

## 3D Imaging in Forensic Science and Toolmark Examination

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### Abstract

Tool mark examinations are central to forensics ballistics and trace evidence analyses that have been carried out using comparison microscopes to compare microscopic surface marks. With the advent of 3D imaging techniques including confocal microscopy, laser profilometry, structured light scanning and white light interferometry, it has become possible to perform quantitative analysis of tool mark topography. This review aims to discuss the development and applications of 3D imaging techniques in tool marks and firearms examinations especially Virtual Comparison Microscopy (VCM) and computational methods of comparative analysis. The sources used in this review include scientific literature on 3D surface acquisition, virtual comparison, quantitative characterization of tool marks, statistical classification and technique validation. The conclusions from the research suggest a high degree of usefulness of these techniques in quantitative and repeatable analysis of tool marks. In one of the validation studies, VCM was validated by 107 examiners who performed analysis in 40 test sets and obtained 3 false positives in 693 different source comparisons (0.43%) and 0 false negatives in 491 same source comparisons (0.0%). Validation of confocal microscopy with the principal component analysis and support vector machine classification yielded empirical error rate of 3.5% at the 95% confidence level. However, variations in the imaging technologies used, data analysis process, datasets and methods of validating results make it hard to make direct comparisons between different studies. In general, 3D imaging coupled with computerized analysis holds a lot of potential as a method for replacing toolmark analysis.

**Keywords:** Toolmark; Forensics; Imaging; Microscopy; Ballistics; Profilometry; Striations; Firearm; Topography; Metrology

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### 1. Introduction

Toolmark evidence is one of the most common physical types of evidence found in crimes related to burglary, forced entry, use of hand tools, and firearms(Rao, et al., 2020). Toolmarks arise from the contact of a hard instrument, such as a screwdriver, bolt cutter, pry bar, or part of a gun, with a softer object .In the process of contact, microscopic properties of the tool surface can be transferred to the touched surface and be potentially used as an identifying characteristic in comparison between questioned marks and the suspected tool. Classical approach to the forensic analysis of toolmark evidence has been the comparison microscopy where microscopic patterns of questioned and known marks are visually compared(Chaklos et al., 2005).However, although traditional comparison microscopy is still an essential technique in forensic analysis, its interpretation is primarily based on subjective visual assessment of an examiner.(Scurich et al., 2023). The problem of lack of objective techniques in pattern and impression evidence has been addressed in recent scientific reviews by NAS and PCAST(Olaborede et al., 2020). 3D imaging became an alternative to conventional comparison microscopy by capturing the topography of a toolmark in terms of height data. These techniques therefore ensure that the measurable features on the surface of an object remain intact to allow for computation later. Several experiments have been carried out to prove the

quantitative ability of 3D imaging. (Weller et al., 2012) studied breech-face marks from 10 consecutive pistol slides made using nine test fires for each slide. This provided a dataset with 90 fired cartridge cases and 8,010 comparisons, of which 720 were known matches and 7,290 were known non-matches(Roth et al., 2015).The mean correlation score for matching comparisons was  $0.82 \pm 0.06$  while the one for non-matching comparisons was  $0.20 \pm 0.03$ . There was no overlap between the two sets of distributions. It was shown that 3D surface measurements could quantify breech-face marks into matches and non-matches.

Statistical analysis of 3D topography has also been achieved in the case of firearm toolmarks. (Gambino et al., 2011) analyzed 58 primer shear marks obtained from four Glock Model 19 pistols by applying high-resolution 3D surface measurement in addition to principal component analysis and support vector machines. An empirical error rate of 3.5% at 95% confidence was achieved. Another more extensive validation study was performed to assess the validity of 3D Virtual Comparison Microscopy (VCM). In this research, (Chapnick et al., 2021) performed an error-rate study that comprised 107 participants and 40 test sets of fired cartridge cases. In the primary group of qualified examiners, 3 false positives occurred out of 693 comparisons (0.43%), whereas no false negatives were detected in 491 comparisons (0.0%). This information provides practical data about the

effectiveness of 3D VCM but, at the same time, reveals the necessity of performing independent validation and error rate studies.

The use of 3D technology is not limited only to firearm examination. (Chu et al., 2013) conducted an automated identification study of bullet signatures based on CMS criteria by examining bullets from 10 consecutively manufactured barrels. Their results showed how 3D surface characteristics could be transformed into striae measurements for further automated comparison (Roberge et al., 2019). Unlike conventional 2D images, 3D imaging creates a digital model of surface heights variations that could be measured either in micrometres or even nanometres depending on imaging technology used. Such data could be analyzed using registration, cross-correlation, statistical and machine learning approaches. However, disparities in instrumentation, acquisition parameters, algorithms, datasets, and validation methodologies complicate the process of making comparisons between research studies. (Obuchowski et al., 2015). Other difficulties encountered include the traits of subclasses, insufficient number of representative datasets, standardization, and the independent validation of computing techniques. Consequently, this review is meant to analyze the basics, techniques, uses, and computing techniques related to 3D imaging in forensic toolmark analysis. The current challenges in terms of validation and standardization as well as the future developments, which involve the use of artificial intelligence and machine learning in an organized manner, will be discussed. (Yiran et al., 2025)

