LOW-COST CRIME SCENE MAPPING:
REVIEWING EMERGING FREEWARE, LOW-COST METHODS OF 3D MAPPING AND APPLYING THEM TO CRIME SCENE INVESTIGATION AND FORENSIC EVIDENCE

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Declaration

I declare that this thesis does not contain any material submitted previously for the award of any other degree or diploma at any university or other tertiary institution. Furthermore, to the best of my knowledge, it does not contain any material previously published or written by another individual, except where due reference has been made in the text. Finally, I declare that all reported experimentations performed in this research were carried out by myself, except that any contribution by others, with whom I have worked is explicitly acknowledged.

Signed:

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A Literary Review

Abstract

Within the realm of 3D mapping, three technologies dominate; Laser, which excels at long range measurements with relatively high accuracy; Structured light systems, which excel at short range measurements at very high accuracy; and Photogrammetry, which uses only photographs, and can vary heavily with accuracy. Forensic science often utilises laser technology in a surveying role, however the other two are more specialised and used far less often. A barrier to greater use of 3D scanning and recreation is the generally large cost of the devices, some costing more than $100,000.

Microsoft Kinect brought an infrared camera to the market as part of a gaming console, the Xbox. This camera functions as a mid-range structured light camera, and modified to map and measure a 3D environment. Kinect sensors are low-cost alternatives, and because of their higher accessibility, development of this technology is faster. Additionally, the development of more sophisticated software, and computational power has meant that photogrammetry has also become far more accessible, requiring only a moderate to high quality digital camera, and the accompanying program. These low-cost alternatives may prove to be invaluable for Police departments to attain greater evidence recovery in times of world-wide budget restrictions.

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Introduction to 3D Scanning

In the realm of 3D scanning, there are three currently utilized technologies; laser, Scattered Light Systems (SLS), and photogrammetry. All three produce a similar result: a 3D image of the scanned area that can be manipulated in certain programs, preserving a record of the area that can be viewed at a later date. All three technologies are being employed in currently available devices, with varying price points, and most come bundled with proprietary software for post-processing needs. As a general requirement, high end computers are required to process the data that is generated from any 3D mapping device, and a varying amount of time must be spent to manually process and manipulate the data before any final product can be produced that is visually coherent. All three technologies will be discussed below, with reference to currently available devices that utilize them. All 3D scanning methods require calibration of various parameters to ensure accurate results. In many commercial products, recalibration and certification is available to ensure ongoing reliability, and court room legitimacy.

Most systems require designated tracking points to stitch scanned information together, which often comes in the form of small stickers applied by the user that display differing patterns. This allows the software to have defined stationary points to base all other points from. In other systems, software can recognize naturally occurring areas within a scan as these defined points (such as the corner of a table), which is then recognized later in the processing phase to stitch multiple scans together. Simultaneous Localization and Mapping (SLAM) systems, which map as the scanner moves, use the latter method, and recognize features in real-time as the device moves around an area. SLAM systems are comparatively new, and have been developed as a result of improved technology and computing capabilities. The goal of this review is to assess the technologies utilized in different products, and assess the benefits of each, comparing the emerging low-cost technologies to longer-standing expensive options.

Viewing the 3D model

Despite employing different methods to obtain a 3D model, all methods present the data in the same fashion at some point in the process. Most commonly, this is referred to as a 'point cloud', and can be envisioned as a cloud of dots in 3D space, that condense in areas to represent solid objects (Figure 1). A point cloud viewed from very close may not appear solid, but when viewed from a distance shows the points as a solid surface. From this point cloud, further processing can develop the information into what is known as a 3D mesh (Figure 1). The reconstructed mesh is essentially an approximate minimum-weight triangulation to the point cloud constrained to be on a two-dimensional manifold (1). The mesh can be reconstructed at varying levels of detail (point spacing) to increase or decrease detail of the object. An increase in detail (reduction in spacing) will show much smaller differences in an object, at the cost of longer processing times, and a greater chance that errors will be visible (Figure 2) (2).

For more accessibility, mesh models may be imported into a game engine such as Unity®, which allows it to be directly interacted with via computer or video game controls, and even viewed through augmented reality wear such as the Oculus® Rift or HTC® Vive. In this capacity a scanned object, be it a small exhibit or an entire outdoor scene, may be captured, recreated, and viewed at a later date.

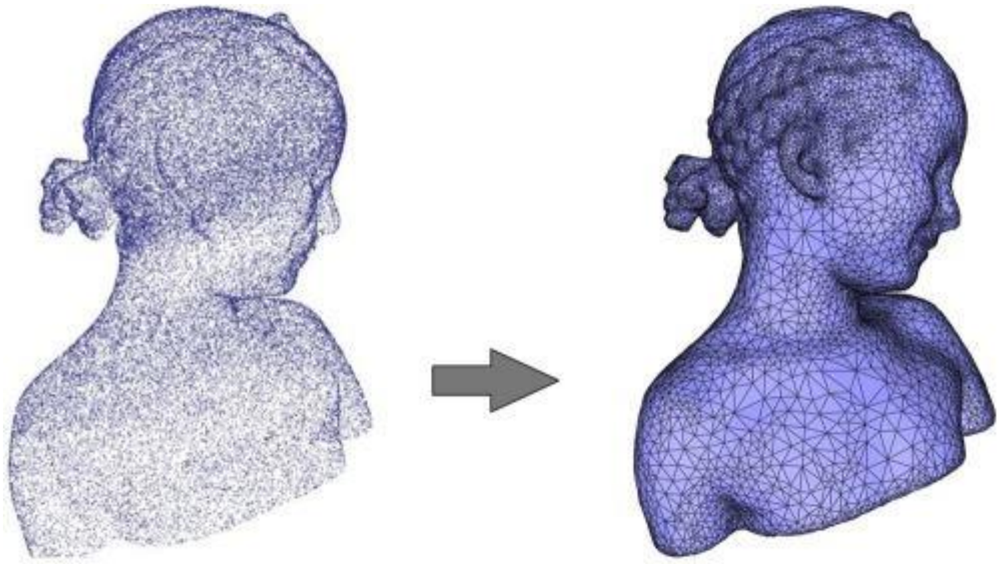

Figure 1. Point cloud to 3D mesh: Poisson reconstruction. Left: 120K points sampled on a statue. Right: reconstructed surface mesh (2)

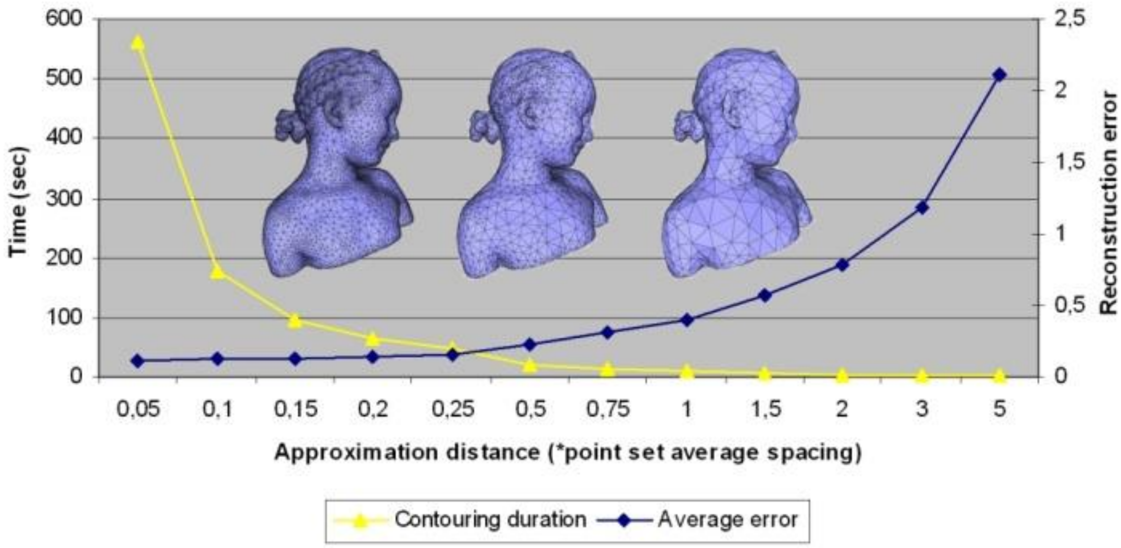

Figure 2. Varying detail of 3D surface mesh. Contouring duration (seconds) and reconstruction error (mm) against several approximation distance parameters (2).

Laser Scanning

Laser scanning, also known as Light Detection and Ranging (LiDAR) or Airborne Laser Scanning (ALS) technology is currently in use in many professions world-wide, notably in meteorology[1], surveying[2], architecture[3], and mining[4]. Shortly after the invention of the laser, it was combined with radar's ability to calculate distance by measuring the time for a signal to return, and applied initially to meteorology for cloud measurement (3). Laser scanning technology has been refined for use in numerous fields and is often mounted to aircraft for mapping and scanning, however this review will be focusing on terrestrial laser systems (TLS) due to the applicability to crime scenes. TLS devices project a class 1 laser, which is deemed safe under all conditions of normal use (4). Class 1 lasers are not visible to the human eye, and pose no danger unless viewed through magnification lenses. The greatest benefit of laser scanning systems is their range, which is far greater than SLS or photogrammetry, and can travel and scan hundreds of meters from the source, varying with the system (5). Other benefits include density and accuracy of measurements, with high automation and fast data delivery times, with the disadvantage of cost and lack of manoeuvrability (5). Laser scanning is also unaffected by light level in a scene, and can be used in both day and night scenarios. Low lighting does affect the colour registration by any complimentary RGB (red, green, blue) cameras, and visibility of any objects in the scan, however accurate measurements are still able to be taken.

[1] YouTube: Cloud Physics Lidar – CPL [https://www.youtube.com/watch?v=QBIKUZAzRxk]
[2] YouTube: TOPCON Scanner.wmv [https://www.youtube.com/watch?v=_a_CE-pLfLs]
[3] YouTube: 3D laser scanning and architectural modelling [https://www.youtube.com/watch?v=FkVkisk9WXY]
[4] YouTube: 3D Laser Scanning – Underground Mine Mapping [https://www.youtube.com/watch?v=8HdgliagAds]

Most TLS devices in use today utilise a tripod mounted device, which sits stationary while the scan takes place, usually in the centre of the room. The device consists of a horizontally rotating head with sensors to pick up returning laser beams, with a central vertically rotating laser. The laser is emitted and returned in pulses of up to one million points per second, and on-board software collates the points into a point cloud. The scanner cannot see in a small circle around its base, nor can it see objects that are occluded by other objects (Figure 3). If the occluded area is important to the final scan, these areas must be scanned again by moving the scanner to a separate location that covers the desired area. Objects obstructed from many angles may be unable to be scanned by stationary laser scanners.

Handheld laser scanners tend to be targeted towards small scale item scanning for fields such as metrology and engineering, offering accuracies of <1mm, although are not designed to capture larger environments or scenes. The Zebedee scanner, developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO), is designed to be a portable handheld scanner. It achieves this by utilising the walking momentum of the user to generate differing capture angles of the device (6). The scanner is a small 2D laser mounted on a spring and held in the hand of the user, as it wobbles back and forward it creates a 3D image of the angles it can visualise, and stitches them together using a SLAM system[5]. Due to the relatively low-technology of the Zebedee scanner, it is a cheaper option to other laser scanners. The Zebedee scanner is already in use by Queensland Police (7) for crime scene mapping.

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[5] YouTube: CSIRO Zebedee 3D Mapping [https://www.youtube.com/watch?v=gKPp2MYBYX0]

Laser scanners have difficulty scanning through water due to the refractive nature of the surface altering the lasers trajectory (8). This has crime scene implications if there is evidence such as a murder weapon, or even a body, deposited under water (e.g. in a swimming pool at the home), that cannot be visualised from the scan (9). Like other scanning methods, Laser also encounters problems when scanning areas inclusive of a mirror, as the laser reflects off the mirror, and registers the reflection from object in the mirror as being behind the mirror (rather than in front of it). Errors like this can be dealt with in data processing by experienced users.

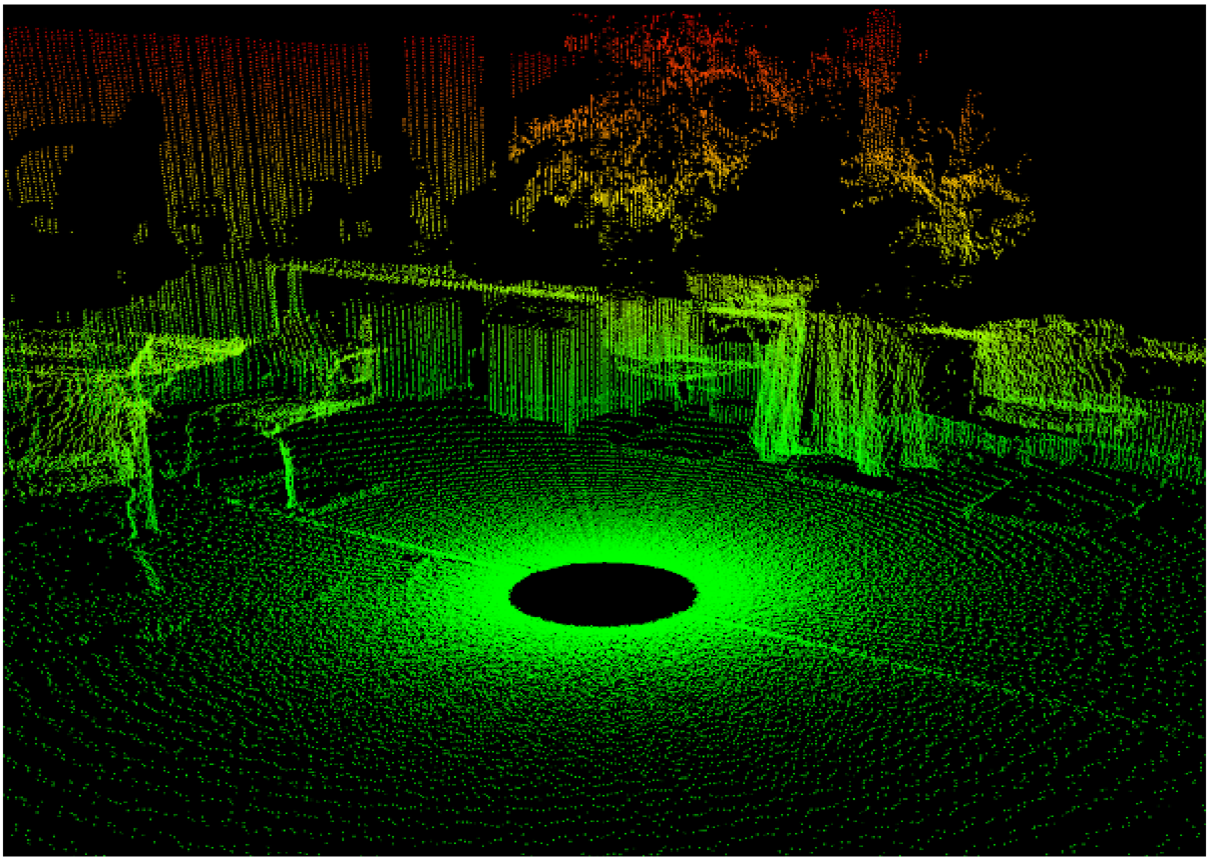


Figure 3. An example of the inside of a room captured with laser scanning technology (10) and displayed in a point cloud. Colours represent confidence in the point accuracy: Green for high confidence, ranging to red for low.

An emitted laser may not always return a single laser reflection. Any emitted laser pulse that encounters multiple reflection surfaces as it travels toward the ground is split into as many returns as there are reflective surfaces (11). The first returned laser pulse is the most significant, and will be associated with the closest feature in the landscape to the laser emitter, if the surface is solid and non-reflective, this will be the only return detected. For an aerial laser scanner, further returns may indicate vegetation structure such as leaves and small branches, and the final returned point would indicate the ground, or a sturdy branch (11). Scanners capable of detecting multiple returns are able to use this data to assist in modelling the 3D environment, gathering more accurate models for vegetative scenes, or with reflective areas like road signs.

