scanning interferometry	1	N/A
Point laser profilometry	4	Spot size range 1.7 to 30 µm
Confocal microscopy	2	One system uses a Nipkow disk
Focus-variation microscopy	1	N/A

Table 1: 3D measurement systems evaluated

		Vertical Scanning Interferometer	Point Laser Profilometers	Confocal Microscopes	Focus-Variation Microscope
Light Source		White light	Laser	Laser or White light	White light
Objective Lens Magnification		1x to 50x	Typically N/A (TTL 0.5x to 2.0x)	10x to 100x	10x to 100x
Working Distance (mm)		7.4 (at 10x)	4 to 38	10.1 to 0.3	23.5 to 3.5
Resolution (µm)	**Vertical**	0.03	0.01 to 0.05	0.01 to 0.001	0.1 to 0.01
	Lateral	Not stated	1 to 30	3.1 to 0.12	1.1 to 0.4
Max. Surface Angle (°)		13.1 (higher for non-specular surfaces)	70	70 (85 in future)	90

Table 2: Specification details for each of the 3D principle types evaluated

surface features imaged and the vertical resolution defined for the acquisition. As a result, this capability is used as a comparative measure between systems tested in this study. To give some idea of acquisition speeds, one confocal microscope (with 10x objective lens) could image a 10 mm x 2 mm area of a fired bullet in less than 10 minutes, compared to a point laser profilometer that took about 60 minutes to image the same area. The focus-variation microscope with a 10x objective lens could acquire a similar sized area in a time frame more comparable with that of the confocal microscope.

Measurement data collected by each instrument is represented in a three-dimensional Cartesian coordinate system. The z-axis, also described as depth or height in the literature, is the additional axis afforded by 3D imaging techniques over 2D techniques. The relative alignment of the sample's surface, with respect to the interrogating ray geometry of the instrument, determines how the topographical features are sampled and quantised in each of the x, y and z axes. In this study the z-axis is arranged to be approximately perpendicular to the samples surface. Note that the spatial resolving power in each of the instruments' imaging axes may differ significantly.

Vertical Scanning Interferometer

A beam of white light from the source initially passes through a neutral density filter preserving the short coherence length of the white light. A beam splitter then separates the beam into two parts; directing one part towards the sample via an objective lens and interferometer, and the other onto a reference mirror.

Recombination of the two reflected beams forms a high contrast pattern of interference fringes when the waves are in phase i.e. when the sample surface is in focus. The fringes appear as bands of light and dark that connect points of equal height. Their number and spacing is determined by the relative tilt between the sample and surface mirror.

Due to the short coherence of the filtered light source, only shallow depths of field are in focus, hence the sensor head must scan over a vertical height range. This generates a series of interference patterns, which are captured by a charge-coupled device (CCD) camera to produce interferograms.

The interferograms are then analysed by a computer program to determine the surface height at each pixel through the measurement of fringe coherence. The software can then output various graphical representations of the surface including a topographic 3D model.

Point Laser Profilometers

These sensors typically use a triangulation or confocal method to acquire displacement measurement data on a CCD. Two of the systems evaluated use the triangulation method and the other two employ the confocal method. The latter method is a more recently developed system and has the advantage of tolerating changes in surface colour without calibration [21].

The triangulation method focuses the laser beam onto the surface of the sample using a lens. The relative position and intensity of the resultant beam spot is detected by a CCD in the sensor head. This information is used measure the topography of the sample by computing the coordinate position of the beam spot as it traverses or scans the sample.

The laser within the confocal sensor head is focused upon the sample by a vibrating objective lens. When the sample surface is in focus, the reflected beam converges through a pinhole and strikes the CCD. The position of the objective lens enables the height (in the z-axis) to be determined; out of focus light does not enter the pinhole or reach the CCD. Only one of the systems enabled a choice in the magnification of the objective lens, which utilised through-the-lens (TTL) focusing.

Confocal Microscopes

This technique employs a similar principle to that of the confocal point laser profilometers in that it combines the ability of the optical microscope to use inter-changeable objective lenses to achieve greater magnification and surface resolution. Of the two systems tested, one used a laser light source while the other used white light.