**Table:1 Comparative Overview of 3D Imaging Methods for Forensic Toolmark Examination**

| S . No | Tool mark / Evidence | 3D Imaging Method | Comparison Approach | Sample Size (n) | Total Comparisons (n) | Match Comparison (n) | Non-match Comparison (n) | Key Finding | References |
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| 1 | Br<br>ee<br>ch<br>-<br>fa<br>ce<br>m<br>ar<br>ks<br>on<br>fir<br>ed<br>ca<br>rtr<br>id<br>ge<br>ca<br>se<br>s | Con<br>foca<br>l<br>micr<br>osco<br>py | 3D<br>cro<br>ss-<br>cor<br>rel<br>ati<br>on<br>an<br>aly<br>sis | 90<br>ca<br>rtr<br>id<br>ge<br>ca<br>se<br>s | 8,0<br>10 | 72<br>0 | 7,2<br>90 | No<br>ove<br>rla<br>p<br>wa<br>s<br>obs<br>erv<br>ed<br>bet<br>we<br>en<br>ma<br>tch<br>ing<br>and<br>no<br>n-<br>ma<br>tch<br>ing<br>cor<br>rel<br>ati<br>on<br>sco<br>res;<br>sub<br>cla<br>ss<br>too<br>lm<br>ark<br>s<br>we<br>re<br>obs<br>erv<br>ed<br>but<br>we<br>re<br>not<br>det<br>ect<br>ed<br>by<br>the<br>cor<br>rel<br>ati<br>on<br>ana<br>lysi<br>s. | W<br>ell<br>er<br>et<br>al.<br>20<br>12 |
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| 2 | Fir-<br>ing-<br>pi-<br>n<br>im-<br>pr-<br>es-<br>si-<br>on<br>s<br>on<br>ca-<br>rtr-<br>id-<br>ge-<br>ca-<br>se<br>s | Nan-<br>ofoc-<br>us<br>μSu-<br>rf<br>conf-<br>ocal<br>micr-<br>osco-<br>py;<br>20×<br>obje-<br>ctiv-<br>e;<br>1.6<br>μm<br>nom-<br>inal<br>later-<br>al<br>pixe-<br>l<br>spac-<br>ing | Co-<br>ng-<br>rue-<br>nt<br>M-<br>atc-<br>hin-<br>g<br>Ce-<br>lls<br>(C<br>M<br>C) | 74<br>fir-<br>in-<br>gs<br>/<br>ca-<br>rtr-<br>id-<br>ge-<br>ca-<br>se<br>s | 2,7<br>01 | 1,1<br>65 | 1,5<br>36 | 12<br>fals-<br>e<br>neg-<br>ati-<br>ves<br>am-<br>on-<br>g<br>94<br>6<br>kn-<br>ow-<br>n-<br>ma-<br>tch<br>co-<br>mp-<br>aris-<br>ons<br>;<br>co-<br>mb-<br>ine-<br>d<br>firi-<br>ng-<br>pin<br>and<br>bre-<br>ech-<br>-<br>fac-<br>e<br>ana-<br>lysi-<br>s<br>im-<br>pro-<br>ved<br>dis-<br>cri-<br>mi-<br>nat-<br>ion<br>. | Ot-<br>t et<br>al.<br>,<br>20<br>17 |
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| 3 | Bul-<br>let<br>rif-<br>lin-<br>g<br>m-<br>ar-<br>ks | 3D<br>topo-<br>grap-<br>hy<br>mea-<br>sure-<br>men-<br>t<br>usin-<br>g<br>Nan-<br>ofoc-<br>us<br>μSu-<br>rf | Au-<br>to-<br>ma-<br>ted<br>Co-<br>ns-<br>ec-<br>uti-<br>ve<br>M-<br>atc-<br>hin-<br>g<br>Str-<br>iae<br>(C<br>M<br>S)<br>an-<br>aly-<br>sis | 25<br>fir-<br>in-<br>gs<br>/<br>ca-<br>rtr-<br>id-<br>ge-<br>ca-<br>se<br>s | 12,<br>97<br>0 | 10 | 12,<br>96<br>0 | 14<br>of<br>15<br>un-<br>kn-<br>ow-<br>n<br>bul-<br>lets<br>we-<br>re<br>cor-<br>rec-<br>tly<br>ass-<br>oci-<br>ate-<br>d<br>wit-<br>h<br>the<br>10<br>con-<br>sec-<br>uti-<br>vel-<br>y<br>rif-<br>led<br>bar-<br>rels<br>;<br>1<br>wa-<br>s<br>inc-<br>onc-<br>lusi-<br>ve;<br>no<br>fals-<br>e<br>ma-<br>tch-<br>es<br>we-<br>re<br>rep-<br>ort-<br>ed. | Ch-<br>u<br>et<br>al.<br>,<br>20<br>13 |
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| 4. | Bull et al. and impression | 3D surface topography measurements | Automated feature extraction and machine-learning classification using similarity features | 10,384 land-to-land comparisons | 10,384 | Not reported | Not reported | The automated method correctly identified the land impressions in the James Hambly dataset and successfully analyzed the 10,384 land-to-land comparisons. | Harrell et al., 2017 |
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| 5. | Striated screw driver tool marks | Alcon Infinite Focus Microscope                  | Multiscale registration and cross-correlation of 3D-derived toolmark profiles | 10 screw drivers | 230   | 50  | 180   | KM: 0.929 ± 0.060; KNM: 0.205 ± 0.128; real-vs-real KM: 0.958 ± 0.027; KNM: 0.227 ± 0.130; angle difference: 0.618 ± 4.179°. | Baker et al., 2016    |
| 6. | Impressed screw driver marks     | 3D surface imaging / automated toolmark signatur | Automated similarity-value comparison                                         | 100 marks        | 4,950 | 450 | 4,500 | Match: 0.838 ± 0.164; Non-match: 0.3                                                                                         | Chumbley et al., 2010 |