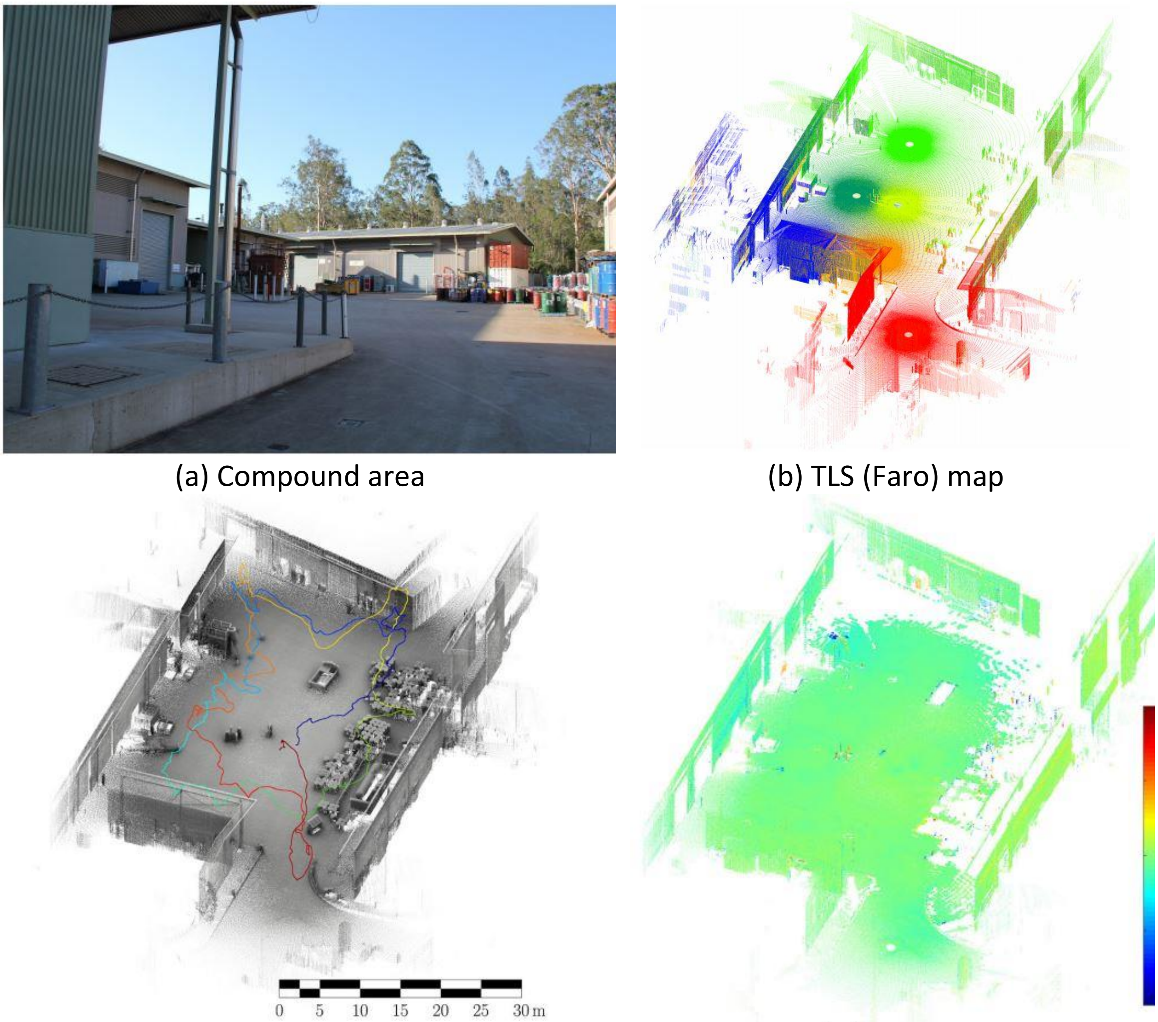
Further development of the technology and software utilised by the Zebedee system at CSIRO has led to the creation of an unmanned aerial vehicle (UAV) mounted laser scanner system, capable of accurately and clearly scanning outdoor environments relatively quickly[6,7] (12), known as the Hovermap. The system utilises a SLAM based system, running on the same software as the Zebedee handheld scanner. Being a SLAM system, it can be used in areas with little to no GPS coverage (such as caves and indoors) without losing accuracy due to poor reception or wobbling in flight. A large constraint of an aerial system is the weight restriction, meaning the Hovermap has been reduced to 1130g to be able to be carried by, and attached to any rotorcraft aerial vehicle (12). The integration of a drone-mounted scanner allows access to areas that could not normally be accessed by ground based stationary or handheld scanners, such as tall towers and the tops of unusual

[6] YouTube: The bentwing 3D Aerial Mapping System [https://www.youtube.com/watch?v=R7S1xXr3VMM]
[7] YouTube: Hovermap UAV lidar mapping payload – overview and examples [https://www.youtube.com/watch?v=aMiqxXpVEVc]

architecture. An additional advantage is that it also allows for low scan times of only a few minutes for large areas or buildings. The data can be easily combined with scan data from the Zebedee scanner as they utilise the same system, technology, and software, allowing for a high detail scan of the interior and exterior of a scene. The Bentwing scanner (previous iteration of Hovermap using same technology) was compared to a stationary tripod-mounted scanner, the Faro® Focus 3D, to scan the same compound area (Figure 4). The comparison showed that the aerial scanner was capable of almost no error when compared with the market standard, calibrated TLS (12). The scanning times differed immensely, with the Faro Focus taking close to an hour to scan at 6 separate points, and the Bentwing taking only 6.8 minutes flight time.

As technology becomes more compact and lightweight, aerial drone mapping is likely to become the most convenient and efficient mapping method, certainly for outdoor environments, and potentially for indoor environments as well.

CSIRO researchers are currently developing a new prototype of the Hovermap Scanner, utilising a new product from Velodyne (13), the Velodyne Lidar PUCK® (VLP-16), which has 100m range, 16 channels, and dual returns (14). Dual returns allow the Hovermap to more accurately map outdoor scenes with vegetation such as trees, while still showing a notable ground model beneath them. This advanced model has been tested by CSIRO, showcasing a dense point cloud model over a large area (Figure 5)



(a) Compound area (b) TLS (Faro) map

(c) *Bentwing* map (d) Error map

Figure 4. A comparison between Bentwing data and terrestrial laser scan (TLS) data acquired with a Faro Focus 3D. Note that the data were acquired months apart, and various objects in the environment were moved between the scans. (a) Photograph of the compound area captured approximately from the centre of the bottom-right (red) TLS scan in (b). (b) 3D point cloud of the compound composed of six stationary scans from a Faro Focus 3D TLS. The scans have been registered using the iterative closest point algorithm. Each of the six scans is rendered in a different colour. (c) 3D point cloud map generated with Bentwing, coloured using an ambient occlusion shading routine. The trajectory of the quadcopter is indicated and coloured according to time (blue to red). (d) The Bentwing point cloud coloured by error relative to the TLS data. Points from objects that have moved have been removed from the scan by thresholding the errors; however, some points near the boundaries of these objects still remain (and can be seen to have relatively high error values) (12).

(a)

(b) (c)

Figure 5. Hovermap prototype scan using VLP-16 scanner (a) Overview of large scene dense point cloud, (b) accuracy of defined sharp shapes showing little noise, and (c) dual return allowing for measurement of vegetation of ground below (13)

Market Technology

An example of a market TLS is the Faro® Focus 3D, although many other devices exist by other brands that encompass the same technology and basic build structure, such as the Trimble X8. The Faro Focus 3D boasts a range of 0.6 – 330m, with accuracy of ±2mm at furthest range, reducing with closer targets. The unit also features an inbuilt RGB camera, GPS, compass, height sensor and dual axis compensator (15). These features allow this device and others like it to log its position and compensate all measurements by any disparity in horizontal level. Each laser dot creates a point on the point cloud, which is then overlayed with the colour information from the RGB camera, and can be merged with other scans via the GPS coordinates, inbuilt software recognition, and manual user input. The Faro Focus 3D is currently in use by the Western Australia Police as their primary crime scene scanning device, while Queensland Police use the ZEB1 handheld scanner (9).

The CSIRO Zebedee scanner design is available as the ZEB1 from GeoSLAM (16) for ~$30,000, with a newer model known as the ZEB-REVO recently becoming available, for ~$44,000. Other handheld laser scanners such as the Polhemus® FastSCAN and Creaform® MetraSCAN offer an accuracy of up to 0.13 and 0.04mm respectively, however they have relatively small scanning volumes of up to 16.6m^3 (17). Creaform® offers numerous models of scanner for varying tasks with differing accuracy, scanning times and price points of around $20,000 to $100,000. The new prototype model of the Hovermap utilising the VLP-16 laser scanner are expected to be a purchasable product towards the end of 2017 (13).

Structured Light Systems

Structured Light Systems (SLS) are considered one of the most reliable techniques for recovering the surface of an object (18). The technique is based around the projection of a coded light pattern onto a surface or object, which can then be viewed by one or more cameras (Figure 6). Since the pattern is coded and known, correspondence between the known pattern and the viewed pattern indicate the shape of the surface, this variation is decoded, and the 3D information is obtained (18). Two major pattern projection types can be classified as fringe pattern and structured dots. Often devices also utilise an RGB camera to detect colour for the resulting 3D models.

(a) (b)

Figure 6. Example image of structured light reflected off surface (a) original scene, (b) thresholded gray-code image (19).

Fringe Pattern

A fringe pattern projection is a predetermined, and possibly proprietary pattern that is intentionally projected by the device. A number of differing pattern techniques exist, which vary in complexity from simple black and white stripes, to grey-scale pixel patterns (Figure 7), each with differing benefits and accuracy (18). Fringe pattern devices can offer accuracies of up to 0.03mm, far surpassing other technologies.

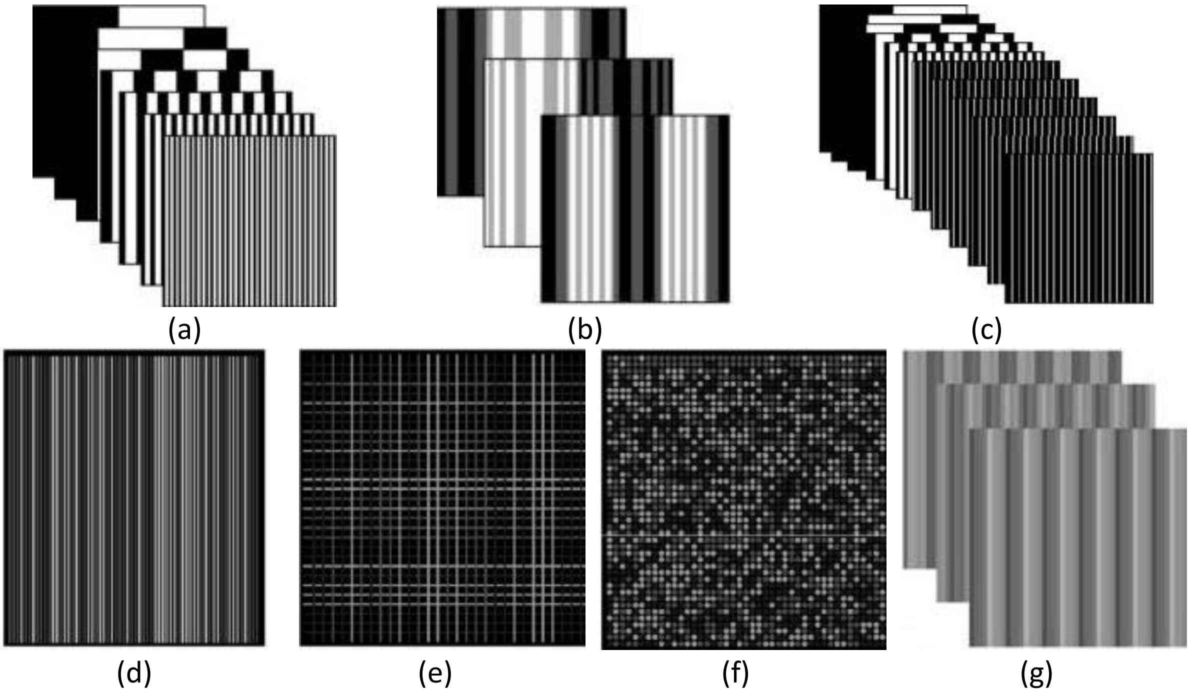
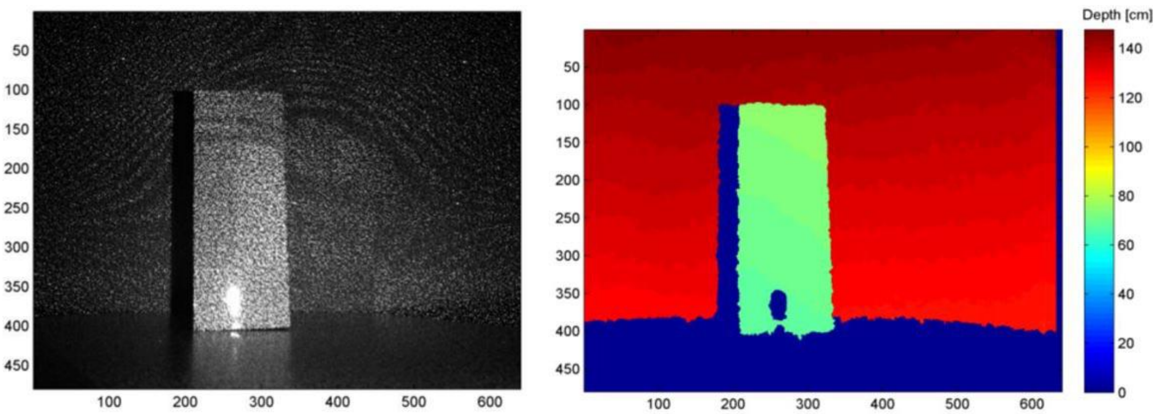


Figure 7. Patterns corresponding to the implemented techniques: (a) Posdamer; (b) Horn and Kiryati; (c) Gühring; (d) De Bruijn; (e) Salvi; (f) Morano; (g) Sato (18)

Structured dot - Infrared

Structured dot patterns are still a structured light pattern, however each individual device differs. The structured dot pattern that is projected is determined by a diffraction grating in front of the laser, and the individual diffraction that occurs from that lens (20) (Figure 8). Each device is calibrated against a surface of known shape and distance to determine its pattern. As a general rule, structured dot pattern units use infrared light, which means that the scanning is invisible to the human eye, and requires less power to project. Infrared is electromagnetic radiation at wavelengths of 700-1000nm (longer than that of visible light which is 400-700nm), and is emitted mostly as thermal radiation by objects and organisms in everyday life (21).

Structured dot SLS devices are generally quite mobile, as the combined emitters and receivers can be contained within small devices, and can be powered in some cases from laptop/tablet power supplies. In general, these devices do not seem to match up to the accuracy of Laser and fringe pattern SLS systems, however are far less expensive. Research has shown that the random error of depth measurement increases with increasing distance to the sensor, and ranges from a few millimetres up to about 4cm at the maximum range of the sensor. The quality of the data is also found to be influenced by the low resolution of the depth measurements (20)



(a) (b)

Figure 8. (a) Infrared image of the pattern of speckles projected on a sample scene, and (b) the resulting depth image (20).

One technology that makes depth scanning feasible is the wide availability of affordable depth cameras, such as those deployed in the Microsoft Kinect system. Microsoft's Kinect was primarily designed for natural interaction in a computer game environment: Essentially – a physical movement based video-game console. The characteristics of the data captured by Kinect have attracted the attention of researches from other fields (20). The Kinect is at the core of a new wave of research into SLAM technology, which has led to a number of papers being published over the last few years (22). Several datasets and benchmarks have been created to test and compare the algorithms used for SLAM systems, the most popular of which is the Technical University of Munich (TUM) benchmark dataset (23), founded by the University of Technology Munich in 2011. The TUM benchmarks can be utilised by other Kinect systems to assess the accuracy of their build, via set measurements and calibrations of motion capture, depth, and colour accuracy.

The technology has been used and tested in archaeology, with a Kinect scanner generating a 25m tunnel in 20 minutes for use in visualising a dig site (24). Some research concluded that it would be possible to build complete robot navigation and interaction systems solely based on a Kinect (25), which could lead to autonomous crime scene mapping, removing much of the risk of contamination. Using this technology in practice, researchers were able to scan up to 50m across environments to cm accuracy, with errors of around 1% (26). However, the Kinect SLAM system has mostly been evaluated for indoor environments rather than outdoor, as indoor environments contain more recognisable points to map. The system has been found to be able to robustly deal with difficult data in common indoor scenarios, while being fast enough for online operation (27).

However, researchers also discovered that Kinect based sensors suffered drastically higher error rates during night scans, highlighting the need for sufficient lighting on scenes (25). Scanning time has yet to be properly theorised, as the time spent scanning an object depends on the skill of the operator, as well as the objects complexity and surface, and the lighting. In a test of a Kinect based sensor, a 25m corridor was reconstructing with a SLAM sensor in 20 minutes, however better supporting algorithms may reduce time needed to scan. Future technology is still being developed to produce similar SLAM products, a notable mention is Google's Project Tango®. Project Tango is the inclusion of an IR based RGB-D scanning system in Google's new mobile phone hardware, turning a mobile phone into a small, portable 3D scanning system (28). The device is not meant to immediately replace existing 3D scanning technology, as it is understood that it cannot compare to the accuracy of other dedicated systems, however it is a promising future for the portability and accessibility of 3D scanning.

