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Aspects of 3D surface scanner performance for post-mortem skin documentation in forensic medicine using rigid benchmark objects

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ABSTRACT

Background: Patterned light 3D scanning has historically been targeted towards industrial and manufacturing applications. Forensic 3D skin surface scanning is relatively new and appears to contain aspects of off label usage. Based on how patterned light scanning has been published to work, we assumed that naturally rough surfaces' 3D scan validity to improve with extensive calibration of such a 3D-scanner whereas we assumed the same not to be true for industrially smooth surfaces. Using rigid benchmark objects matching aspects of typical post-mortem skin injuries and an object with smooth plastics surface, that hypothesis was tested.

Methods: A 3D-scanner that captures stereoscopic images from patterned light was used. Impact of calibration extent on perceived differences between digital 3D models of industrially smooth and naturally rough objects was quantified with an experimental subjective comparison of 3D data appearance between minimal (MC) and extensive calibration (EC) against matched photos by 13 judges. Using extensive calibration, we then conducted (a) qualitative appreciation and (b) quantitative characterization of small surface regions to determine recognition rate of surface features.

Results: Extensive calibration significantly improved the perceived quality of digitized naturally rough surfaces but turned out to not have a significant impact on the perceived quality of considerably smoother industrial surface digitization (G2 Likelihood Ratio Chi-square statistic $p < 0.0001$). After calibrating the device exceeding manufacturer's recommendations, it adequately represented $98 \pm 1\%$ of naturally rough surface contained features sized as small as 0.3 mm within a user attended scan time of 8–12 min per object.

Conclusions: Significantly reduced apparent quality of patterned light scanner derived 3D models of rough surfaces may base on calibration recommendations that seem to be geared towards more efficient scanning of industrially smooth surfaces. As stripe pattern analysis typically includes non-linear approximations, a 3D scanner calibration process for rough detailed surfaces might benefit from as many small variations of distance and angles across the whole scanning volume as can be afforded by the user. Off label use entails reevaluation of devices for their intended new application.

1. Background

1.1. *Forensic pathology—technical 3D surface representation requirements*

Courts typically rely on forensic pathologists to document injuries for the purpose of negotiating interpretation and legal significance. During these deliberations, newly raised hypotheses may require details not discussed initially. Skin surfaces can be fully digitized using 3D scanning technology. Other than direct visual analysis, applications of precisely digitized surfaces in forensic pathology include reconstructive juxtapositioning [1,2], facial [3] or dental [4] landmark projection for the purpose of quantifying shape match. Highly detailed skin surface documentation with 3D fidelity was first introduced through forensic photogrammetry [5–8]. Later, 3D surface scanning [9,10] or CT data-derived 3D surface extraction [11,12] were introduced to forensic pathology.

Controversial or discriminating morphologic evidence may appear small to the naked eye and can be overlooked. Such pathology can include hard to detect needle-marks that may raise suspicion of poisoning [13], tentative cuts which may indicate self-infliction [14], relevant details for the distinction of inter-individual bite mark differences [15,16], needle marks [17] or soot patterns that may be important for drawing conclusions about weapon, ammunition and shooting range [18–20]. There are a number of instances where conclusions about the cause of injury shapes [21,22] seemed to

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provide the basis for judicial verdicts. Upon digitization, any single real feature requires a minimal resolution of 16 to 24 data elements in each dimension (pixel, voxel, 3D coordinate points) for an adequate representation [23] while representation of 50–60 data elements per feature would be a good resolution.

1.1.1. *Forensic pathology applications of automotive 3D scanning*

Most commercially available 3D surface scanners do not appear to be geared towards scanning naturally rough surfaces such as possibly injured skin. We contend that 3D scanner devices are built primarily for technical applications domains such as industrial design, reverse engineering and rapid prototyping. Such surfaces typically contain smooth and mostly straight or curved surfaces joined by edges or bends, holes, slots, pockets or grooves [24], which is reflected in the range of test objects used for industrial scanner evaluation [25]. Such digitized 3D surfaces may contain scanning artifacts originating from specular reflectance, directional effects [26], or even discoloration.

Medicolegal pioneers adopting 3D scanning into forensic medicine used 3D scanners clearly advertised and sold for industrial applications, CAD (computer aided design). Examples include the ATOS II Scanner by GOM International (Switzerland)[9] whose applications – in 2002 – were listed as quality control for blow molding, sheet metal, tool manufacturing and wind tunnels as well as reverse engineering for sculptures, torso models, deformation measurement and mold production as can be seen from their archived 2002 website [27]. Subke et al. employed an ABW scanner [28], that, at the time, was built for industrial usage including foot sole scanning for orthopedic insoles [29]. So 3D scanning's adoption into forensic pathology started as off-label use [30].