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|        |                                                                     | e<br>acq<br>uisit<br>ion                                    | so<br>n                                                                                                                                                  |                  |                                                             |                             |                             | 78<br>±<br>0.0<br>96;<br>Thr<br>esh<br>old<br>:<br>0.6<br>5;<br>FP<br>R:<br>0.2<br>2%<br>;<br>FN<br>R:<br>13.<br>55<br>%.                                                                                |                                              |
| 7<br>. | Sh<br>ea<br>r-<br>cu<br>t<br>pli<br>er<br>to<br>ol<br>m<br>ar<br>ks | Opti<br>cal<br>3D<br>tool<br>mar<br>k<br>topo<br>grap<br>hy | Co<br>rre<br>lati<br>on<br>-<br>ba<br>se<br>d<br>Wi<br>lco<br>xo<br>n<br>ran<br>k-<br>su<br>m<br>T1<br>sta<br>tist<br>ica<br>l<br>alg<br>ori<br>th<br>m. | 50<br>pli<br>ers | 39<br>65<br>ret<br>urn<br>ed<br>co<br>mp<br>ari<br>so<br>ns | No<br>t<br>rep<br>ort<br>ed | No<br>t<br>rep<br>ort<br>ed | Hi<br>gh<br>sep<br>ara<br>tio<br>n<br>bet<br>we<br>en<br>kn<br>ow<br>n<br>ma<br>tch<br>es<br>and<br>no<br>nm<br>atc<br>hes<br>;<br>co<br>mp<br>lete<br>sep<br>ara<br>tio<br>n<br>not<br>ach<br>iev<br>ed | Sp<br>ott<br>s<br>et<br>al.<br>,<br>20<br>15 |

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| 8<br>. | Im<br>pr<br>es<br>ed<br>bo<br>lt-<br>cu<br>tte<br>r<br>to<br>ol<br>m<br>ar<br>ks                                                                 | 3D<br>conf<br>ocal<br>-<br>base<br>d<br>surf<br>ace/<br>topo<br>grap<br>hy<br>ima<br>ging                                       | Au<br>to<br>ma<br>ted<br>too<br>lm<br>ark<br>sig<br>nat<br>ure<br>ge<br>ner<br>ati<br>on<br>and<br>si<br>mi<br>lar<br>ity<br>me<br>tri<br>c                            | 10<br>bo<br>lt<br>cu<br>tte<br>rs | 4,9<br>50 | 45<br>0                     | 4,5<br>00                   | Ma<br>tch<br>:<br>0.8<br>88<br>±<br>0.1<br>59;<br>No<br>n-<br>ma<br>tch<br>:<br>0.4<br>34<br>±<br>0.1<br>31;<br>Thr<br>esh<br>old<br>:<br>0.7<br>9;<br>FP<br>R:<br>0%<br>;<br>FN<br>R:<br>18<br>%. | Pa<br>tte<br>et<br>&<br>Ch<br>a<br>m<br>po<br>d<br>20<br>24 |
| 9<br>. | Sh<br>ea<br>r-<br>cu<br>t<br>m<br>ar<br>ks<br>on<br>co<br>pp<br>er<br>wi<br>re<br>pro<br>duc<br>ed<br>by<br>sli<br>p-<br>joi<br>nt<br>pli<br>ers | Alic<br>ona<br>Infi<br>nite<br>Foc<br>us<br>Mic<br>rosc<br>ope<br>G3;<br>opti<br>cal<br>3D<br>surf<br>ace<br>topo<br>grap<br>hy | Co<br>rre<br>lati<br>on<br>-<br>ba<br>se<br>d<br>sta<br>tist<br>ica<br>l<br>an<br>aly<br>sis<br>usi<br>ng<br>Wi<br>lco<br>xo<br>n<br>ran<br>k-<br>su<br>m<br>T1<br>wit | 50<br>pli<br>ers                  | 3,9<br>65 | No<br>t<br>rep<br>ort<br>ed | No<br>t<br>rep<br>ort<br>ed | Kn<br>ow<br>n<br>ma<br>tch<br>es<br>sho<br>wed<br>high<br>er<br>T1<br>val<br>ues<br>tha<br>n<br>no<br>n-<br>ma<br>tch<br>es,<br>wit<br>h<br>res<br>ults<br>obt<br>ain                              | Sp<br>ott<br>s<br>et<br>al.<br>,<br>20<br>15                |