Errors encountered by Kinect-based SLAM systems can build up over long periods of scanning, which can culminate in distances being over or under measured by several cm after large volumes of scan data. This is solved by algorithms designed to create 'loop closure'. Loop closure is the analysis of each frame of data for frame-to-frame visual feature matching (25). The accuracy of the feature matching is dependent upon the algorithm used, but most mapping devices use some method of loop closure programming to complete scanning. Further research is being conducted on existing models such as 'Kintinuous' (29), to increase accuracy and add further features such as dense colour application and increases to processing speed (30).

Market Technology

An example of technology currently available in the market that utilises a fringe pattern SLS is the Artec® Spider. The Spider is a handheld scanner that uses blue light to project a pattern, then reads the pattern to determine the 3D data of the object. The Spider claims an accuracy of 0.03-0.05mm, however with such accuracy, the trade-off tends to be a reduced field of view (FoV): In the Spider's case, the FoV is 180 x 140mm, and a working distance of 170-350mm (31). Like any portable scanning device, the Spider requires a considerable power source, necessitating a portable battery pack for extended scanning, and considerable computational power for real-time viewing and post-processing. The Spider Scanner retails for $19200 from their website (32). Mantis® Vision F5 Scanner also utilizes fringe pattern SLS, as well as an IR camera for added depth measurements. The F5 is comparatively portable, however more expensive, retailing in the realm of $50,000 to $60,000 (Pers. Comm. Distributors).

The Faro® Freestyle is a handheld IR based structured dot system that utilises an IR projector, with dual IR cameras, and an RGB camera. The inclusion of two IR cameras allows the system to utilise triangulation between the two to further increase the accuracy of measurements. The Freestyle is relatively cheap in comparison to other devices, retailing in the realms of $7-10,000 (pers. comm. distributors). There is no technology available on the market that uses a Kinect based SLAM system, however the Kinect itself is available to be purchased from many technology stores, for $100-200, with multiple online resources for building the system (29) (33) (34). For a complete system, the requirements are a Kinect camera and attaching cables, a computer, and a power source. To make the system portable, the computer can be a laptop, and the power source a portable battery pack. A sufficient set-up would be very cost effective, purchasable for less than ~$1000, with the trade-off being self-assembly and installation.

Photogrammetry

Photogrammetry is a broader description of many types of photographic techniques to capture information, such as satellite, aerial and terrestrial photogrammetry. However, Forensic use will almost always utilise Close Range Photogrammetry (CRP) as a method, due to the distance and range required for police work. CRP is a technique representing and measuring 3D objects using data stored on 2D photographs (35). CRP encapsulates image measurement and interpretation in order to derive the shape and location of an object from one or more photographs of the object (Figure 9). In principle, photogrammetric methods can be applied in any situation where the object to be measured can be photographically recorded (36). The technique is relatively low cost, requiring only a camera and the Photogrammetry software for analysis. CRP is perhaps the cheapest method of capturing an object or area in 3D, when considering that any Forensic or Policing operation will already be in possession of appropriate quality cameras. Photogrammetry is also a cost saving measure as it can be conducted on historic or amateur images of a scene, requiring only processing time (36).

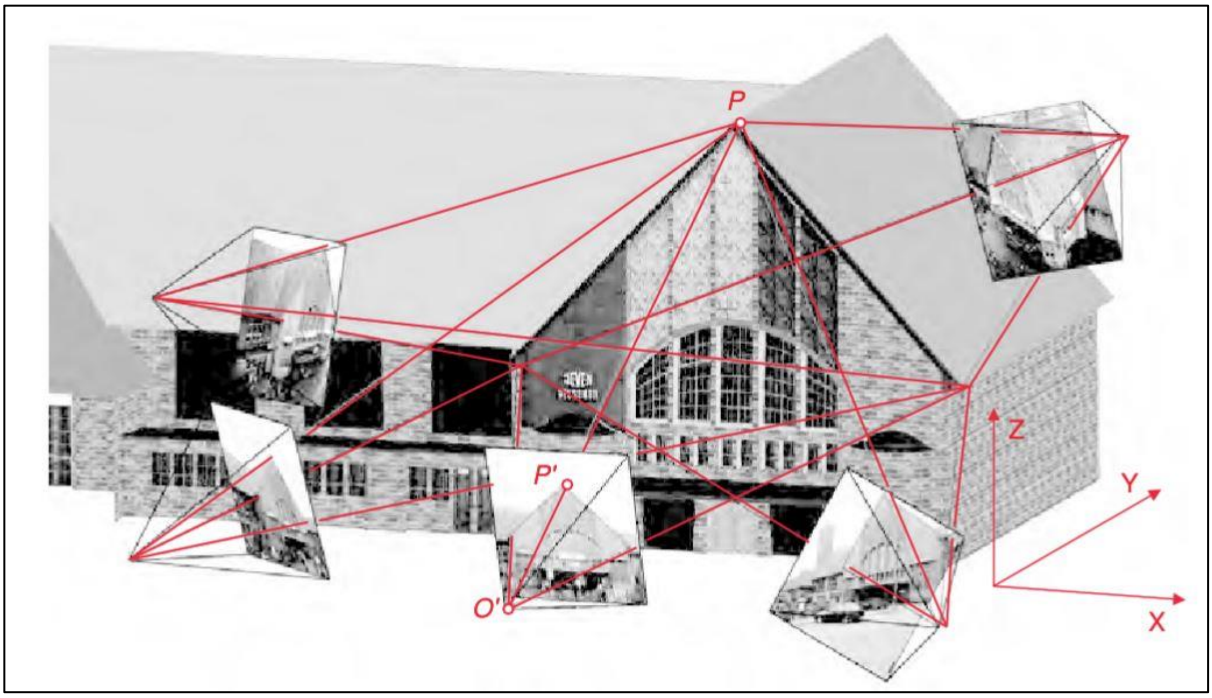


Figure 9. Principles of photogrammetric measurement (36)

The uses of photogrammetry are varied, and can be applied to almost anything in photographical evidence, which includes frames of a video if they are of high enough quality (known as videogrammetry, which utilises the same methods). It can be used for both the standard uses such as traffic accident recording and crime scene measurements, to more difficult measurements like estimating the height of criminals, reconstructing bullet trajectories, and even detecting environmental pollution from aerial imaging for corporate criminal cases (36).

CRP requires a scale in the images to determine the size of the object or area contained within the photos, which corresponds with standard forensic photographic practice. The software can then recognise the scale distances in the photographs, and scale the object accordingly. Accuracy of the resulting 3D output is determined by the quantity and quality of the photographic input. For best results certain methods and procedures need to be observed, and appropriate training undertaken before use, as it is possible that due to photographic mistakes, a complete 3D output may not be achievable. CRP, as with other 3D scanning methods, struggles with capturing highly reflective surfaces such as mirrors and polished metal, as well as refractive surfaces such as glass and water (36).

With newer aerial drone technology, including extended flight times, range, and camera portability, aerial photogrammetry is a potential solution for quick overall scene capture of extended outdoor environments. Currently numerous companies have used aerial drone photogrammetry to scan premises such as golf courses[8], farmland[9], and historic buildings[10]. There are currently a number of purchasable apps for consumers to utilise with their mobile phones or existing drones, as well as pre-package options, which include drones with appropriate cameras, software, and applications. Aerial drones have access to GPS systems, and can autonomously map flight paths and take appropriate photographs to create a finished 3D map. Scientific literature does show some use of aerial drone mapping utilising laser systems for cave mapping (37), and Construction and Engineering (38), however the forensic use of aerial photogrammetry does not appear to be documented. It is likely that it has been employed for this purpose, as the forensic application does not differ from any other, although when referring to accuracy of measurements, further mapping (non-drone) would be required for court-room precision.

Market Technology

Multiple photogrammetry software suites exist for the analysis of the photographs of a scene/object, such as Photomodeler® (39) and Photoscan® (40), and with advancements in technology and software, they require minimal knowledge or training to be usable. Each come with training tips to achieve the best possible results with their software. UAV mapping applications include DroneDeploy®, Altizure®, and FPV Camera®, with most being compatible with any mobile phone operating system or UAV. Drone prices differ dramatically by brand and retailer, but adequate UAVs can be reliably purchased for $1500–2000.

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[8] YouTube: Linden Golf & Country Club [https://www.youtube.com/watch?v=V_UYg_2iaW0]
[9] YouTube: NDVI Mapping with DroneDeploy – The Ag Scout Series [https://www.youtube.com/watch?v=TpWphckjhRw]
[10] YouTube: DroneDeploy Review – ArchiCopters [https://www.youtube.com/watch?v=ld2lAeaz6Vw]

Body

Mapping in 3D has already been utilized in many professions and specialisms, including forensic investigation. While not novel, the technology and use of it is still being developed, and being further specialised for different applications. Current uses for scanning and 3D technology in the field of Forensics include; bite mark reconstruction; impact pattern matching (41); Bloodstain Pattern Analysis (BPA); Scene reconstruction; Crash scene reconstruction; Footwear and tyre impressions evidence; and suspect identification and facial analysis.

Bite mark and impact pattern reconstructions

Forensic science often encounters bite marks and tool marks on the skin of victims. Matching these marks to the source using only 2D methods can mean that certain aspects of the comparison are either not visualised or left up to the imagination. The method presented in Figure 10 utilises 3D scanning of a recorded bite mark injury, along with a dental cast of the suspect (42). The manipulable nature of the 3D environment means that the elasticity of skin can also be simulated to conform to the expected impact position. For a victim that survives an assault, the injury will heal, and the tool/bite marks may change shape over the course of the healing. However, with proper capture techniques, the comparison can be done at any point post-examination (once a weapon or suspect teeth are found) without calling in the victim again. Similarly, if the victim is deceased, it eliminates the need to re-examine the body to assess any potential matches (41).

Using the same methodology as bite marks, a visualisation of the contact between a murder weapon, and the impact injury can be created (Figure 11), allowing for greater ease of comparison, and demonstration to a jury (41)

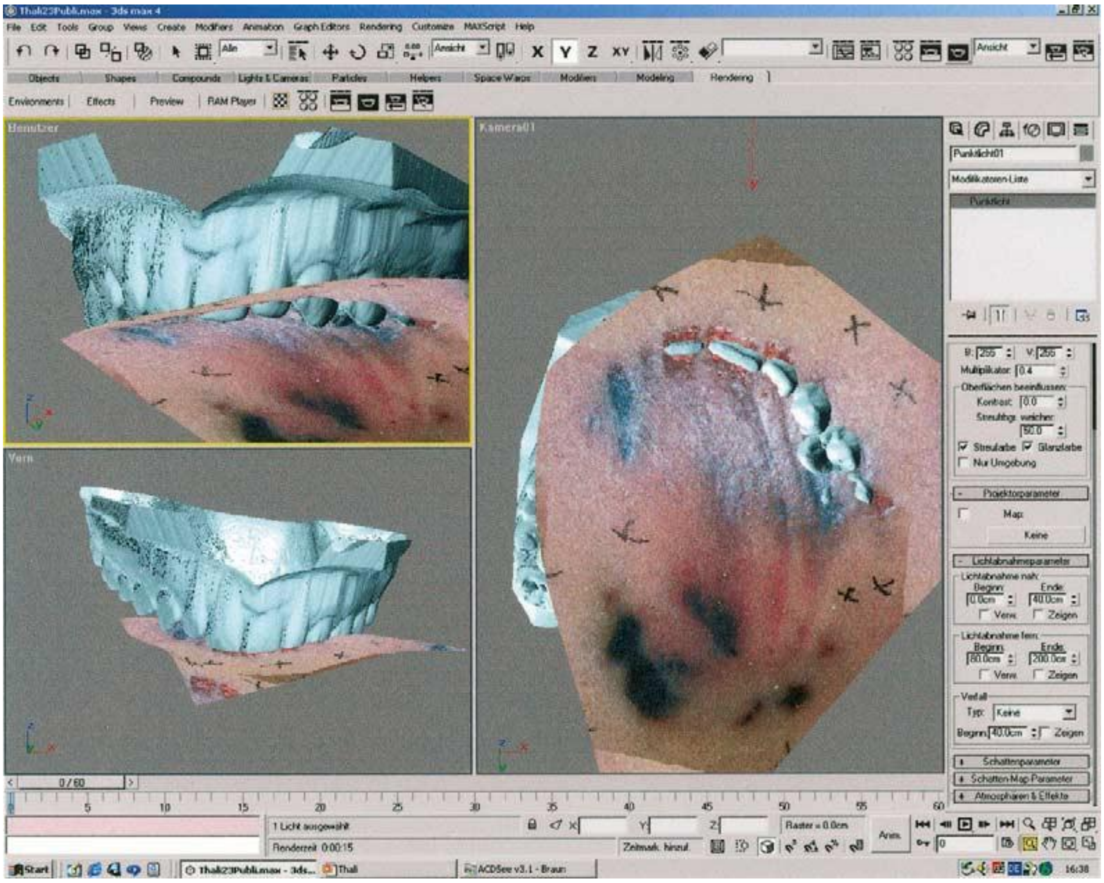


Figure 10. The bite mark and the digitised casts of the suspects were examined with respect to matching shapes, angles and dimensions in the 3D CAD programme. (43)

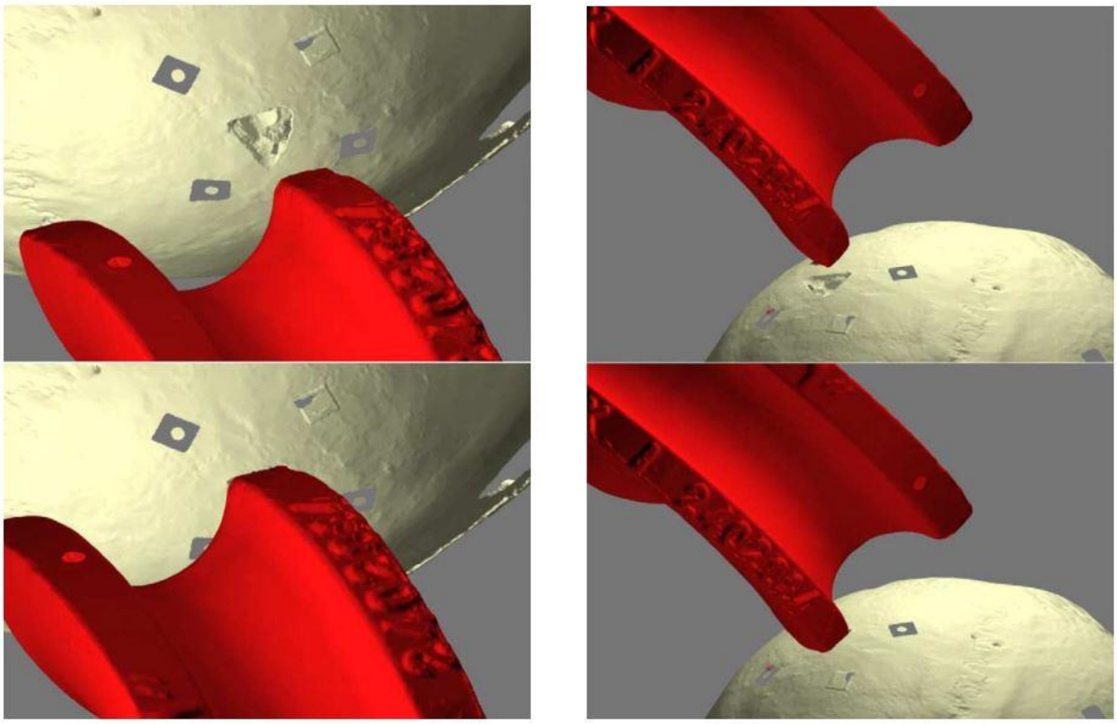


Figure 11. 3D visualisation of the match and the impact angle of the injury-causing tool with the two impression fractures (41)

Scene Surveying and Reconstruction

Proper documentation of physical evidence at both crime scenes and post-mortem examination is crucial for downstream analysis, interpretation, and presentation in court (44). The benefits of 3D evidence over conventional photography or mapping include the potential to generate accurate measurements of areas not measured at the time. Additionally, 3D scanners may be used on a crime scene to scan the boundaries of the scene, graves, footprints, impressions, fire scenes with delicate evidence, and even post-mortem injuries (44). Laser scanners are already in use around the world, and in Australia, with the Western Australia Police using the Faro® Focus 3D Scanner to produce complete crime scene scans. These scans can then be imported into a Computer Aided Design (CAD) program such as AutoCAD®, and recreated as a 2D floor plan for court room presentation (Figure 12) in poster format.