The white light system also employed a multi-pinhole principle, rather than a single pinhole, on a rotating disk within the microscope. This spinning or Nipkow disk has pinholes arranged in a spiral shape. The multiple pinholes enables the microscope to effect a scanning multiple light source to expand the analysis area to that of the objective lens field of view.

Focus-Variation Microscope

This microscope uses an operating principle that combines the small depth of field of an optical system with vertical scanning function to collate images and depth information over a large depth of field. Images with almost 1000 times greater depth of field can be imaged in comparison to a conventional light microscope.

The light source is modulated white light that travels to the sample surface via a beam splitter and an infinity-corrected objective. The reflected light is then projected back through the beam splitter onto a colour CCD. At each vertical scanning height an image is captured and for each position on the object sharpness is calculated. It is the variation in sharpness that is used to extract the depth information and generate a 3D model of the surface.

Results and Discussion

We believe there are a number of requirements that a system must fulfil for successful use as a ballistics imaging tool. These include:

• acceptable vertical and lateral resolution, such as 0.1 μm vertical and 1 μm lateral resolution [10, 11];
• good lateral resolution for low power magnification to ultimately reduce the size of the acquired data set to a manageable level;
• acceptable working distance, especially if using high power objectives, to enable measurement of deep impressions, such as firing pin marks, prevent collision between the objective lens and the sample, and also to account for potential issues with deformed samples or eccentricity during rotation;

• reasonable speed of data acquisition;
• ability to image steep transitions from the LEA to GEA (groove engraved area) and sides of firing pin impression;
• rotary system option available to improve imaging of cylindrical samples;
• versatility of use for the system outside the field of firearm identification;
• suitable price to enable use in a large number of laboratories and research centres.

The following sub-sections detail the results and overall evaluation of each technique, keeping in mind the proposed criteria. For comparative purposes, the NIST 'standard bullet' was utilised with the curvature removed and a Gaussian filtered reference profile, made using a contact stylus profilometer with tip radius of 2 μm; this can be seen in Fig. 3. The evaluation length is approximately the central 1.4 mm of LEA 5 nominal width of 2.21 mm.

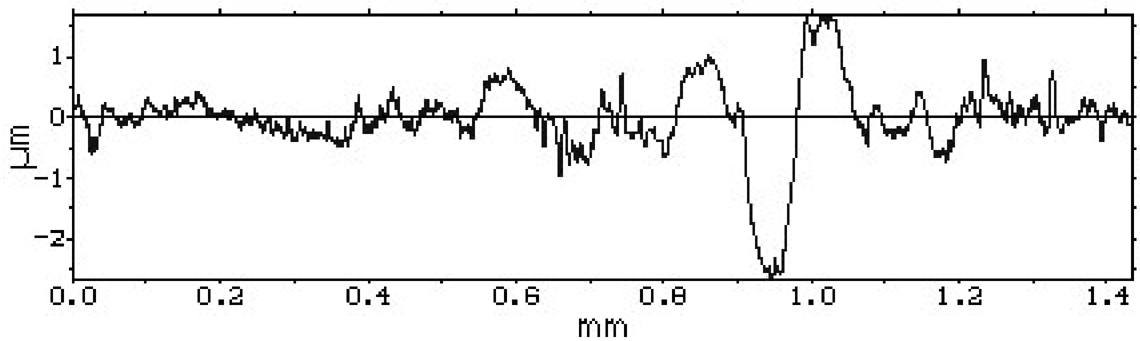


Figure 3: NIST 'standard bullet' LEA 5 evaluation profile using stylus profilometer