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|             |                                                                                       |                                                                                 | h<br>an<br>80<br>%<br>lea<br>sh.                                             |                                      |                |                |                | ed<br>for<br>>9<br>8%<br>of<br>co<br>mp<br>aris<br>ons<br>.                                                                                                                                                                                     |                                                                   |
| 1<br>0<br>. | Im<br>pr<br>ese<br>d<br>ch<br>ise<br>l<br>to<br>ol<br>m<br>ar<br>ks<br>in<br>le<br>ad | Not<br>3D<br>ima<br>ging<br>; 2D<br>surf<br>ace-<br>prof<br>ile<br>anal<br>ysis | T1<br>-<br>ba<br>se<br>d<br>sta<br>tist<br>ica<br>l<br>alg<br>ori<br>th<br>m | 50<br>0<br>to<br>ol<br>m<br>ar<br>ks | 51,<br>00<br>0 | 13,<br>50<br>0 | 37,<br>50<br>0 | Str<br>on<br>g<br>ma<br>tch<br>-<br>no<br>n-<br>ma<br>tch<br>sep<br>ara<br>tio<br>n;<br>co<br>mp<br>lete<br>sep<br>ara<br>tio<br>n at<br>the<br>50<br>0-<br>50<br>0<br>pix<br>el<br>sett<br>ing<br>(ex<br>clu<br>din<br>g<br>out<br>lier<br>s). | Sp<br>ott<br>s<br>&<br>Ch<br>u<br>m<br>bl<br>ey<br>(2<br>01<br>5) |

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| 1<br>1<br>. | Pu<br>nc<br>h<br>M<br>ar<br>ks<br>(I<br>m<br>pr<br>ese<br>d<br>To<br>ol<br>m<br>ar<br>ks<br>) | 3D<br>Disc<br>-<br>Sca<br>nnin<br>g<br>Con<br>foca<br>l<br>Mic<br>rosc<br>opy                                      | 3D<br>Cr<br>oss<br>-<br>Cor<br>re<br>lati<br>on<br>Fu<br>nct<br>ion<br>(C<br>CF<br>M<br>A<br>X)<br>;<br>ful<br>ly<br>aut<br>om<br>ate<br>d<br>bli<br>nd<br>co<br>mp<br>ari<br>son | 40<br>pu<br>nc<br>h<br>m<br>ar<br>ks | 40<br>0 | 20 | 38<br>0 | All<br>20<br>un<br>kn<br>own<br>pu<br>nc<br>h<br>ma<br>rks<br>we<br>re<br>cor<br>rec<br>tly<br>ide<br>ntif<br>ied<br>;<br>ma<br>tch<br>and<br>no<br>n-<br>ma<br>tch<br>co<br>mp<br>ari<br>sons<br>we<br>re<br>cle<br>arl<br>y<br>sep<br>ara<br>ted<br>. | Zh<br>en<br>g<br>et<br>al.<br>,<br>20<br>14        |
| 1<br>2<br>. | Di<br>ag<br>on<br>al<br>cut<br>ter<br>m<br>ar<br>k                                            | Con<br>foca<br>l<br>micr<br>osco<br>py<br>and<br>scan<br>ning<br>whit<br>e-<br>light<br>inter<br>fero<br>metr<br>y | Con<br>sec<br>uti<br>ve<br>Matc<br>hin<br>g<br>Str<br>iae<br>(C<br>M<br>S)                                                                                                        | 80<br>pr<br>ofi<br>les               | 80      | 74 | 6       | 74/<br>80<br>pro<br>file<br>s<br>cor<br>rec<br>tly<br>ide<br>ntif<br>ied<br>(92<br>.5<br>%)                                                                                                                                                             | He<br>ik<br>ki<br>ne<br>et<br>al.<br>,<br>20<br>14 |

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| 13. | Saw marks on human bone                     | Micro-computed tomography (Micro-CT)        | Measurement and statistical comparison of saw-mark properties; regression analysis of toolmark width | 270 saw marks                           | 270 | No t reported | No t reported | 8 tools showed significantly different saw mark properties, with 94% tool-width prediction accuracy. | Norman et al., 2018 |
| 14. | Knife cut marks on porcine costal cartilage | Tool Scan 3D scanner; 3 µm/pixel resolution | No rm alize d cross-correlation of 3D surface signals                                                | 10 knives; 20 samples per test material | 20  | 10            | 10            | High est separation: K M = $0.92 \pm 0.06$ ; K N M = $0.23 \pm$                                      | Weber et al., 2021  |

|     |                                             |                                                                    |                                             |                     |                            |     |      |                                                                                                          |                                                 |
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|     |                                             |                                                                    |                                             |                     |                            |     |      | 0.03.                                                                                                    |                                                 |
| 15. | Diagnostic cutter marks on 2-mm-thick wires | Scanning White Light Interferometry (SWLI) and Confocal Microscopy | Cons ecutive Matching Striae (CMS) criteria | 80 profiles         | 80                         | 74  | 6    | 74 of 80 profiles correctly identified; 3D profiling enabled reliable comparison across imaging devices. | Heikkinen et al., 2014; Kassamakov et al., 2010 |
| 16. | Bolt-cutter impressioned tool mark          | 3D image acquisition and 3D toolmark signatures                    | Improved Fast Normalized Cross-Correlation  | 10 marks per cutter | 4,950 pairwise comparisons | 450 | 4500 | Matches showed higher similarity; false-positives                                                        | Bachrach 2007                                   |

|      | arks               |                                        | relation<br>(IF N C C)                    |          |                       |    |     | erate = 0% , false-negative rate = 18 %.                                                                 |                     |
|------|--------------------|----------------------------------------|-------------------------------------------|----------|-----------------------|----|-----|----------------------------------------------------------------------------------------------------------|---------------------|
| 17 . | Dented Impressions | 3D disc - scanning confocal microscopy | ACCFMAX (maximum areal cross-correlation) | 40 marks | 190 known comparisons | 10 | 180 | Minimum matching AC CF MAX 69.31 %; all 20 unknown marks were correctly identified to the source punch . | Zheng et al. , 2014 |