The accuracy of the laser measurements, and ability to view the crime scene as a whole element is crucial for understanding the scene, and is of particular use in organised crime (such as motorcycle gangs), where the use of fake walls in a house will be obvious when viewing the overall image and floor plan (9). Free software such as Google SketchUp® can also be used to recreate or build a 3D model of a crime scene (45) in the same way as AutoCAD® (Figure 12), however has the advantage of being freeware (46). SketchUp also offers an enormous online library of 3D models that can be quickly searched and imported into existing scenes.

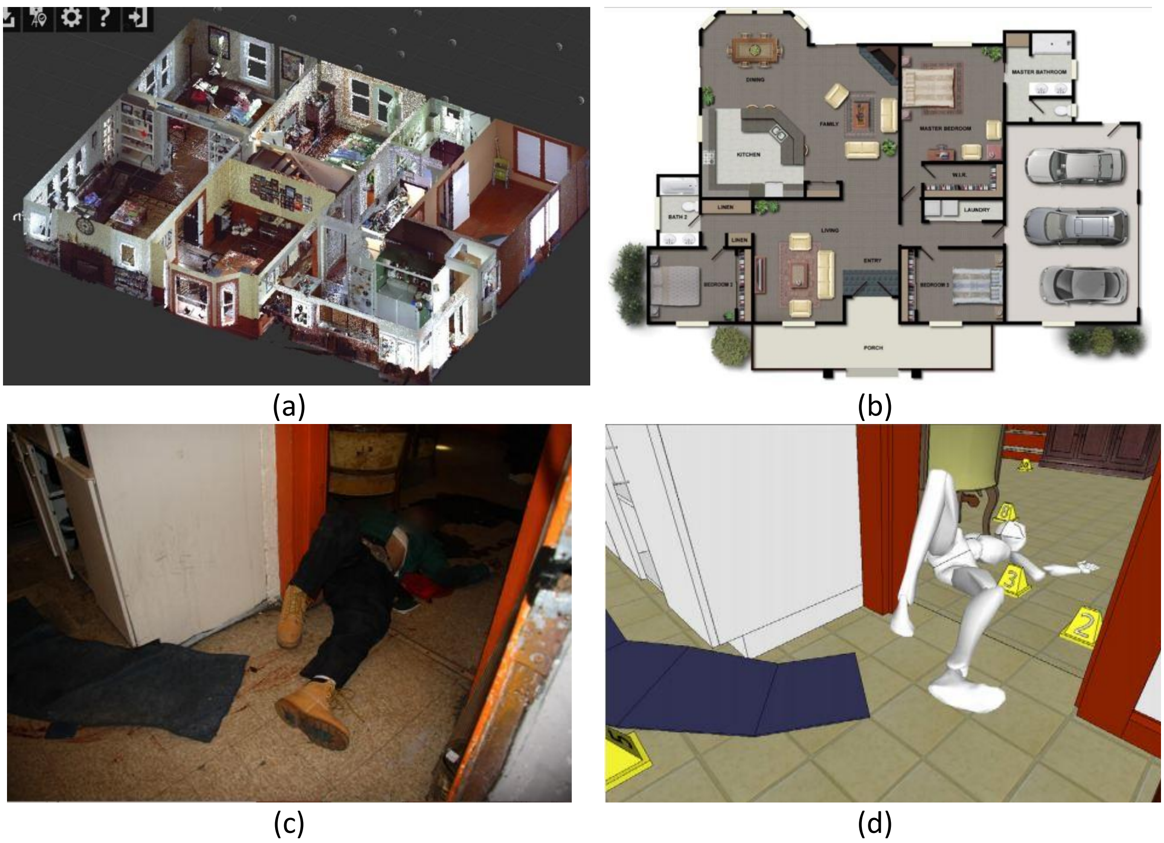


Figure 12. Example images of (a) Faro® Focus 3D scanned house, and (b) 2D Floorplan created in AutoCAD®, (c) Photograph of body from crime scene, (d) View within SketchUp® model corresponding with photograph

Scene surveying with SLAM scanners has been accomplished both on the ground and in the air. CSIRO's Hovermap scanner has been tested on mock crime scenes, clearly showing the environment, victim, and small objects on the scene (Figure 13) (13). However, smaller detail such as a screwdriver in the grass near the body, was not able to be picked up by the scanner due to the noise generated from the grass (13). New iterations of the Hovermap scanner, with dual return laser sensors, will make it easier to filter out vegetation, and be a valuable tool for the location of burial sites in bushland areas, or mass graves after wars (13).

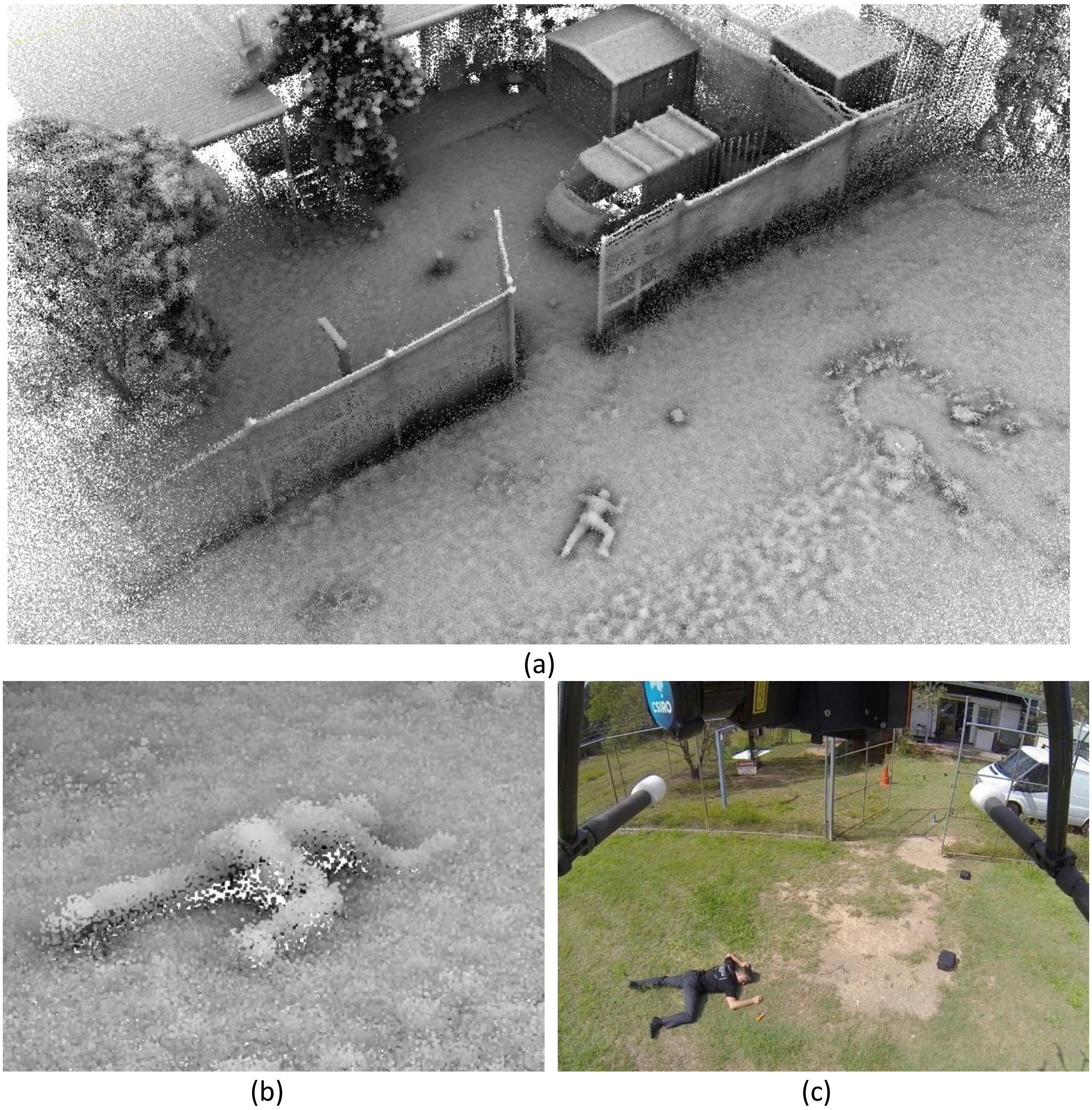


Figure 13. 3D environment generated by CSI developed Hovermap UAV-mounted laser scanner (a) overall scan of scene, (b) close-up of dot cloud of body, and (c) photograph view from UAV showing scene (13).

Footwear and tyre impressions

Many 3D methods have been used to document footwear and tyre impressions in crime scenes, and as 3D evidence, almost any method can be used to capture some level of detail. However, the fine detail of footwear impressions evidence may only prove to be useful if specific randomly acquired characteristics (RACs) can be identified (47). Differing 3D capture approaches and technologies can be applied to footwear impressions to capture varying levels of detail. Although unlikely to be applicable in Perth, footwear impressions in snow have been reliably recreated using a fringe pattern scanner, using methods suitable for impressions in soil, sand or other materials (48). This kind of data shows the possibilities of the 3D model, as it demonstrates notably greater clarity of detail than plaster casting (Figure 14, 15), while having no damaging impact on the original print. Furthermore, the 3D model can be compared to a 3D model of the imprinting shoe, and moved in a manner similar to how the print was deposited (Figure 13) (48).

(a) (b) (c)

Figure 14. Results of optical scanning of footwear impressions in snow: Accurate, high resolution 3D models. (a) The imprint causing shoe, (b) the ceramic plaster casting, (c) the optically scanned impression in snow (48)

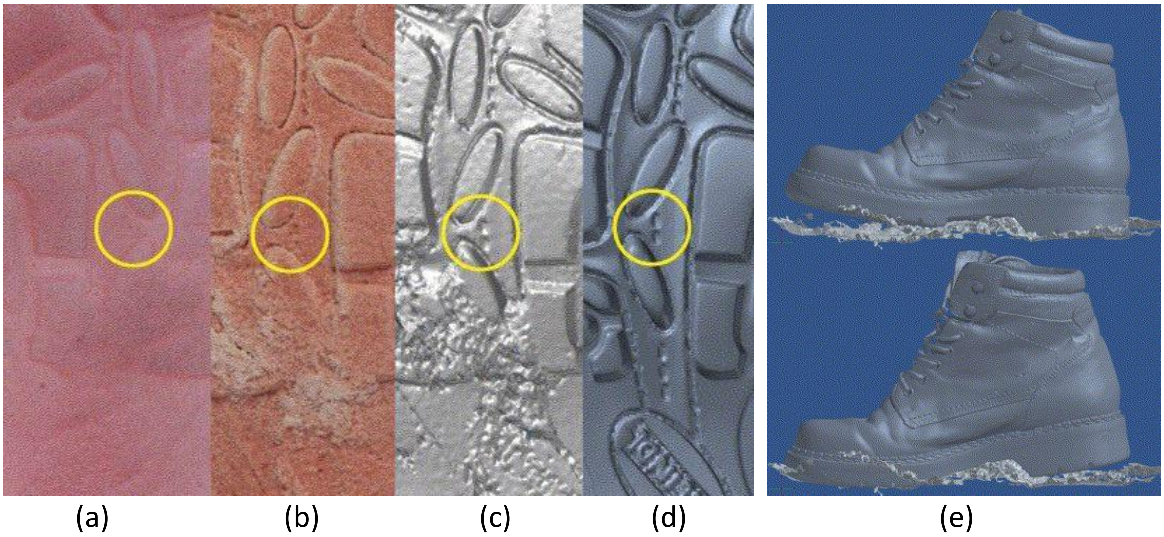


Figure 15. Appearance of fine details of 3D scanned shoe (yellow circle) from different methods: (a) Photograph after spraying impression with wax to increase contrast, (b) result of casting with ceramic plaster, (c) result of 3D surface scanning, (d) Digital 3D model of imprint causing shoe, and (e) reconstruction of the various positions of the shoe while walking on the ground with software (48)

Comparisons of impression scanning techniques between laser scanning and photogrammetry found that although there was a slight reduction in accuracy, photogrammetry was still able to produce highly accurate 3D models of outsole impressions (Figure 16), while taking less time to obtain the data on scene, and with fewer limitations of surface applicability (49). Western Australia Police utilise lighting and photography as the main tool for acquiring outsole impressions (9), recreating the impression with photogrammetry is a simple step, with no added cost.

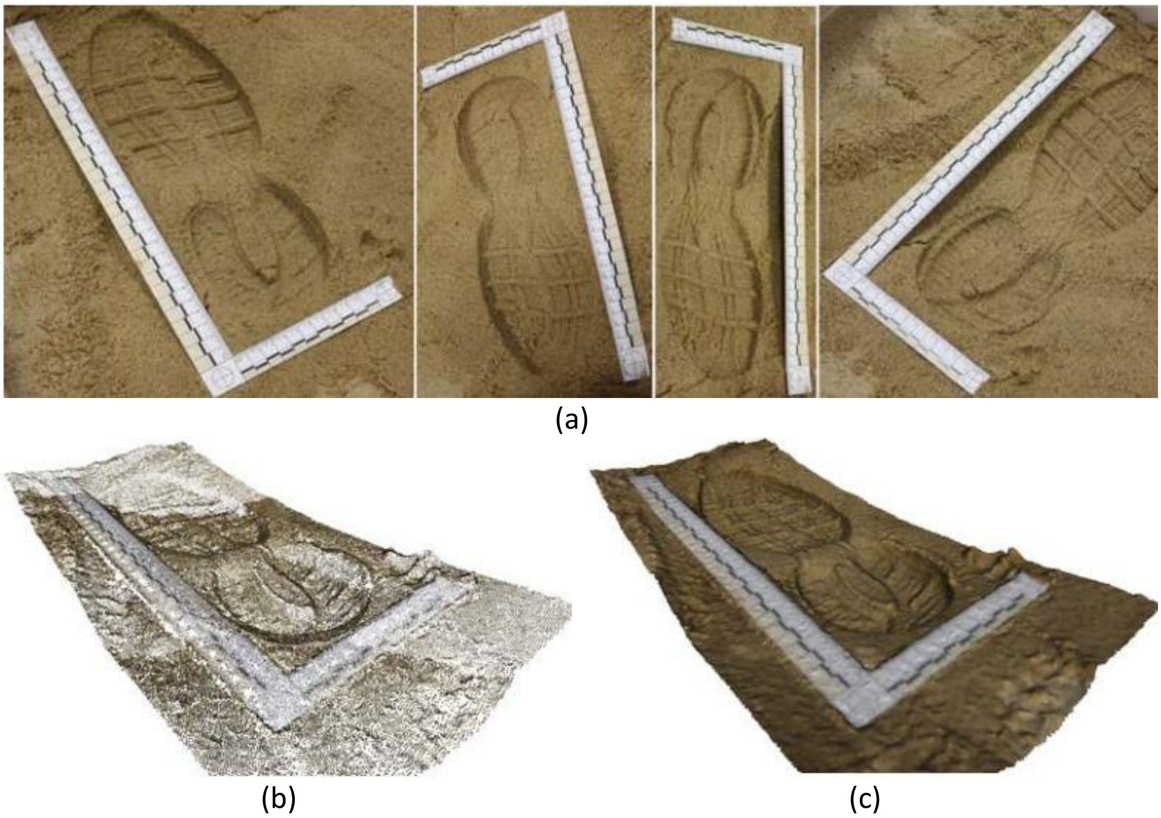


Figure 16. A photogrammetric reconstruction of an outsole impression in sand (a) input images taken on digital camera, (b) 3D point cloud generated from software, (c) reconstructed 3D model from point cloud (49)

Crash Scene Reconstruction

Crash scene reconstruction can be undertaken with both high cost Laser devices, or low cost photogrammetry (35). Both techniques are non-contact measurements, which can be undertaken at the scene. With the development of high quality cameras, much higher quality photogrammetry can be undertaken. A study this year has shown that photogrammetry can be reliably used to recreate a crash scene to cm accuracy (Figure 17) (35). Crash scene reconstruction can also be undertaken with Laser scanners, such as the Faro Focus 3D used by Western Australia Police to accurately scan a crash from all sides, including any length of road involved. A benefit of laser scanning devices is that, due to their range, they can be set up on the road-side, without the need to stop traffic. Additionally, due to the pre-set accuracy of laser measurements, no scene set-up is required such as the placement of scale bars or focus points, allowing for much faster data capture on scene. This is of particular use when scanning at a later date, when traffic has resumed. The resulting point cloud can be cleaned up to remove any 'ghost' images of passing vehicles.