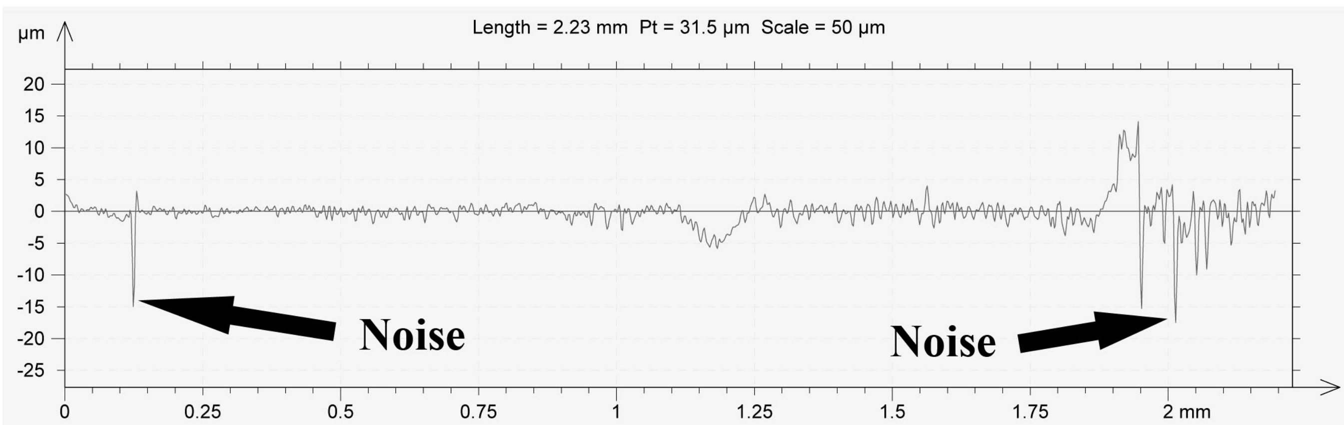


Figure 4: Surface profile of LEA 5 'standard bullet' using a confocal point laser profilometer

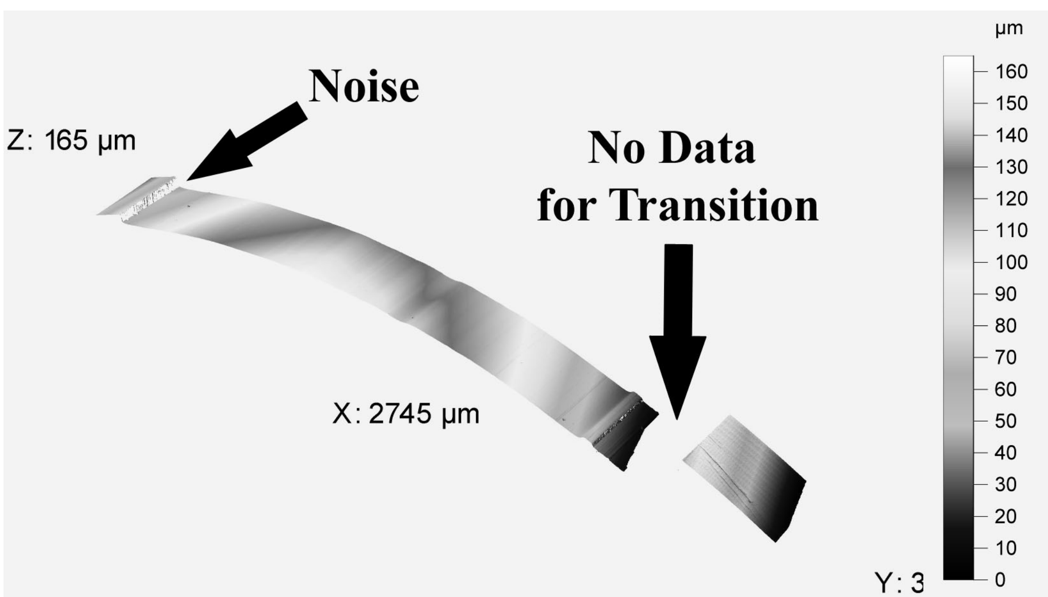


Figure 5: 3D model of LEA 5 'standard bullet' from a confocal white light microscope (50x objective lens)