|      |                                                     |                                              |                                                                 |                                      |              |              |              |                                                                                                         |                        |
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| 18 . | Fracture marks – fractured stainless-steel surfaces | 3D laser confocal microscopy                 | Spectral analysis and matrix-variate distribution and QDA       | 10 fracture pairs                    | 600          | 60           | 540          | All true matches and non-matches were correctly classified ; lowest match posterior probability >99.96% | Dawood et al. , 2022   |
| 19 . | Lock-picking marks on cylinder pins                 | 3D Confocal Laser Scanning Microscopy (CLSM) | Automated classification of 4 lock-opening methods using 15 cla | 20 key pins from 4 locking cylinders | Not reported | Not reported | Not reported | Random Forest and Rotation Forest performed best, with TPR >80%                                         | Clausing et al. , 2012 |

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|             |                                                                                                                         |                                             | ssi<br>fie<br>rs.                                                                                                                                                                                                      |                   |    |                             |                             | and<br>TN<br>R<br>>7<br>0%                                                                                                                                                                     |                                                    |
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## 2. Fundamentals of Forensic Toolmark Examination

Tool marks are created through the transfer of microscopic surface characteristics from a tool to an impression made on a soft surface because of contact between the tool edge or face and the surface (Bachrach et al., 2010). Tool marks can be observed at places where burglary and forced entry takes place, and in fired bullets and cartridge cases where firearm components are the tools. The

fundamental idea behind the analysis of such impressions is that the microscopic surface characteristics of a tool, which originate during its manufacture and modification, can be transferred to the surface of the tool mark. Experimental research has shown that these microscopic characteristics can be responsible for the creation of similar tool marks from the same tool. For instance, (Weller et al., 2012) studied breech-face marks that were created with 10 pistol slides consecutively manufactured, where 9 test fires took place from each of the slides, thus producing 90 fired cartridge cases and 8,010 comparisons. The dataset comprised 720 known-match and 7,290 known-non-match comparisons, where the mean correlation scores were  $0.82 \pm 0.06$  and  $0.20 \pm 0.03$ , respectively, with no score distribution overlap.

The characteristics of toolmarks can be categorized into three major types. First, class characteristics are intended design characteristics of all tools of the same type and include the dimensions and shape of a screwdriver blade or barrel rifling (Rowe et al., 2019). Second, subclass characteristics are formed through manufacturing and may be common for tools manufactured using the same conditions; however, this may cause a wrong association since they are viewed as individual characteristics. Individual characteristics are accidental microscopic characteristics created during manufacturing, grinding, and, most importantly, through usage when the tool is worn out, corroded and damaged. It was also proved that recognizing the differences between reproducible individual characteristics and manufacturing characteristics is critical even in 3D studies as subclass toolmarks could be found on breech faces but were not found in the correlation analysis (Weller et al., 2012).

The second type of classification of toolmarks is based on the method of formation. Striation marks are created because of the tool moving along the surface under some pressure. It includes the marks made by the motion of a screwdriver on the metal surface in case of forced entry and the marks made by the bullet moving inside the rifled barrel of a gun (Hueske et al., 2006). Marks created by pressing a tool on a surface are called impressed marks, including hammer face marks, punch marks, and firing pin marks. Both kinds of marks were studied in quantitative topography studies. (Zheng et al., 2014), for instance, performed a blind, automated study of toolmarks using 2D stylus measurement method for striated chisel marks and 3D disc-scanning confocal microscopy for impressed punch marks; all unknown toolmarks were properly attributed to the tools that created them using maximum cross-correlation method. It should be noted that the pattern of the marks is influenced not only by the tool but also by the angle of attack, the force, the direction of motion, the hardness of the surface and contamination.

The impact of these formation variables has been observed in quantitative experiments. According to (Baiker et al., 2016), screwdriver tool marks showed known match similarity scores higher than mean known non-match scores even at an angle difference of 40°. Automated estimation of the angle of attack gave the result of  $0.618 \pm 4.179^\circ$ , showing that the geometry of the formation of the marks could be quantitatively estimated rather than being a mere qualitative variable.

With the knowledge of this variability, marks are made on test substrates in order to cater for the variability in the suspected tool. In the process of examination, the marks can be placed side by side in a comparison microscope and assessed depending on how similar their pattern, positioning, and relative striation or contour sizes are. This is especially useful when it comes to small or hard surfaces for which quantitative 3D profiling becomes highly valuable. (Heikkinen et al., 2014) analyzed tool marks made by diagonal cutters on 2 mm thick wires through confocal microscopy and scanning white-light interferometry. With consecutive matching striae criteria, 74 of 80 marks were accurately matched.

### 3. 3D Imaging Technologies Used in Forensic Examination

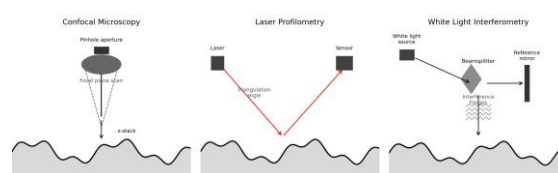
The three-dimensional imaging captures the surface of the toolmark as a series of height measurements on a grid, not as an image with light and shadows. This topographic map enables measurement of depth, width, and spacing of features in micrometres. There are several techniques that are currently being employed by forensic labs to capture this information, and each one operates on a different physical principle.