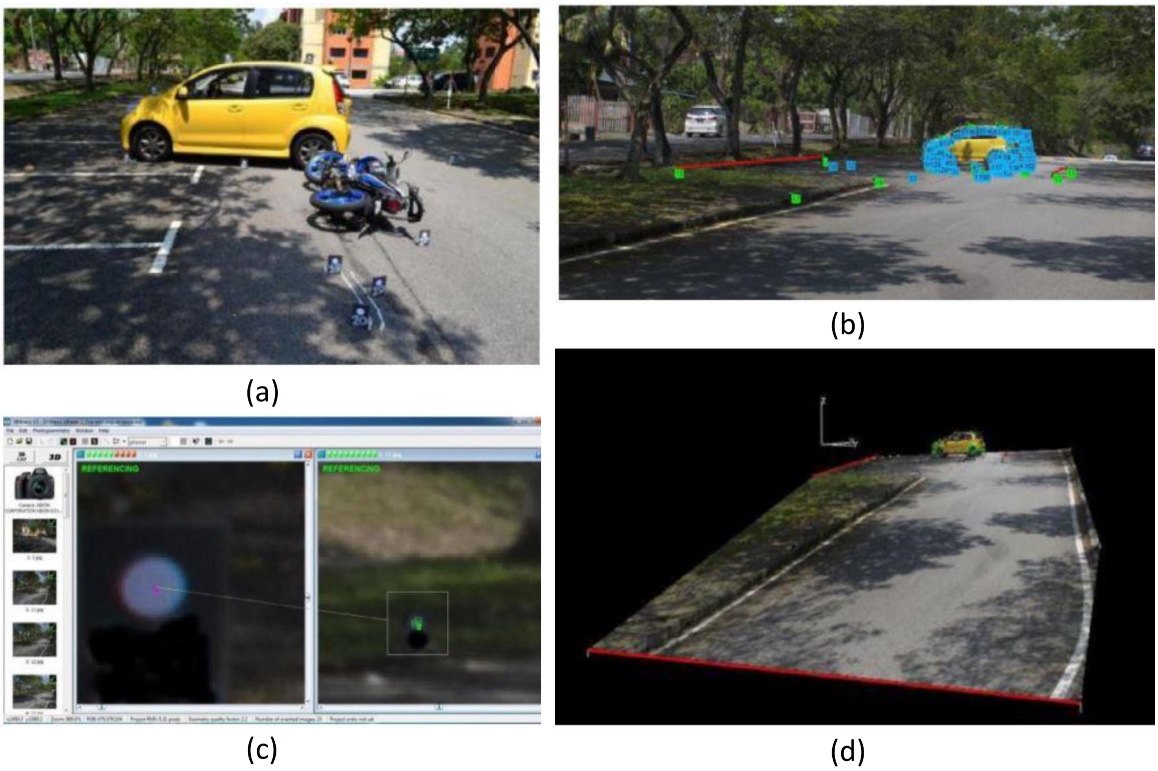


Figure 17. (a) Evidence markers on traffic accident scene, (b) Scaling distance, (c) Centroid determination function, (d) 3D modelling traffic accident scene (35)

Reconstructing the scene of a murder can be done completely within the 3D environment, eliminating the need for multiple personnel time on scene, and use of expensive equipment and clean-up. Two cases were reconstructed in 3D to assess the possibility of murder by intent or accident, which involved a gunshot in self-defence, and a reversing car crushing a woman (50). The scene information was captured by multiple technology types and imported to a 3D environment, where it could be manipulated to play out different scenarios, and compare damage caused. In the case of a gunshot, the body of the victim was scanned using photogrammetry and an SLS fringe pattern scanner, and the internal injuries defined with a Magnetic Resonance Imaging (MRI) scan. The environment was scanned using a TLS, and imported into a 3D environment, where all of the scans could be combined and manipulated (50). This combination of technologies for their best suited task is an example of a well-funded team working on a major crime such as Homicide, which may not be the case of many Police departments, and specifically when dealing with volume crime such as burglary.

Crime scenes can also be reconstructed in 3D where the originally collected material evidence is largely insufficient, in particular when no image of the crime scene is available, through the use of publicly available databases such as Google Maps, Google Street View and available construction and architecture archives (51). In a case study, researchers were able to reconstruct a scene in 3D using scans of the area, 3D models of actors, and historic plans to assess the accuracy of five different and contradictory statements of events. Reconstruction results must be interpreted with a degree of caution, as they cannot be an exact representation, and should not be the sole basis of a judgement in court. However, the method has been shown to work in narrowing down possible scenarios, and so is therefore still valuable (51).

Suspect identification and facial recognition

Skilled users can recreate facial structures in 3D modelling programs such as Blender® or ZSculpt®, which were developed, and primarily used for, modelling of video game characters (Figure 18). Programs like this require a skilled user to manipulate them with speed, and even with pre-set face builds, may take longer than traditionally drawn suspect facial reconstructions. However, the benefit of a 3D manipulable face that can be viewed from different angles and adjusted at any point would be a valuable tool for identifying persons of interest. Efficient face recognition has been achieved using 3D reconstruction techniques, from 2D drawings or images, which can then be manipulated into front and profile facing poses for computer recognition (52)[11]. Although unlikely to be a necessary technique during an investigation, a person may be scanned in specially constructed booths that utilise many strategically placed cameras to create a photogrammetric reconstruction of the person which can then be used in a 3D scene model.

Figure 18. 3D render of actor, showing body shape and facial profiles.

Worldwide there has been a push for police officers to begin wearing body mounted video cameras at all times, such as the popular GoPro® camera. This is largely due to public criticism in countries such as the USA, where Police brutality is perceived as unaccountable.

[11] YouTube: Jeremy Meeks (a.k.a handsome felon) Speed Sculpt [https://www.youtube.com/watch?v=Q-eWz5EynZA]

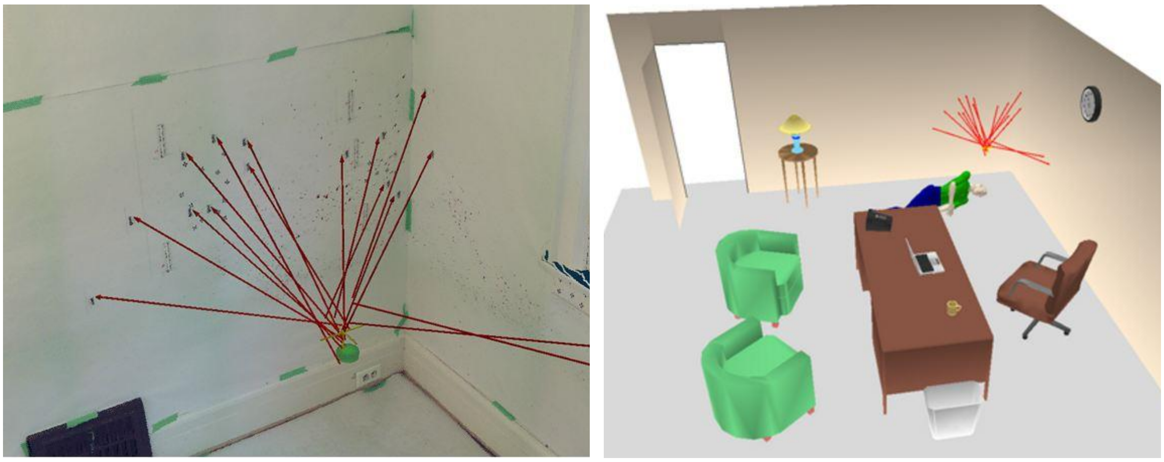
As the need for police accountability is spreading throughout the world, the effectiveness of body cameras is being assessed for other uses. Aside from benefits such as increased transparency, reduced police brutality, and reduced false claims of police brutality (53), there are hopes that body mounted cameras may be able to be used for real-time facial recognition.

Facial detection has advanced rapidly through recent years (54), with a specific focus on cameras present in smart phones and other mobile devices. Research has shown that new facial recognition algorithms can be trained to recognise additional samples incrementally over time (with an updated database for example), while using less computational speed than previous methods (55). No proof of concept has been done for real-time facial recognition linked with criminal databases through GoPro® type cameras. This is due to the rates of data-transfer needed from a body mounted camera to external computational software, as well as the refining of a database for use in particular areas for real-time results to be feasible. As an interim, the recordings of the camera can be stored temporarily on the device, and then transferred to a larger storage system either after each interaction, or at the end of shift, for comparison with known criminal databases (56).

TASER International ® are the most popular provider of police-mounted body cameras in the United States, which can offload storage to the cloud via accessible wireless internet, and although not currently able to, TASER plans to integrate this data with real-time facial recognition (57). TASER has announced their intention to roll out live-streaming capabilities in 2017, which in turn is monitored by facial recognition technology software with powerful computational speeds off-site. This technological development must be treated carefully in regards to public opinion, as privacy is becoming a very public concern (57).

Blood Pattern Analysis

Blood Pattern Analysis (BPA) has utilised 3D methods for accurately reconstructing blood trajectory for many years (58), with court validated software such as HemoSpat® (59) (Figure 19). Computer software like this has the benefit of being 3D evidence that can be manipulated in front of an audience to allow greater perspective of a scene, which cannot be delivered through photographs. 3D BPA evidence can also be integrated with 3D crime scene documentation to tell a complete story, and allow for easy visual manipulation of the event. HemoSpat® uses information gained from technical photographs of each individual blood-drop, which is then manually placed within the software. The software then analyses each drop to determine its trajectory, and builds a complete pattern reconstruction. The software requires these highly accurate photographs, as blood spatter a few millimetres in length may be the most appropriate for point of origin determination. This accuracy over a potentially large scale distance means that although BPA is unlikely to be able to be completed with a 3D scan of the event, it can be integrated with photography based measurements to give a visual effect of the event (Figure 19).



(a) (b)

Figure 19. (a) HemoSpat® data imported into 3D model viewing software CloudCompare® and aligned with 3D scan of event, and (b) HemoSpat® data imported into manually generated environment in The Crime Zone® software (59)

Conclusion

In the 3D mapping field, there seems to be a certain technology standard across all fields: In short this is TLS devices such as the Faro Focus 3D®. These devices are most commonly used as they are able to be purchased in a complete kit, with calibrated (and re-calibratable) sensors to a certified accuracy. Newer versions of TLS units are much lighter and more portable than older models, being easily able to be transported, set up, and packed down by a single operator. Newer models also have options like carbon fibre builds to drastically reduce the weight of tripods, boxes, or other accompanying items. TLS devices however are very large-scale, and not useful for mapping small exhibits such as murder weapons, injuries, or anything sub-centimetre scale. It is not expected that a single device or technology would be able to compete for superiority for all aspects of 3D scanning, as each have their benefits and drawbacks. Integration of multiple technologies and methods could lead to extremely accurate and complete 3D reconstruction of crime scenes.

Small scale evidence is best handled by traditional SLS scanners like the Artec Spider®, which show very impressive levels of detail in finished scans, however accounts of practical use tend to show that this level of detail comes at the cost of many days of scanning and data processing. It is unlikely that in any police department, multiple days could be justifiably dedicated to the processing of a single exhibit from a single case. SLAM scanners provide in some sense a middle ground between the far-ranging TLS, and the close-ranging SLS scanners. Able to accurately recreate a scene with multiple rooms and all evidence within, while being highly manoeuvrable and able to quickly capture all sides of evidence and exhibits within the scene. The development of a Kinect-based SLAM scanner is significant in that it provides a 'jack of all trades – master of none' solution, and is applicable to many fields of use. Due to its low cost and accessibility, Kinect-based SLAM scanners are the technology of choice for many researchers and because of this, the technology and its software are able to develop much more rapidly than other scanning devices.

One of the most significant advances in scanning technology has been done by the CSIRO, in its development of the Hoverwing. UAV mounted scanning has the benefits of a handheld scanner, but is not restricted by being attached to ground-level. This allows the scanning of much larger scenes, in far less time. The Hoverwing also brings with it great potential for further research in other fields, as there are many areas that would benefit greatly from being scanned that are simply out of reach. Though not a market device yet, the Hoverwing is unlikely to be a low-cost option, utilising expensive high-end scanning technology mounted on an industrial-grade drone. However, the on-scene time saved may prove it to be cost-effective over long-term use.

Current published research into the forensic application of Kinect-based SLAM scanners is almost non-existent. Although SLAM technology is present in much research, it has been based around the creation and modification of the technology. There have been attempts to recreate crime-scenes with SLAM based scanners, as well as many other scanner types, however these attempts have generally not been done in a scientifically measured manner, generally providing a proof-of-concept that it could be utilised by the industry. This study will attempt to compare the low-cost technology of both a Kinect-based SLAM scanner and photogrammetry, to existing expensive scanners such as the Faro Freestyle. The research will be aimed directly towards the capturing of forensic evidence such as body recovery, exhibit recovery, BPA and footwear impressions, using methodology employed by these forensic disciplines. A key driver of the research is the current funding deficit being faced by Western Australia Police, as well as Policing departments around the world. If newer technology can be created in-house at a much lower cost, then forensic departments may be able to capture evidence faster and more accurately than before, avoiding the cost barrier.

Ideally in the future it will be possible to utilise a single device to scan entire scenes in detail, with increased focus on smaller evidence types to capture minute detail. The final product would be annotated with information from the scene, and manipulated for presentation to a jury. A single device that can do this is not currently available, and is unlikely to be available for the foreseeable future. For the moment, it should be considered a possibility that all evidence on a crime scene that is visible to the eye, could be scanned and presented in a single 3D model. Using currently available technology, it is very likely that this single all-encompassing model could be created, and used to storyboard a crime, however would require access to multiple expensive scanner types, and some generous computational power.

Limitations

This review was limited in the information it could obtain from currently available technologies. Many new and developing products maintain proprietary control over any system information, to gain copyright and a market advantage. As such, much of the current market information is based off reviews, reseller information, and second hand specification sheets (hosted elsewhere to the manufacturer website). Along the same line, emerging technology is kept secret, so as to be the sole producer, and any developments leading to the technology may not be advertised in any way, nor be published in any scientific manner. It is likely that much of the future technology is grounded in science already published, however knowing what will develop is not possible from an outside perspective.

This review was also limited by information available to the public pertaining to current police procedures and technology. There is an understandable limit on the information police departments give out to the general public in regards to what techniques they employ and what devices they use, to restrict criminal counter-actions

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Part Two
Manuscript

LOW-COST CRIME SCENE MAPPING:
REVIEWING EMERGING FREEWARE, LOW-COST METHODS OF 3D MAPPING AND APPLYING THEM TO CRIME SCENE INVESTIGATION AND FORENSIC EVIDENCE

Abstract

New and emerging technologies have the potential to develop into low-cost alternatives for crime scene surveying, specifically: the Microsoft Kinect and photogrammetry. The Kinect is a very low cost infrared depth camera that can be used as a handheld scanner to map a crime scene, while photogrammetry utilises existing high quality forensic photographic techniques to create a 3D model of the area, or exhibit. These two technologies were tested against the Faro Freestyle (an existing market product) to determine how each could capture and display evidence commonly found at crime scenes. The Kinect based scanner proved to be problematic, providing low quality output, with relatively fast scanning, and was difficult to assemble and use. Photogrammetry proved to excel at capturing small detail such as outsole impressions in sand, however was inadequate for capturing scenes larger than a single room.

Keywords

Forensic science, crime scene surveying, 3D, photogrammetry, simultaneous localization and mapping, footwear impression evidence

Introduction

Surveying of crime scenes by forensic departments is dominated by Terrestrial Laser Scanners (TLS) such as the Faro Focus 3D®. These TLS units collect at a quick capture rate and provide high quality, and accurate data [1] with which to base a floor plan, or measure any distances post-scene. These units can cost in excess of $100,000, which can be prohibitive to police budgets. Newer, far more cost-effective technologies are developing that may be able to replace TLS units for scene surveying, or at least provide niche benefits.

The Microsoft Kinect® first emerged as an accessory to the Xbox gaming system, but its low cost has allowed further research to be conducted on the hardware, where more expensive laser technologies might not be feasible [2]. It has been utilised by numerous researchers as a Simultaneous Localisation and Mapping (SLAM) device, able to track objects and create a 3D map of its field of view as it is passes across an area [3]. However, this system has no market product, and must be constructed and programmed by the user, and requires some computer and software coding experience. Conversely, the process of photogrammetry requires nothing more than a high quality digital camera (such as those already in use by forensic personnel), and the accompanying software. This study used Agisoft Photoscan® to process the images, although other software is available. The Faro Freestyle® is a handheld infrared scanner like the Kinect, however is a market product, and able to be integrated with data captured from Faro's TLS, the Focus 3D®.

While these three technologies have been studied and used for 3D mapping, their use in forensic science, and processing of crime scenes has not been thoroughly examined and compared. This study aims to test the limits of these technologies in a crime scene setting, and to determine their effectiveness in their current state, and future potential. The purpose of this study is to determine whether these technologies are feasible, and if they can provide some added benefit to currently utilised TLS units. If so, can they be incorporated into specific forensic disciplines, and what benefits could they provide.

Materials

The following materials and their costs were sourced for the relative technology tested (Table 1). Costs such as a high quality digital SLR and a laptop are not included as it is assumed that Forensic departments will already be in possession of these items.