Vertical Scanning Interferometer

Although vertical scanning interferometry is mainly suited to rough sample surfaces, the requirement to detect interference fringes on-screen at the correct focal point makes analysis difficult and time consuming. When the analysis area has minimal points at the same height, such as in bullet LEAs, it can be especially difficult or impossible to distinguish these fringes. On bullet GEAs, where the surface was less variable, the technique was more successful.
Note that the author recognises that identifications are made upon the examination of the LEAs; GEAs can aid this identification but are not the critical areas where the opinion of identification is formed. LEAs are used for identification as they are the areas where the lands in the barrel rifling engrave most consistently and therefore, variability from shot to shot is reduced. GEAs are less consistent for identification due to the dependence of the 'tightness of fit' of the bullet to the barrel bore (obturation). Typically, there will be areas of the GEA on the fired bullet that have not come into contact with the rifling and therefore marks are not transferred unto it. This means that one bullet may display a set of striae in a GEA that are not displayed in the next fired bullet.

The standard 50x objective lens working distances are typically 1 mm or less, making imaging of firing pin marks potentially difficult. However, the accuracy and precision of this technique is excellent.

Unfortunately, this system was incapable of imaging steep slopes > 70 ˚, so data was not acquired within these areas; a conclusion also reached by Bachrach [11]. As a result, this technique is not optimal for the measurement of all types of ballistic samples.

Point Laser Profilometer

Point laser profilometers compute the coordinate position of the incident laser beam upon the sample. A relative translation between the interrogating beam and the sample will produce a line profile of the surface and may take the form of a helical scan (about a rotating sample). A surface which is not normal to the laser beam will change the shape of the beam footprint and can alter the coordinate measurement performance. For example, increasingly steep incident angles produce increasing beam smear, which can lead to erroneous measurements.

Nonetheless, point laser profilometers can have excellent depth resolution, down to 10 nm, although, their lateral resolution is typically limited to the spot size of the laser. The smallest spot size tested was 1.7 µm and consequently this would not provide sufficient lateral resolution for their application to imaging ballistic samples.

On the smooth calibration surfaces, specular artefacts were observed, which were not consistent between repeat profiling and an example is illustrated in Fig. 2. These artefacts were not observed using any of the other techniques and are therefore an inherent issue associated with these sensors. Such artefacts were also seen in Bachrach's research paper on true bullet samples [11]. Two of the evaluated systems also suffered when the samples surface reflectance altered, resulting in no acquisition of data in that area.
Fig. 4 shows the profile measurement for a point across LEA 5 on the 'standard bullet' after curvature removal. Profiles of the 'standard bullet' obtained with point laser profilometers appear to be noisier than those of the other techniques (compare to Fig. 6), making measurements and profiles potentially less accurate. Noise is illustrated in Fig. 4 where there are large, sharp spikes; again, these are not true representations of the sample surface.

Due to the disadvantages associated with this technique, these systems were deemed as not wholly appropriate for use as a ballistic imaging tool.

Confocal Microscope

Confocal microscopes can have a high data acquisition speed, with excellent vertical resolution and/or excellent lateral resolution (refer to Table 2). The two systems tested both had excellent vertical resolution, but the laser scanning system had better lateral resolution. Ultimately, lateral resolution is a function of the wavelength of the interrogating light and for low power objective lenses, the lateral resolution criteria may therefore not be met.

For example, if most striations upon fired bullets are between 1 and 10 µm in width, a lateral resolution of 3 µm may not be sufficient to image the unique striae. However, conventional wisdom suggests that 'excessive' lateral resolution could lead to the inclusion of highly variable, potentially misleading striae in the comparison, such as obtained when imaging in 2D with objectives higher than 80x. On the other hand, these highly variable striae may be able to be investigated and characterised in the future using 3D data. From these considerations it was evident that a compromise between the two resolutions seemed necessary to image surfaces of all ballistic sample types.

The system using a Nipkow disk is being successfully utilised in the application of ballistics imaging within the FTI IBIS TRAX-3D systems. However, the observed inability of the sensor head to image steep slopes generates the potential for crucial areas of the ballistic specimen to be missed. Examples of such areas include the transitions from LEA to GEA and the sides of firing pin marks.