In confocal microscopy, a three-dimensional surface is captured by capturing multiple images of the sample from different focal planes and retaining only those portions of the image that are in focus through a pinhole aperture (Wilson et al., 2014). The technique provides excellent lateral and vertical resolutions and works well for fine features such as firing pin marks and fine striations. In laser profilometry, a laser line or point is projected onto the surface of the sample, and the height is calculated based on the location of the reflection of the laser line or point. It is fast and good for large areas; however, highly reflective or very inclined surfaces can result in data noise and voids (Li, et al., 2019). White light interferometry uses the interference of the light waves that are reflected from the sample and from a reference mirror. This method allows obtaining extremely high vertical resolution, usually in the nanometer range, and is suitable for smooth samples, but is prone to vibrations and steep slopes. (Makrushin et al., 2012). Focus variation microscopy technique, employed in several types of instruments, uses a shallow depth of field combined with vertical scanning to measure

rough and steep surfaces. In cases when a mark is situated beneath the surface of bone or any other opaque substance, a micro-CT scan can help to visualize the inner geometry of the structure, though with the resolution worse than that of surface imaging techniques (Waltenberger et al., 2021).

Not a single instrument works equally well for all types of traces. It depends on the size of the mark, its material and resolution needed, scanning time, budget available, etc. For exchange of information and comparison scans are usually stored in open file formats such as x3p, keeping both height values and parameters of the measurement. As one and the same mark may produce slightly different scans on different instruments, calibration of the measurements against certified reference standards is necessary. (Gröhl, et al., 2022)

Fig. 1. Schematic principles of common 3D surface imaging techniques used in toolmark examination



**Figure 1.** Schematic operating principles of the three most widely used 3D surface acquisition techniques in forensic toolmark examination: confocal microscopy (optical sectioning through a pinhole aperture), laser profilometry (triangulation of a reflected laser spot/line), and white light interferometry (interference fringes generated between the sample and a reference mirror).

**Table 2.** Overview of Common 3D Surface Imaging Techniques Used in Forensic Toolmark Examination

| Technique           | Physical Principle                                                                           | Typical Resolution              | Best Suited For                                   | Key Limitations                              |
|---------------------|----------------------------------------------------------------------------------------------|---------------------------------|---------------------------------------------------|----------------------------------------------|
| Confocal microscopy | Optical sectioning of in-focus light through a pinhole aperture across multiple focal planes | Sub-micrometre lateral/vertical | Fine features (firing-pin marks, fine striations) | Slower acquisition; limited working distance |

| Technique                  | Physical Principle                                                                    | Typical Resolution       | Best Suited For                                             | Key Limitations                                             |
|----------------------------|---------------------------------------------------------------------------------------|--------------------------|-------------------------------------------------------------|-------------------------------------------------------------|
| Laser profilometry         | Triangulation of a projected laser point/line reflected from the surface              | ~1 µm, larger scan areas | Large or curved surfaces; rapid scanning                    | Noise/data voids on reflective or steeply inclined surfaces |
| White light interferometry | Interference between light reflected from the sample and a reference mirror           | Nanometre-level vertical | Smooth, flat samples requiring very high vertical precision | Sensitive to vibration; struggles with steep slopes         |
| Focus variation microscopy | Vertical scanning combined with a shallow depth of field to track best-focus position | Sub-micrometre           | Rough or steep surfaces (e.g., fractured or textured marks) | Acquisition time increases with surface roughness           |

| Technique                            | Physical Principle                                         | Typical Resolution  | Best Suited For                                                       | Key Limitations                                             |
|--------------------------------------|------------------------------------------------------------|---------------------|-----------------------------------------------------------------------|-------------------------------------------------------------|
| Micro-computed tomography (micro-CT) | X-ray attenuation reconstructed into a 3D volumetric model | Tens of micrometres | Subsurface/embedded marks (e.g., marks under bone or opaque material) | Lower resolution than surface-only methods; cost and access |

#### 4. Applications of 3D Imaging in Toolmark Examination

One of the more mature applications of 3D imaging technology is in firearm examination. Firing pin marks, ejector marks on cartridge cases and breech face marks, as well as the striations found on bullet lands and grooves, can be scanned and compared digitally. Virtual comparison microscopy involves aligning the two scans and viewing them simultaneously on a computer screen to recreate the conventional side-by-side comparison without the need to handle the samples repetitively. Since the information is available digitally, a second expert can examine the case for verification remotely and in another laboratory without shipping the samples (Jones et al., 2022).

Other than firearm examination, there are other areas where 3D imaging has been used to analyze evidence collected from burglary or forcible entry cases. Screwdriver, plier, diagonal cutter and bolt cutter striated marks have been analyzed using surface profiles created using topography data (Patteet, et al., 2024). Punch, chisel and hammer impressed marks have been analyzed in the same manner using areal correlation of the impressed marks. In this case, the height data help separate the shape of the impression from the surface roughness and enable the comparison of features which correlate with the tool.

Further applications apply the technique to unconventional forms of evidence. The surface topography of fractured metal fragments is matched quantitatively and has been used in accident and criminal investigations to reconstruct broken parts (Dawood et al., 2022). Lock mechanism surfaces have been examined to discriminate between the different approaches used to open the lock, whether picking or use of the actual key. In forensic anthropology and pathology, saw and knife marks on bone and cartilage surfaces have been

imaged in 3D to determine the type of implement used, the blade width and the direction of application (Franchetti et al., 2022).