Table 1. Materials and costs for the creation of assessed low-cost technology.

Scanner	Item	Cost
KBSS	Kinect Camera, with USB connector	$205
Photogrammetry	Agisoft Photoscan® Software	$180
Market Scanner	Faro Freestyle®	RRP ~$18,000

The Kinect Based Slam Scanner (KBSS) was created by installing Kinect v2.0 SDK in conjunction with code for the D2D Kinect Fusion sample onto a Windows laptop. The installed code was compiled with Visual Studio 2015 for Windows 8.1. The Camera used was a Nikon D5500 Digital SLR.

The crime scene was created in a demountable building, adjoining a sandy and vegetative area. The room was garnered with evidence commonly found on a crime scene; corpse; pooled blood; impact spatter; blooded outsole impressions; murder weapon with impact spatter; fingerprints (enhanced with black powder); alcohol vessels (can and bottle); cigarette; and a sequence of four 3D outsole impressions in sand.

Methodology

The three technologies were chosen to display different areas of advancement in the field; The Faro Freestyle is the latest market product to aim towards the low-cost market, coming in at a fraction the cost of other handheld scanners; The KBSS is essentially a 'home-brew' type build from bits and pieces of hardware and software, for the lowest possible cost; and Photogrammetry is purely a software related advancement, that requires no hardware purchases or upgrades.

Evidence such as the body, Bloodstain Pattern Analysis (BPA), and outsole impressions were created with staggered evidential strength to assess the limitations of the capturing quality. The body was wearing blood soaked and torn clothes to assess if smaller blood patterns or individual fibres could be detected. The BPA included a large obvious pool on the floor, medium to fine impact spatter on the walls, and fading sequential impressions in blood to determine how strong the visual change was that could be detected. Evidence in 2D (BPA and fingerprints) was used simply to determine if accurate placement within the scene could be achieved, rather than as a visual enhancement assessment.

The 3D evidence was assessed individually, and more thoroughly. A sequence of 3D outsole impressions in sand was created, with some partial and obscured impressions included. For each technology, it was assessed if they could be tied together in a single scan, and if focusing on a single impression could garner an increase in detail if required. Some powdered fingerprints were included in the scene, but only as an exhibit placement assessment. The scene was initially recorded using traditional forensic photographic techniques for the relevant disciplines. Each item was recorded and measured in-situ to compare with measurements from 3D outputs.

For capturing the scene using photogrammetry, the camera was set to F.11, 22mm, ISO100 for overview photos, and F.29, 35mm, ISO100 for technical photos. While photographing the indoor area of the scene, the photographs were taken from the edges of the room facing inwards and aiming at chest height directly ahead. Once the room was circled in this fashion, it was circled again with the photographs taken facing downwards from chest height, and then again facing upwards. The body was photographed as part of the interior model, but also photographed separately using the same circling technique, from different heights. When photographing the outdoor scene, photographs were taken following the walls of the building, and following around each corner facing towards the building (Figure 1).

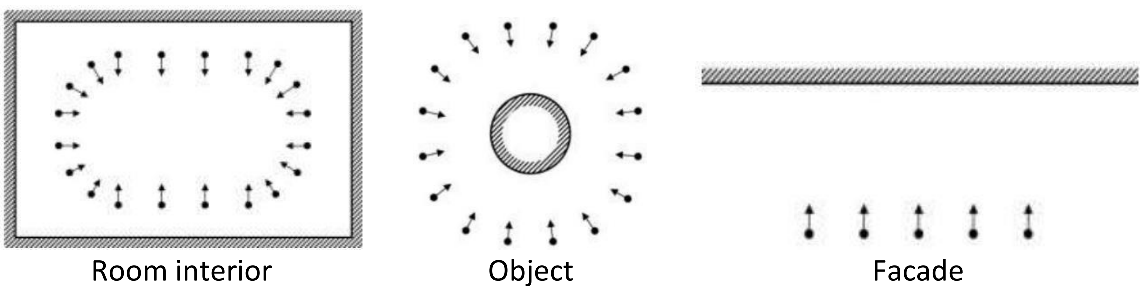


Figure 1. Photography methods for capturing evidence, dots and arrows indicate camera direction.

The outsole impressions in the sand were not targeted specifically during the outdoor run, but were instead photographed separately using a circling technique from different heights. Within each photographical set, a ruler of known distance was placed (1m for interior, exterior, and body scenes, 15cm for outsole impressions and blood pattern analysis) to allow for scaling during data processing. Once photographed, the images were imported into Photoscan®. Within the program the photos were aligned and processed into a dense point cloud, and scaled per the ruler in the model. A further test was later done with the camera set on automatic and not on a tripod, to determine if a quality model could be created using less stringent quality control.

The two handheld scanners were held approximately one metre from the scanned surface or object, and moved slowly and methodically up and down to cover an area before moving sideways to cover the next section, technique followed that of photogrammetry (Figure 1), however in one continuous movement. Individual evidence was scanned separately to avoid scanning volume errors. The Faro Freestyle® scans were scanned in small sections with 40-60% overlap to allow for the software to stitch scans together. Each evidential type was covered with multiple passes, and from multiple angles, to ensure capture to the best of the devices capability.

Results

The scene and evidence within are presented below in Figures 2 to 11 showing visual captures of the 3D model. Figure 2 (below) illustrates each devices ability to capture the interior and exterior of the scenes. The KBSS and Faro Freestyle were unable to capture the scene exterior.

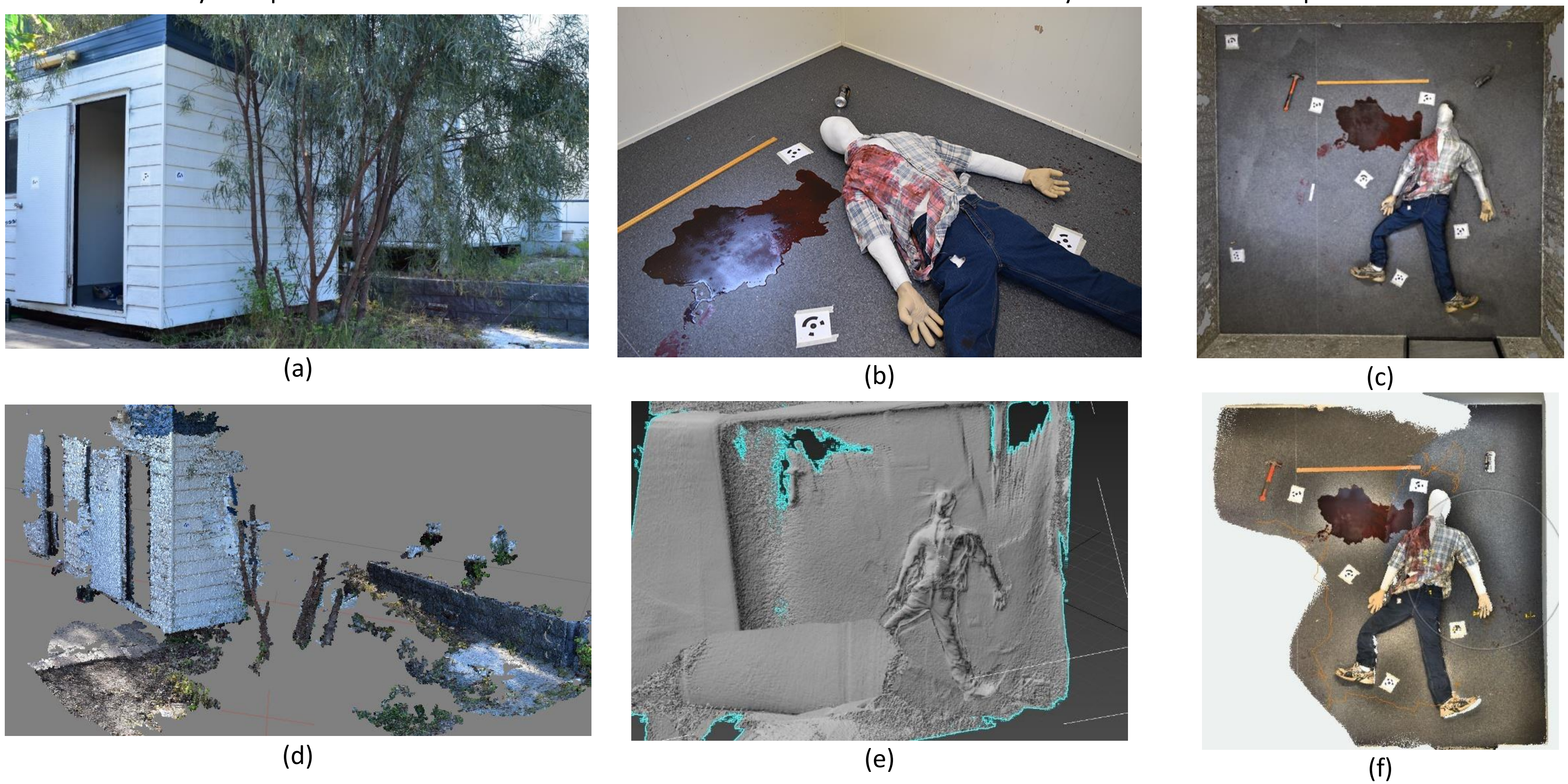
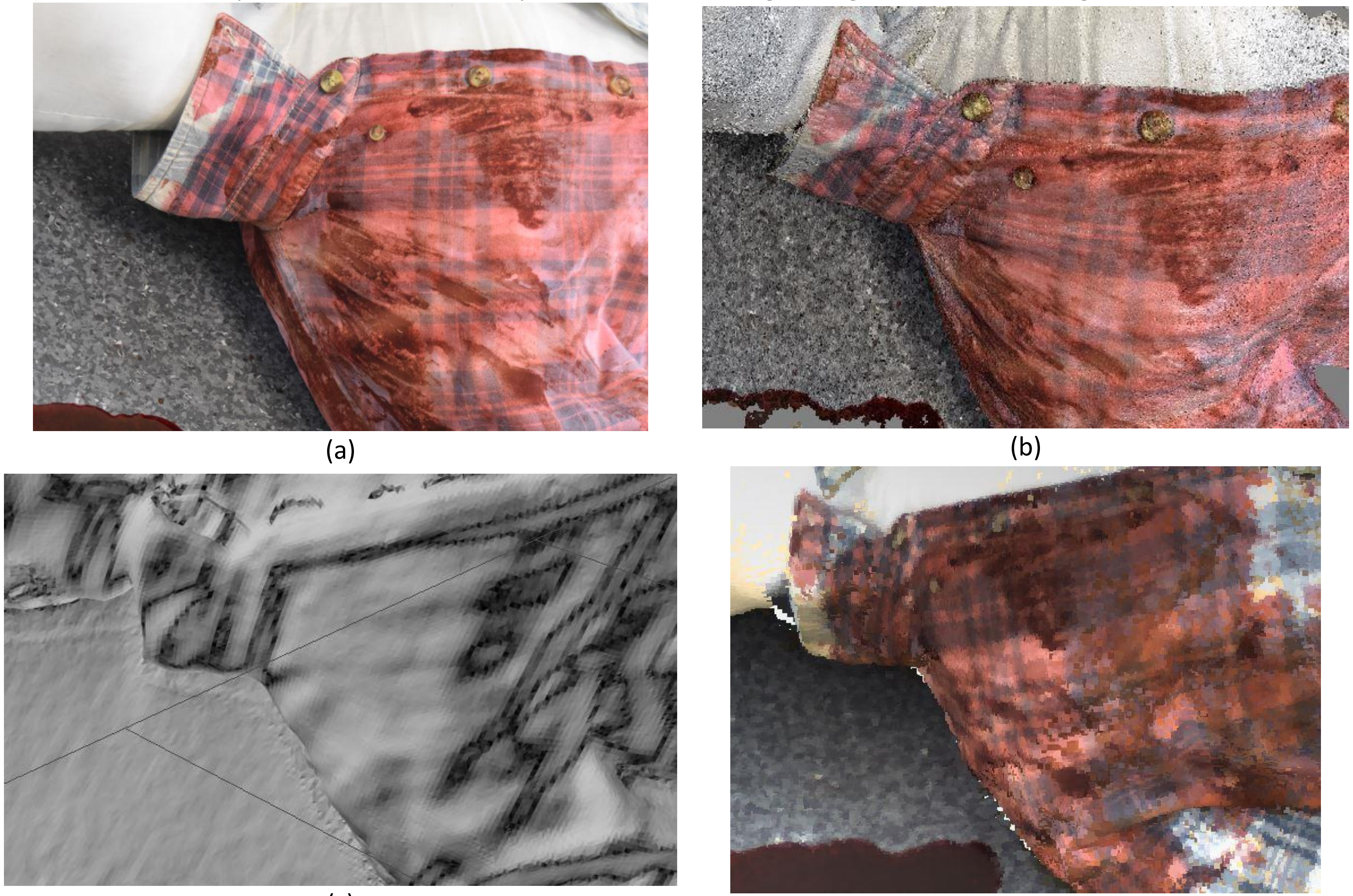


Figure 2. Scene Surveying results; (a) Digital camera photographs of scene exterior and; (b) scene interior; (c) Photogrammetry reconstruction of scene interior and; (d) Scene exterior; (e) KBSS reconstruction of scene interior; (f) Faro Freestyle reconstruction of scene interior.

Figure 3 (below) illustrates the capture of the shirt worn by the victim containing damage and blood staining.



(a) (b) (c) (d)

Figure 3. (a) Digital photo of close-up of blooded shirt 'wounded area' and reconstructions from; (b) Photogrammetry; (c) KBSS and; (d) Faro Freestyle.

Figure 4 (below) illustrates the 3D reconstruction of 2D evidence in the form of BPA and fingerprint impression evidence.

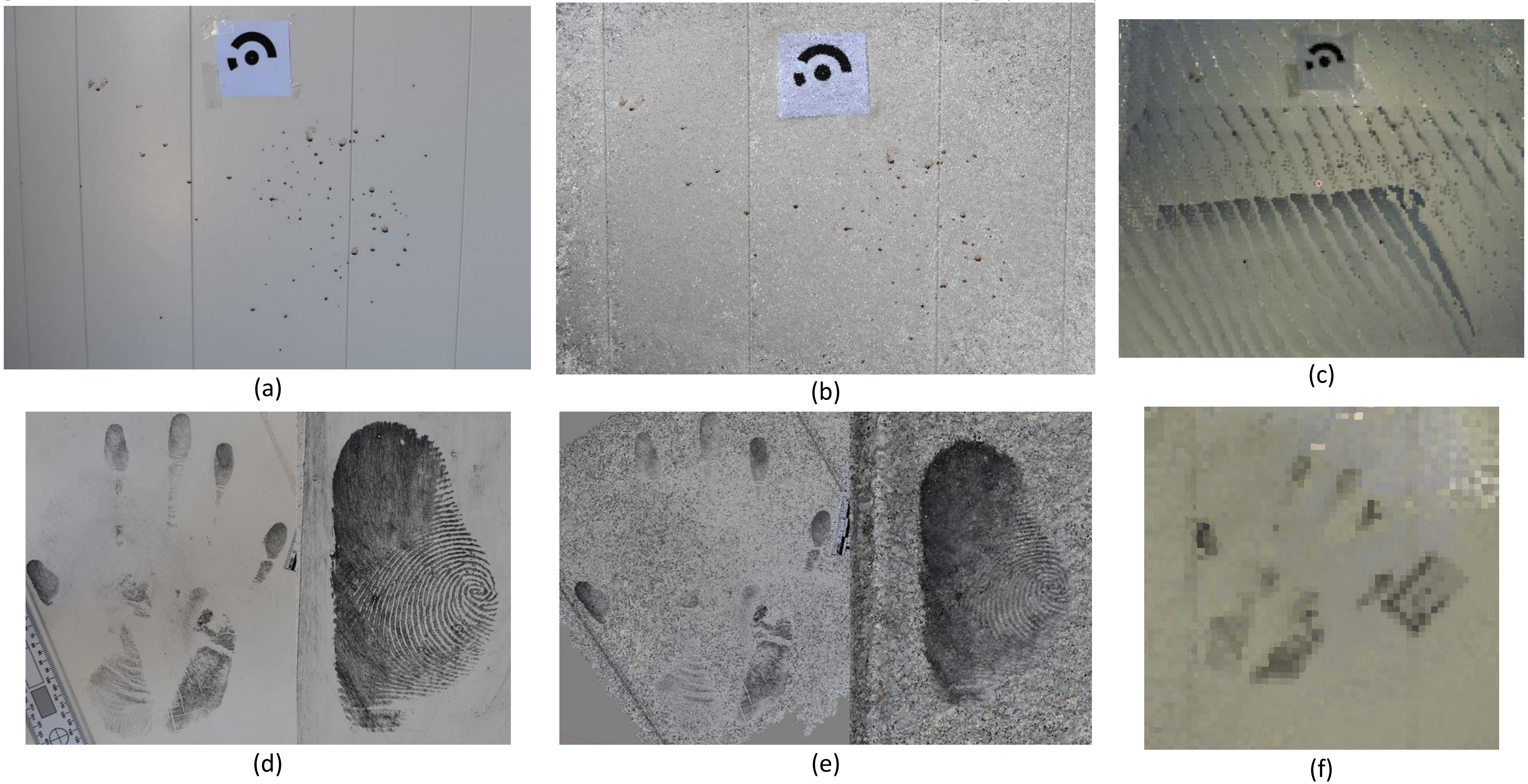


Figure 4. (a) Digital photo of 2D impact spatter (BPA) and reconstructions from; (b) Photogrammetry and; (c) Faro Freestyle. (d) Digital photo of dusted fingerprints and reconstructions from; (e) Photogrammetry and; (f) Faro Freestyle. KBSS returned no visual result.