Fig. 5 illustrates the raw data collected across NIST 'standard bullet' LEA 5 with large gaps and noise in the transitions from the LEA to GEA. This is generally because of the angle of reflection of the laser beam and the numerical aperture of the lens. When the LEA 5 profile width was reduced to omit the transitions, a number of small gaps in the data were also detected where the surface striations were too steep for measurement; this occurred using a 50x objective lens and is illustrated in Fig. 6.

Focus-Variation Microscope

The focus-variation technique is limited to examination of inherently rough surfaces with surface roughness parameter Ra [22] greater than 15 nm. As a result, the relatively smooth surface of the tactile reference standards precluded successful imaging. This limitation does not pose a problem to the examination of inherently rough ballistic samples.

It was observed that this technique was highly capable of imaging the transitional slopes between the LEA and GEA without generating artefacts, which is an excellent aspect to maximise data collection.

Fig. 7 illustrates an example of the raw profile generated across LEA 5 'standard bullet' using only the 10x objective lens with the accompanying 2D image of the 'standard bullet' surface to relate and identify the location of the measurement. The black rectangular box within Fig. 7 locates an evaluation area within the centre of LEA 5 (enhanced in Fig. 8) to aid visualisation of the surface profile.

This system has the potential to image up to 89 ° slopes and therefore damaged specimens can be examined, potentially without as much sample manipulation. The system exhibited very good lateral resolution, even at low powers of magnification and vertical resolution that easily meets the proposed criteria.

Although, this technique is comparatively slower than that of the confocal systems, all surface features of the sample may be imaged and it has working distances which are an order of magnitude greater.

Some of the other systems do have longer working distance objective lenses as an option; however their resolution is typically reduced as a result. The larger working distance should ensure there would be no problem with the surface of the sample hitting the objective lens even when analysing deep firing pin impressions.

Another important factor to consider is the cost of this system, which is significantly lower than that of the confocal systems evaluated.

Conclusions

The aim of this pilot study is to determine which 3D scientific principles were capable of taking the methods of firearms and toolmarks identification into the future. As a result the authors proposed criteria which were felt to be preferable for the discipline and would need to be met by a suitable imaging system. The criteria included the capability to obtain lateral and vertical resolutions of at least 1 µm and 0.1 µm respectively with good lateral resolutions at low power magnification, have acceptable working distances, acquire data within a reasonable period of time and have the potential to image steep sample slopes.

From the evaluation of the four proposed scientific principles (vertical scanning interferometry, point laser profilometry, confocal microscopy and focus-variation microscopy), it appears that both the confocal and focus-variation principles are the most appropriate basis for the continuing technological development of a forensic instrument. Although the confocal systems have an order of magnitude greater vertical resolution (with respect to the sample surface) their inability to image steep slopes means that data may not be captured for some critical areas of the sample, such as in the transitions between LEA and GEA on fired bullets, firing pin impression sides and deformed samples.

The profession requires a system that can fulfil all the proposed criteria and accurately image all surface features. As a result, the vertical scanning interferometer and point laser profilometer technologies were deemed unsuitable for the application to firearm identification. The vertical scanning interferometer experienced difficulties in focusing the instrument for successful acquisition for the sample area, especially within LEAs. The point laser profilometers developed inconsistent and potentially misleading artefacts and higher levels of noise obtained within the raw data made them unsuitable for further investigation.

The 3D imaging technology principle which could offer the greatest future potential in the field of firearms identification is the focus-variation microscope. Although this technology is considered unproven by many in the metrology field, it did offer significant advantages over the other systems. This technique was able to meet all criteria proposed due to:

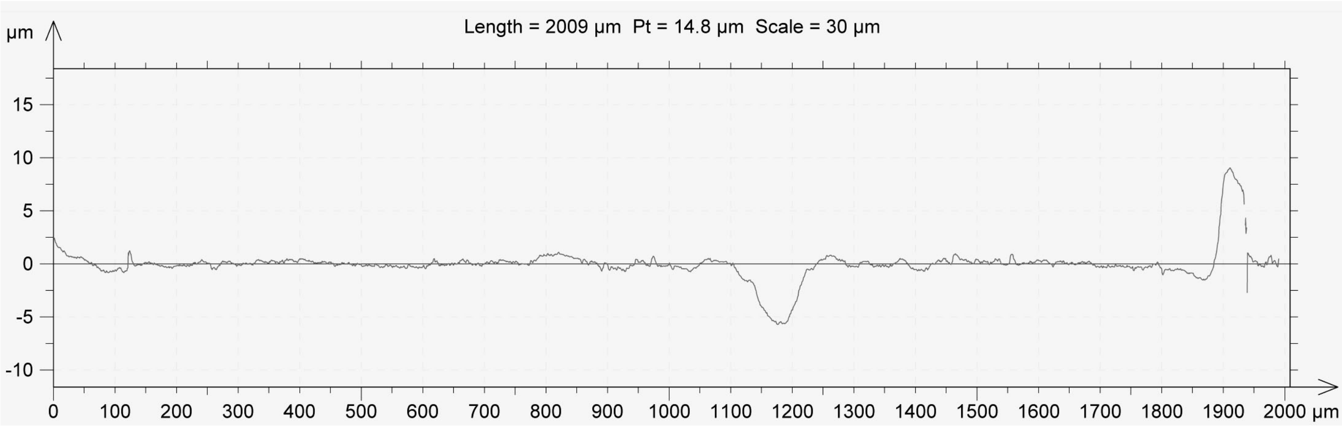


Figure 6: Surface profile of LEA 5 'standard bullet' using a confocal white light microscope (50x objective lens)