The use of three-dimensional imaging in the laboratory setting has other practical advantages. It provides a permanent image that is not affected by the normal wear and tear of manual examination, allows further examination later, and is useful for educational and certification purposes. When paired with statistical methods, it provides the examiner with numerical values of similarity to include in the examination report.

### **5. Computational Methods and Digital Toolmark Comparison**

After a toolmark has been represented in three-dimensional form, computer analysis allows objective comparison of the mark (Chumbley et al., 2017). The procedure starts with pre-processing stage where noise and outliers are filtered out, surface form is taken out of consideration and filters distinguish between fine detail and form and waviness. In striated marks, the surface is reduced to one-dimensional form or profile that reflects the striation pattern on the mark. For impressed marks and cartridge cases, the areal surface is maintained and processed for comparison.

The next stage is alignment or registration of the two surfaces. Since crime scene mark and test mark never have identical orientation, the program must move one surface relative to another and rotate it to find the best agreement position (Gardner et al., 2018). The level of similarity is determined. The most popular similarity measure is cross-correlation which assesses the level of agreement of two profiles or surfaces in the form of single value ranging from zero to one. The higher correlation score corresponds to more similar objects. The scores of known matches are compared to those of known non-matches to determine if the technique is successful in separating the two groups (Cuellar, et al., 2024). A number of specialized algorithms have been proposed based on this principle. The congruent matching cells method segments the surface into cells and compares the number of those agreeing both in terms of their pattern and positions, making it insensitive to partial destruction. Consecutive matching striae method compares the number of consecutively agreeing lines between two striated marks. Rank-based methods such as the Wilcoxon rank-sum test have been used to quantify the comparison of correlations between the matching regions and random regions, thus creating a metric of how improbable the match is to happen accidentally (Hossain et al., 2013).

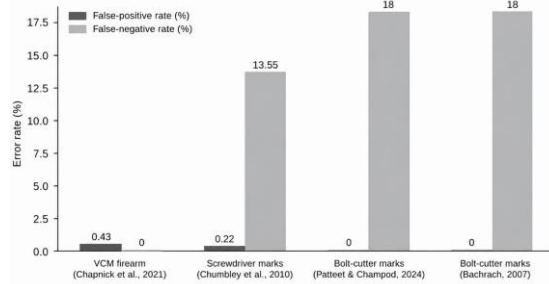
Machine learning methods have brought one more level of improvement. Feature extraction from the surface and subsequent training of classifiers such as support vector machines and random forests have been done for classification purposes, usually preceded by dimensionality reduction through

principal component analysis. Statistical models using spectral analysis or multivariate distributions have also been employed to calculate posterior probability or likelihood ratio for expressing evidence quantitatively. However, the reliability of any algorithm ultimately depends on the quality of input data and representative training sample, as well as independent validation.

### **6. Evidence from Previous Studies and Research Gaps**

As shown in Table 1, published studies from the last two decades consistently demonstrate that three-dimensional data can discriminate between marks created using the same tool and marks created using other tools. In a large-scale validation study of virtual comparison microscopy using 107 examiners, 0.43 percent and 0.0 percent false-positive and false-negative rates were found, respectively, which is comparable to the performance of conventional microscopy. Confocal measurements of breech-face marks had no overlap between matching and non-matching correlation scores, and an automated analysis of bullet striae successfully discriminated unknown bullets and their respective barrels without any false matches. For other tools besides firearms, similar results were observed, albeit with variable performances depending on both the tool and the algorithm used. All the punch mark samples that were scanned using confocal microscopy were correctly matched in blind testing. Seventy-four of the eighty diagonal cutter mark profiles were also correctly matched. False positive rates were very low for impressed screwdriver marks and impressed bolt-cutter marks, while the false negative rates were relatively high, about 14 to 18 percent. Research on bones, cartilages, and broken metals additionally supports the idea that the method can be expanded to other evidence types (Egeland et al., 2021).

However, even with these promising results, there are some important limitations left. Most experiments involve a relatively small set of instruments and consecutively produced items; thus the findings cannot be extrapolated to the overall population of the tools used. Each study uses different devices, resolutions, algorithms, and performance evaluation criteria; therefore, error rates cannot be compared among different experiments. Subclass features still present difficulty for the method, as it increases the similarity between tools. Very few studies deal with realistic settings of damaged marks, marks on various substrates, and worn-out tools. Moreover, there is a lack of publicly available reference datasets and black-box tests of the algorithm by independent examiners. There are some publications in the literature that fail to provide numbers of comparisons used for the true and false matches. This makes it hard to evaluate the soundness of their results.



**Figure 2.** Reported false-positive and false-negative rates from selected 3D toolmark validation studies summarised in Table 1, illustrating the generally low false-positive rates but more variable false-negative rates across tool types and algorithms.

### 7. Advantages and Limitations of 3D Imaging.

One of the primary advantages of 3-D imaging is the fact that it makes the comparison process objective. Height measurements are much more independent of the angle of illumination, shadows and position of the specimen than traditional two-dimensional images, making it possible to record the same mark multiple times, and getting identical results. The possibility of quantifying the results makes it possible to estimate the error rate and similarity using statistics, addressing the requirements of scientific and legal communities regarding the objectivity of pattern evidence (Urbanová et al., 2015). Other advantages are practical in nature. The scan images can be stored, transferred and analyzed later without touching the original exhibit, preserving it and making remote peer review possible. Digitized images can be included into databases, used in training sessions and presented in courtrooms. Automated algorithms can perform comparisons quickly and relieve examiners of work, detecting even very subtle differences that might be difficult to see using a microscope.