Figure 5 (below) illustrates the bloodstained murder weapon, showing the shape and BPA present.

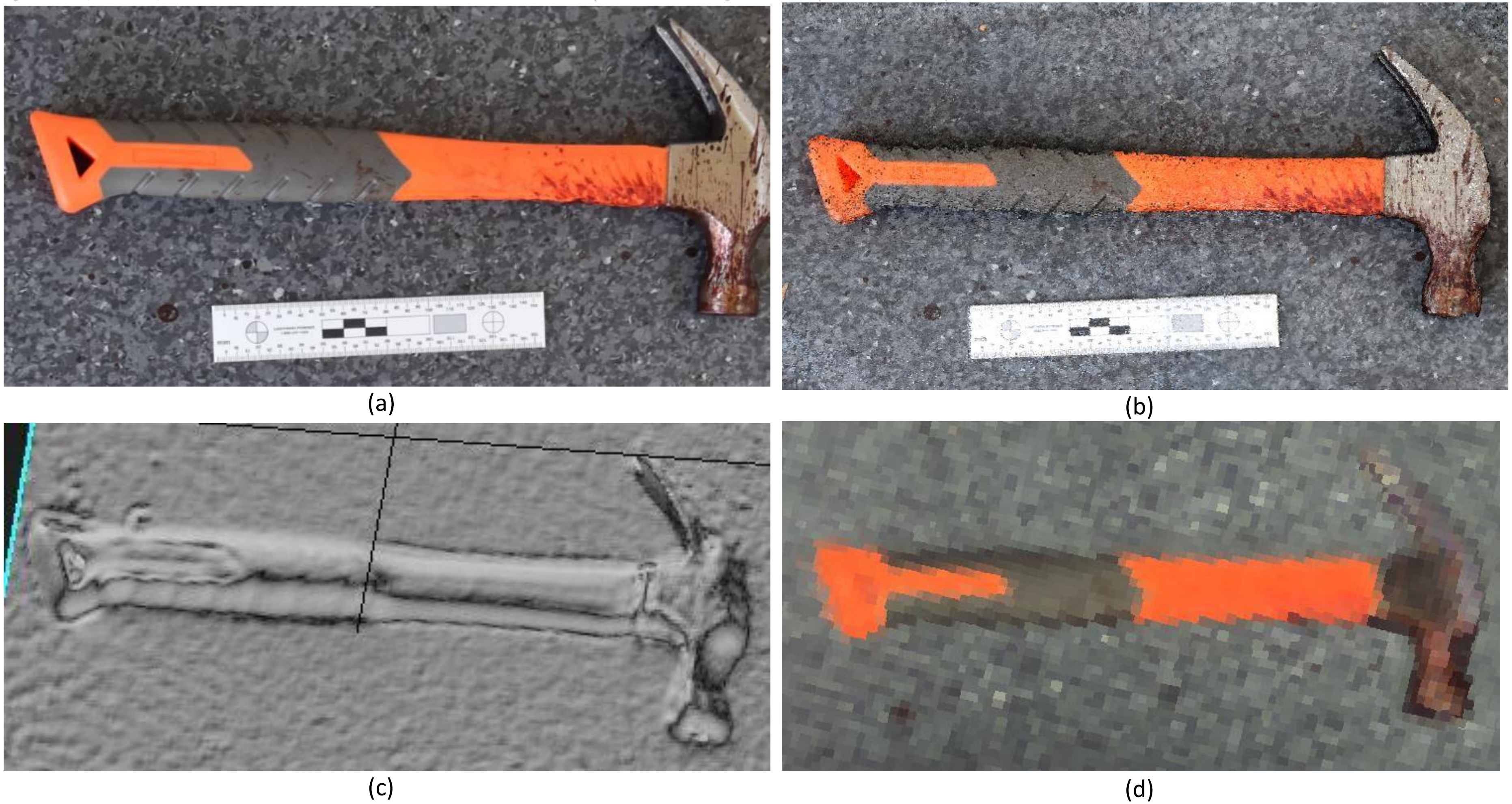


Figure 5. (a) Digital photo of bloodstained hammer exhibit and reconstructions from; (b) Photogrammetry; (c) KBSS; (d) Faro Freestyle.

Figure 6 (below) illustrates the capture of reflective alcohol can on scene.

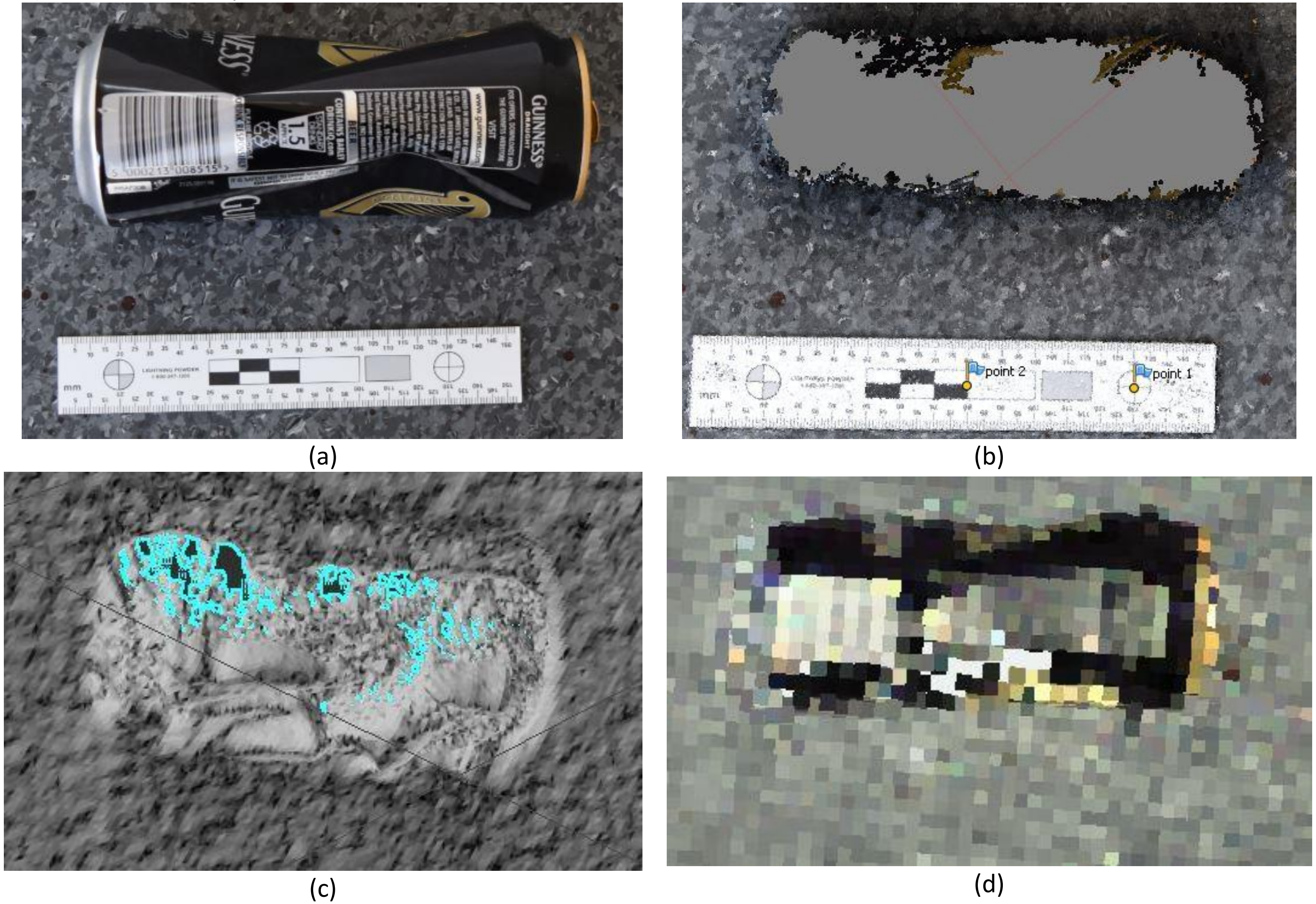
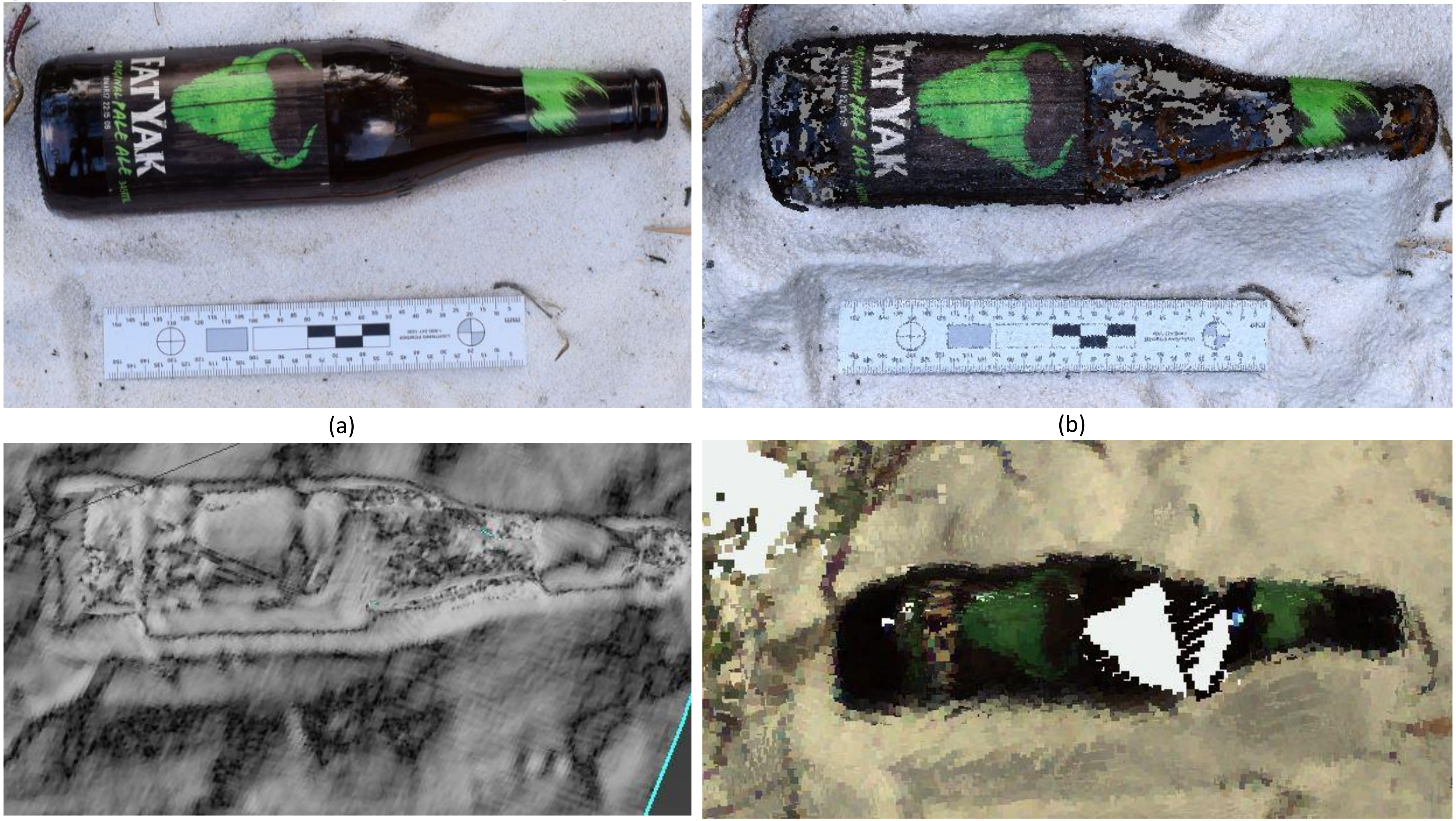


Figure 6. (a) Digital photo of beer can exhibit and reconstructions from; (b) Photogrammetry; (c) KBSS; (d) Faro Freestyle.

Figure 7 (below) illustrates the capture of the reflective glass alcohol bottle on sand at the scene exterior.



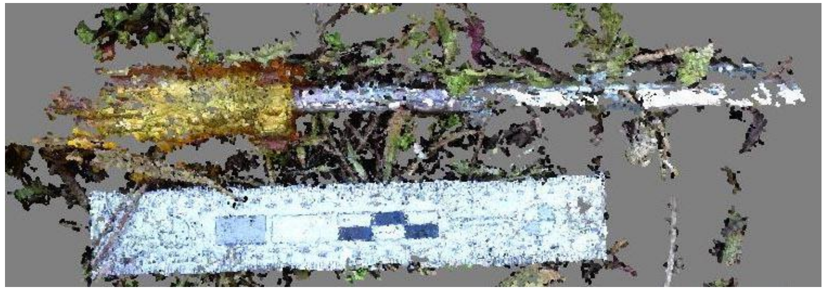
(a) (b)

(c) (d)

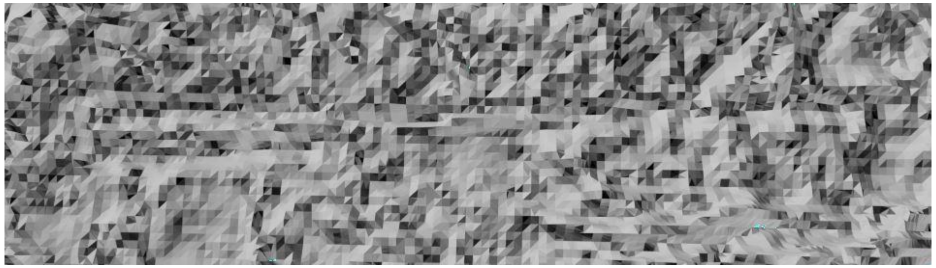
Figure 7. (a) Digital photo of beer bottle exhibit and reconstructions from; (b) Photogrammetry; (c) KBSS; (d) Faro Freestyle.

Figure 8 (below) illustrates the capture of a screwdriver (possible murder weapon) left in long grass and weeds at the scene exterior in a possible attempt to hide evidence.

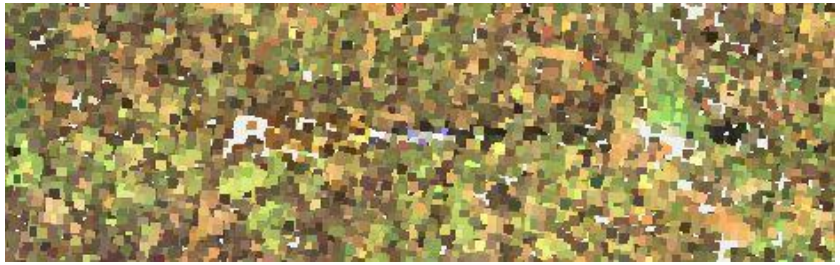
(a)



(b)



(c)



(d)

Figure 8. (a) Digital photo of screwdriver exhibit in grass and reconstructions from; (b) Photogrammetry; (c) KBSS; (d) Faro Freestyle.