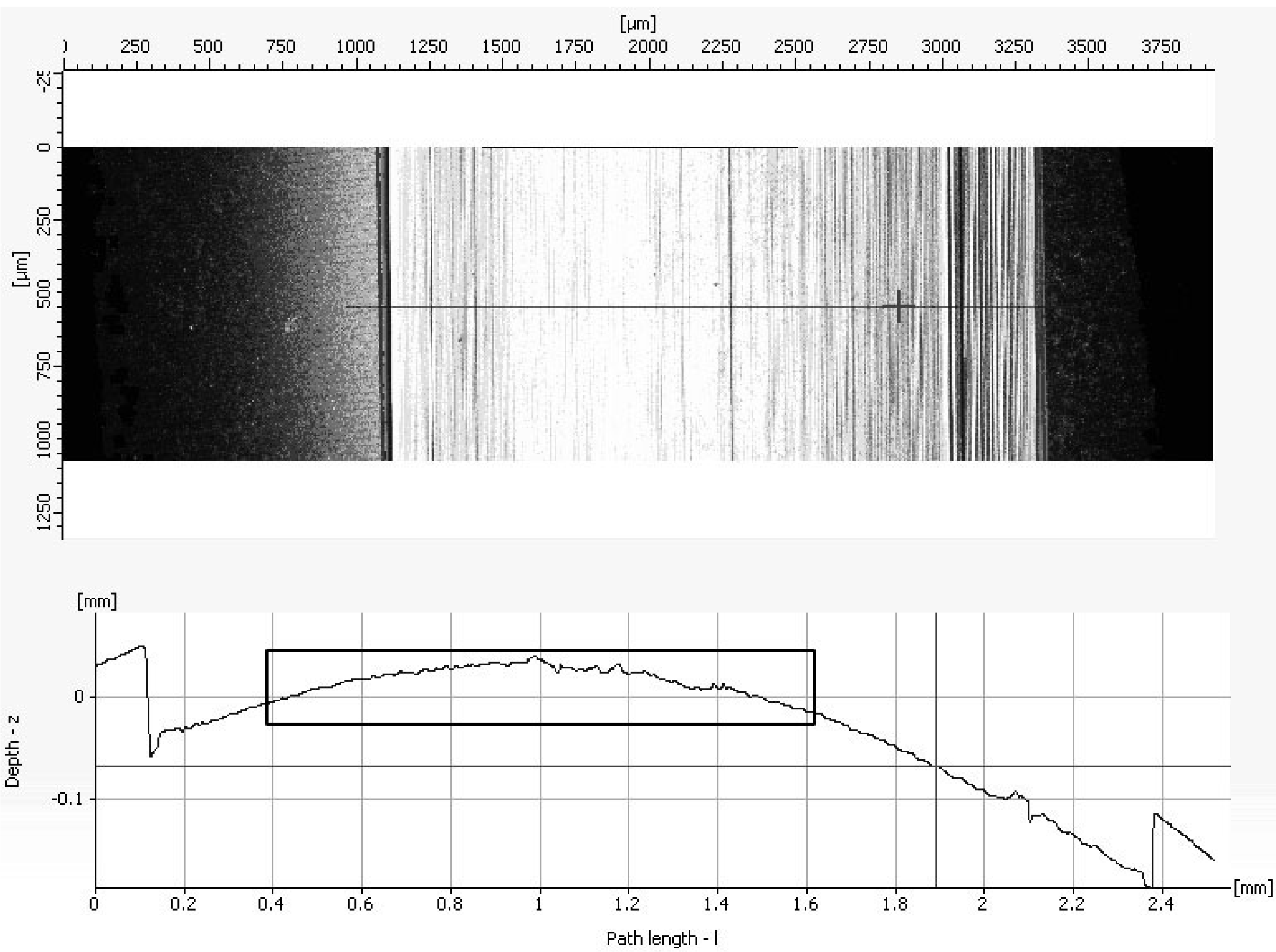


Figure 7: Surface profile of LEA 5 'standard bullet' using a focus-variation microscope (10x objective lens)

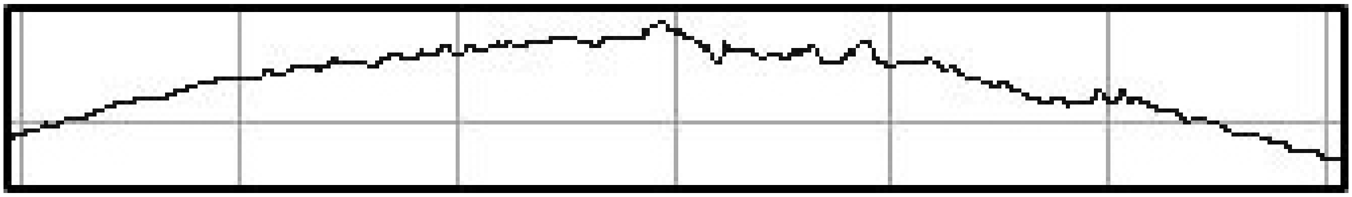


Figure 8: A 1.4 mm evaluation area enhancing the surface profile in the centre of LEA 5 (previously shown in Fig. 7 between 0.4 and 1.6 mm)

- excellent compromise between lateral and vertical resolution;
- reasonable acquisition time;
- optimal working distances to prevent accidental damage to sample and enhance types of surface features analysed;
- minimal generation of artefacts and noise in raw sample profiles;
- true colour representation of sample that is linked to height data;
- ability to image steep slopes, therefore imaging maximum surface features;
- rotational axis for 360 ˚ measurement of cylindrical samples;
- versatility of the technique for other forensic analyses, such as paper analysis;
- reasonable cost.

The ability to image up to 89 ˚ slopes and the working distance of the objective lens may be the most advantageous aspects of the focus-variation principle. This feature would be most beneficial for imaging and measuring relatively deep features, such as firing pin impressions and extractor marks within the extractor grooves of fired cartridge cases, as well as the nearly vertical transitions between spent bullet LEA and GEA. Deformed, fragmented and impacted bullets commonly pose a problem for the firearms examiner; the focus-variation microscope could potentially reduce the requirement to manipulate some samples, which would inevitably reduce examiners sample preparation time.

Although, a number of large and well funded forensic firearms laboratories worldwide may already have 3D imaging technologies, such as FTI IBIS TRAX-3D, there are many smaller laboratories and research facilities that could benefit from a lower cost 3D imaging system to assist in their day-to-day comparisons and accompany their current 2D imaging identifications. As a result, the focus-variation microscope may be presented as a suitable system for such establishments. The identification and documentation of definable striae without the subjective influence of lighting variable may supplement the notes and case work of firearm and toolmark examiners when used in conjunction with the Consecutive Matching Striae (CMS) methodology.

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