However, there are also some limitations to the use of this technology. The equipment is rather costly, requires skilled operators and is time-consuming, especially when performing high-resolution scans of large marks. The results are dependent on scan parameters; reflectivity of the surface and Different systems is not necessarily exchangeable. Highly reflective, dark or steep surfaces may produce data gaps and artifacts. Subclass characteristics, mark distortion and low-quality marks can also influence algorithms, and machine learning approaches can sometimes be considered black boxes where the decisions made are hard to justify in court (Herke et al., 2026). Finally, three-dimensional imaging will not substitute for the expert. Choice of similar areas, adequacy of a particular mark and the interpretation of results still require a human being's intervention. Thus, the use of this technology should be considered as assistance to the expert examination rather than decision-making tool.

### 8. Validation, Standardization and Forensic Considerations

For three-dimensional techniques to be admitted into casework practice, their scientific validity and reliability need to be demonstrated. The National Academy of Sciences report from 2009 and President's Council of Advisors on Science and Technology report from 2016 both stressed the fact that for toolmark and firearm examinations to be scientifically valid, they need to have established error rates using appropriate empirically designed studies. Courts also use the same criteria to admit expert evidence; therefore, validated methodologies are expected to meet high standards (Albright et al., 2024).

A validation procedure should be carried out throughout the whole process of examination, including calibration of instruments based on traceable standards, setting scan resolutions and settings, pre-processing procedures, testing of an algorithm on independent data sets including known matchings, non-matchings and tricky scenarios like consecutively manufactured tools. Black box studies conducted with examiners and proficiency tests would provide realistic estimates of error rates and areas where human and automatic decisions may vary. Standardisation is just as crucial. Uniform file formats, standard measures of quality of the surface and a consistent reporting format would enable the comparison of results produced by different laboratories and reduce the variations observed in publications. Laboratories have to conduct themselves under an accredited quality system where there are documented procedures, competencies, and conclusions verified by a second examiner.

There are a number of forensic implications that arise when dealing with digital evidence. The scans have to be stored securely, with a chain of custody and backed up in order to ensure their integrity and availability. The reports have to specify the limitations of the procedure, avoid any definitive statements regarding its accuracy, as well as the weight of the evidence in language that is compatible with the data, such as similarity scores and likelihood ratios. The examiners need to be taught not just how to use the machine but also what the output means in statistical terms, so that they will be able to defend their results when being cross-examined.

### 9. Future Perspectives

Future toolmark examination techniques will probably incorporate integration between three-dimensional imaging and artificial intelligence methods. Using deep learning approaches, including convolutional neural network, it is possible to discover discriminative features from the surface data and reduce problems associated with noise, incomplete markings, and subclass effects. In order to become practically applicable, the approach

should provide explanations for the result of the analysis and require validation through the use of large and diverse sample sets (Kudonu et al., 2022). One more important direction is related to development of open reference collections for algorithm testing purposes. These reference collections will include scanned data of marks made with different tools under various material and operational conditions. In this way, the testing of different algorithms will become more objective and will use the same set of images. At the same time, it will become a common practice to express the results using the probabilistic framework in the form of a likelihood ratio. Improved technology will result in tools being faster, less expensive and more portable. Portable scanners can be used to record marks at crime scenes, and cloud-based software will enable remote collaboration and peer reviews between laboratories. The combination of different techniques, such as using surface topography together with micro-CT or with two-dimensional images, can provide more detailed information about the marks (Srivastava et al., 2025). Virtual and augmented reality could also be useful for presenting three-dimensional evidence to examiners, juries and judges. Finally, international standards, uniform nomenclature and collaborative validation studies would be required to ensure implementation of these developments on a consistent basis. If these measures are implemented, three-dimensional imaging and computation could become an established part of toolmark and firearms examination.

### 10. Conclusion

Three-dimensional imaging has proven to be a useful and reproducible method of forensic tool mark and firearms identification by converting surface marks into topographic data. As seen from the reviewed literature, it can be applied to firing-pin marks, breech-face marks, bullets, screwdrivers, pliers, cutters, punches, saws, knives, fractures, and locks. Quantitative analysis through cross-correlation, Congruent Matching Cells, Consecutive Matching Striae, statistical classification, and artificial intelligence methods allows for an objective evaluation of questioned and known marks. Encouraging results have been reported in validation studies as to the ability of the technique to discriminate matching from non-matching marks; yet, its effectiveness relies on a particular system, acquisition parameters, analysis procedure, nature of evidence, and dataset. Potential drawbacks include the problem with subclasses, deformation of the marks, artifacts on the surfaces, expensive equipment, lack of representative data sets, and independence of validation. Implementation of three-dimensional imaging requires standardization of calibration, data acquisition, reporting, reference databases, and black-box validation. Three-

dimensional imaging should supplement and not replace expert evaluation. Future studies must emphasize transparency and validation of AI techniques, open reference libraries, probability based reports, portability and interoperability of systems, cooperative validation, and globally unified standards irrespective of the laboratory or varying forensic case environments.

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