A check of the brands listed in a comprehensive 3D scanning overview paper (Table 4 in [31] covering triangulation with pattern projection) shows that even today, patterned light 3D scanners are predominantly industrial scanners [32–45]. Nowhere in sight do applications specifically advertise to contain the capturing of naturally rough or complex surfaces with any specific degree of particularly high similarity to the original.

1.2. *Objective for this study*

We investigated a 3D scanner's performance for what is properly called off label application domain of 3D skin surface documentation in forensic pathology. Initial testing revealed a questionable performance regarding fidelity of rough surface representation while industrially smooth objects appeared to get captured just fine. From evaluation of the technique itself, we assumed that extensive calibration would have the capacity to improve the results. For that purpose, we established a detailed procedure to investigate 3D scanner performance for naturally rough surfaces using a number of benchmark objects. That procedure was then used to compare results of MC (minimal calibration) and EC (extensive calibration) of that patterned light 3D scanner.

2. Methods

2.1. *Benchmark objects*

3D shape features that we focused on when choosing our benchmark objects (Fig. 1) are relevant to forensic skin pathology (Fig. 3): they included superficial or deep abrasions that may contain highly reflective regions such as body fluids or as attached material such as gravel (Fig. 3a and b), penetrating injuries such as gunshot wounds sometimes featuring powder tattooing (Fig. 3d and e) as well as stab wounds caused by knive blades containing serrated (Fig. 3g) or straight (Fig. 3h) edges.

Temporal shape stability for our test objects turned out to be crucial. We compared 3D scans taken at different moments along the time axis, and we compared the real objects' appearances with 3D surface scan details using meticulous time consuming stereomicroscopic inspection. Real skin samples showed to be subject to considerable intra-object variation in their appearance across time (see Fig. 2); shape stability, however, is a hard requirement for testing [46].

So we used two [46] solid benchmark objects: a region of the nasofrontal bone surface of a sheep skull (Fig. 1a) and a washed sandstone conglomerate with quartz inclusions (Fig. 1b). The skull was modified with countersink drillings, boreholes, scratches, and felt pen marks; both objects contained a range of shape features typically encountered in forensic skin pathology such as fractal granularity or roughness, holes, scratches and highly reflective patches, all sized well into the sub-millimeter range of sizes. Also, shape convexity matching macroscopic curvature of ears, hand or feet was represented.

2.2. *3D scanning*

2.2.1. *Device description*

We employed a QTSculptor PT-M1280 surface scanner by Polygon Technology (Darmstadt, Germany). The scanner projects collimated

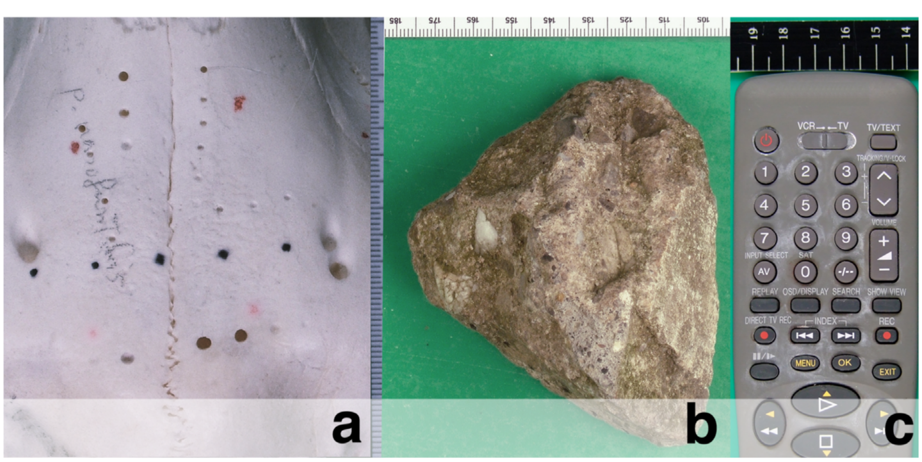

Fig. 1. Benchmark objects used: (a) photo of a sheep's skull containing small intrinsic bone surface features and tool marks, including add-ons such as boreholes, countersink drillings, red and black felt pen marks. (b) Photo of a sandstone conglomerate featuring different inclusions, some of dark light absorbing quality, some highly reflective. (c) Remote control as example of an industrial surface; in addition, it was coated with white anti-reflective spray (partly wiped off after 3D scan and before photography). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)