Figure 9 (below) illustrates the capture of the cigarette butt exhibit in the scene interior

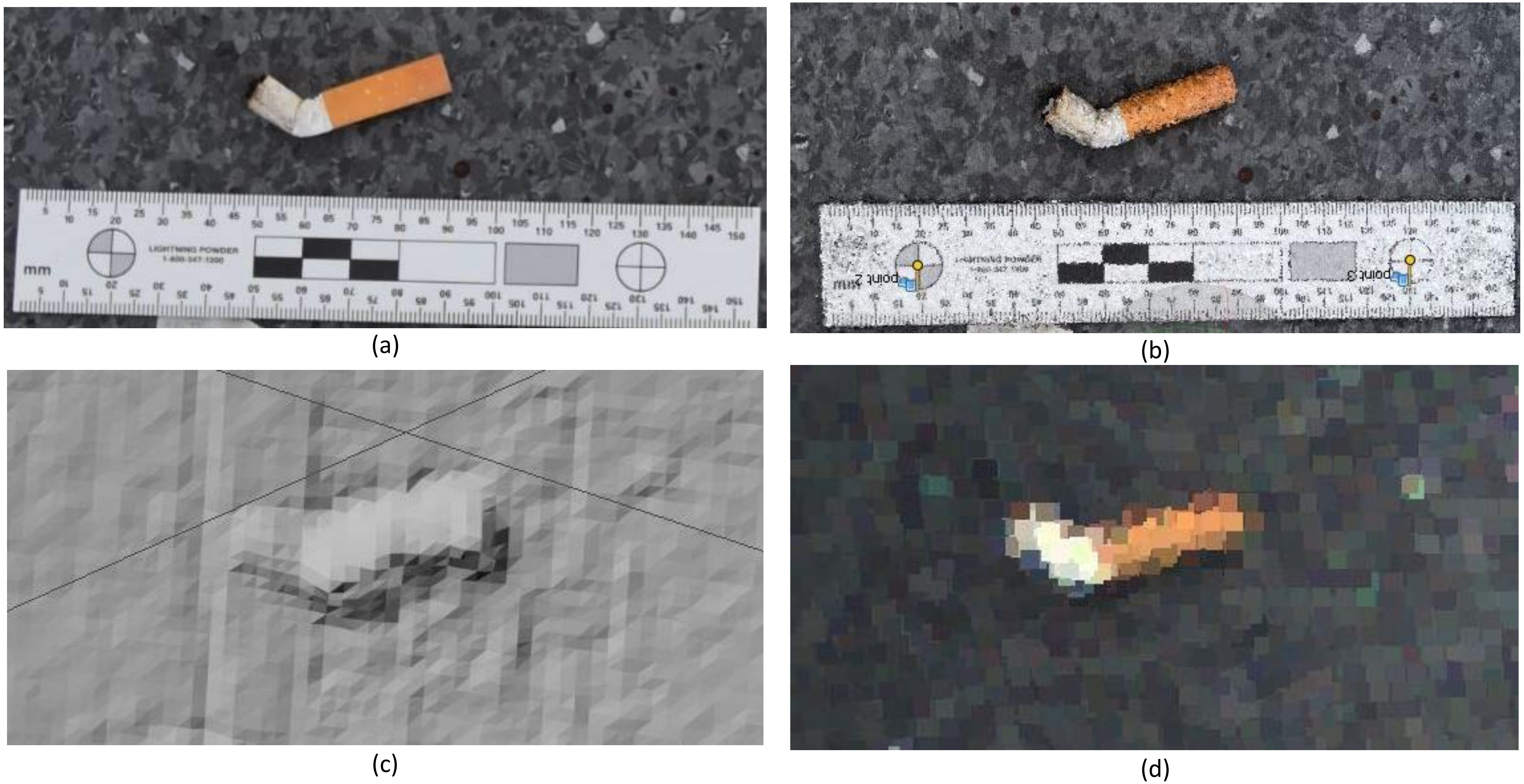


Figure 9. (a) Digital photo of cigarette exhibit and reconstructions from; (b) Photogrammetry; (c) KBSS; (d) Faro Freestyle.

Figure 10 (below) illustrates the capture of a sequence of four outsole impressions in sand by potential suspect.

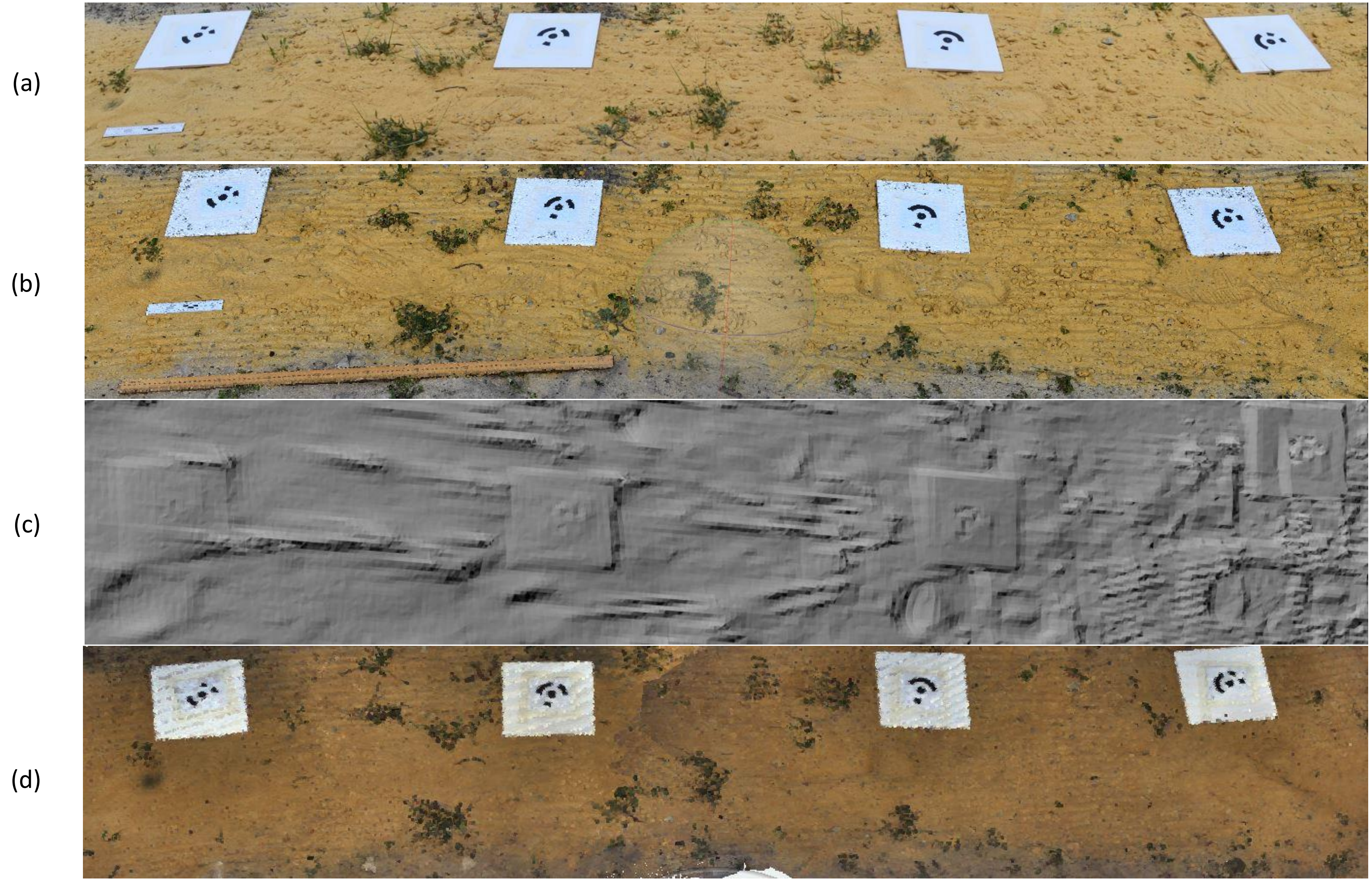


Figure 10. (a) Digital photo of sequence of four 3D impressions in sand and reconstructions from; (b) Photogrammetry; (c) KBSS; (d) Faro Freestyle.

Figure 11 (below) illustrates the capture of a single high quality outsole impression in sand to the best of each devices capability.

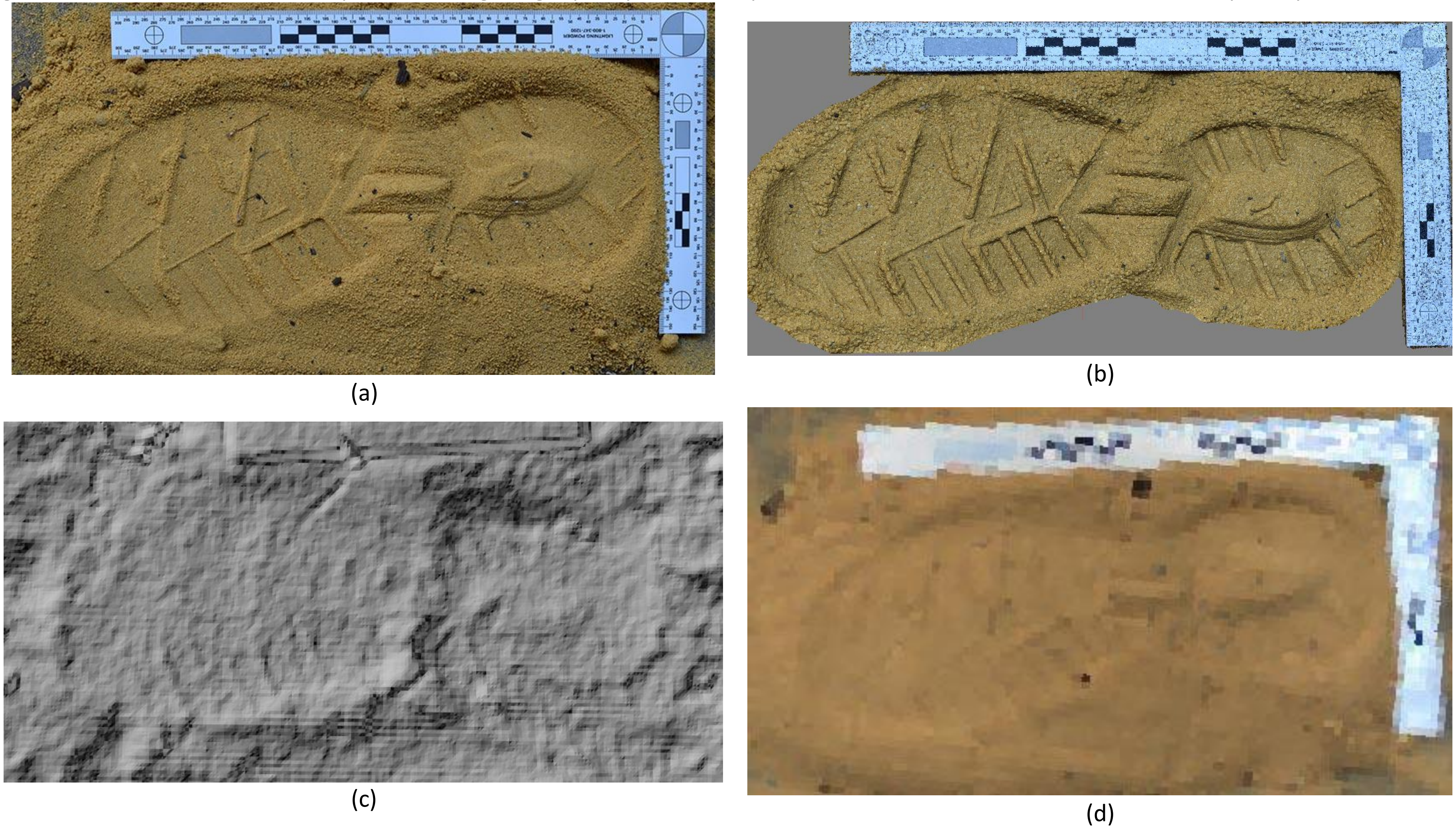


Figure 11. (a) Digital photo of high detail 3D outsole impression in sand and reconstructions from; (b) Photogrammetry; (c) KBSS; (d) Faro Freestyle.

Measurements (Table 2) were taken in AutoCAD® for Photogrammetry and Faro Freestyle results after exporting from Agisoft Photoscan® and Faro Scene® respectively, however measurements are also able to be taken within the respective software. Results for the KBSS were measured in 3DS Max. Each of the evidence types was scored (Table 3) on whether it was deemed to be visible and measurable (VM) from the 3D model, visual but not measurable (accurately) (VNM), not visible at all (NV), or if the scanner returned no result (NR). The usage of 'measurable' was relative to the evidence, meaning if criminal information could be gathered from it.

Table 2. Distances of crime scene evidence as measured in mm by hand (actual), compared to the three tested technologies.

	Actual	KBSS	Faro	Photogrammetry
Room width	2795	3061 (+266)	2812 (+17)	2790 (-5)
Door Frame width	765	784 (+19)	773 (+8)	764 (-1)
Victim Height	1860	1650 (-210)	1829 (-31)	1820 (-40)
Blood pool Length	805	No Result	792 (-13)	799 (-6)
Hammer Length	344	327 (-17)	334 (-10)	342 (-2)
3D Outsole Impression Length	340	431 (+91)	339 (-1)	344 (+4)
Distance between 3D impression 1 and 2	355	335 (-20)	Detail too poor	352 (-3)

Table 3. Visibility and measurability* of forensic evidence by various scanning techniques

Evidence	Real	KBSS	Faro Day	Faro Night	Photogrammetry
Interior scene: General	VM	NV	VM	VM	VM
Blood spatter	VM	VNM	VNM	VNM	VNM
Blooded footwear impressions	VM	NV	VNM	VNM	VNM
Hammer	VM	VM	VM	VM	VM
Can	VM	VNM	VNM	VNM	NV
Cigarette	VM	VNM	VNM	VNM	VM
Dusted Fingerprints	VM	NV	VNM	VNM	VNM
Exterior Scene: General	VM	NR	NR	NR	NR
3D Outsole impression sequence	VM	VNM	NR	NV	VNM
High Detail 3D outsole impression	VM	VNM	NR	VNM	VM
Screwdriver	VM	NV	NR	VNM	VNM

Bottle	VM	VNM	NR	VNM	VM

*VM = Visible and measurable evidence, VNM = Visible but not measurable evidence, NV = Not visible evidence, NR = No Result

A two tailed T-test was performed, and none of the tested scanning technologies showed a significant difference (P=0.05) to the actual measurements, though not all measurements could be taken by all technologies, specifically the KBSS scanner which was unable to output colour for blood or fingerprint measurements. The Faro Freestyle, photogrammetry, and the KBSS displayed a standard deviation of 16.93mm, 14.66mm, and 155.83mm respectively. The KBSS scanner showed by far the biggest error from the actual measurements, while photogrammetry was the most reliable. The accuracy of the Faro Freestyle was worse than the advertised accuracy of ± 1mm at 1m scanning distance [4]. The most contentious measurement was that of the height of the body.

Neither the Faro Freestyle, or KBSS were able to scan the finer details of frayed fabrics, minor blood spatter, or outsole impression ridge detail. Photogrammetry was able to, but required more concentrated photographs to be taken at a smaller scale.

Discussion

It became clear through the scanning process that none of the three technologies tested would be able to provide a complete solution for scanning a crime scene. This was an expected result, as neither Photogrammetry, Kinect Based SLAM Scanners (KBSS), or even the commercially available Faro Freestyle are intended to be able to capture large areas in high detail. In this regard, traditional Terrestrial Laser Scanner(TLS) units are still superior. However, both low-cost alternatives tested proved to have some benefits over both the Faro Freestyle and TLS units.

Perhaps the most striking result of the study was photogrammetry's capability to deliver a very highly detailed result of smaller objects if enough quality photographs were taken. To test the limits of this (or perhaps the limits of the Photoscan software), a singular outsole impression was processed to the highest quality capable by the software. Although this took considerable processing time (upwards of 24 hours per impression), the resulting detail in the 3D model is very high, rendering individual grains of sand to a high level of accuracy, differing by one millimetre to the actual distance. This result is also easier to obtain as it does not require any specific lighting methods or capture (such as oblique lighting from cardinal angles).

A second impression captured using 16 photos from a camera set on automatic, and held by hand was done, and the resulting 3D model was also of a very high quality, taking just over a minute to capture. The results of this attempt are not shown, however it is important to note that there may be no need to use extensive quality controls if there is no improvement in final result. A minimum of 16 photos were taken for the photogrammetry process for each exhibit, however this may not be sufficient to properly capture the detail of the evidence. For example, the blood-stained hammer displayed notable spatter, but with an increase in photos, this detail may be more readily measurable. The hammer displays the issue of only one side of the exhibit being visible, as it was recorded in-situ, which does not display the full extent of the blood. It is expected that all the technologies would be capable of capturing the object from all sides if displayed correctly, at the same quality output as displayed on the exhibit in-situ.

High quality photogrammetry processing is where a very powerful computer becomes necessary, as mid-range computers like the one used in this study could take multiple days to process a model of a single exhibit at the highest detail settings. At this rate, entire crime scenes could take weeks to fully process. Although the computer is usable throughout this process, for forensic investigators this kind of processing time for a single exhibit would be a challenge to dedicate, as further exhibits must be processed, and resources spent elsewhere. Specialised processing hardware can be purchased to process images much faster than this if budget permits.

The need to save time during on-scene capture is perhaps most important in footwear impression examination, where evidence must be collected before all others, as it will be destroyed or contaminated by the traffic of police personnel through the scene. If a high-quality 3D model can be captured in the space of a minute or so, this could potentially improve the workflow of forensic impression teams. This unfortunately only applies to 3D impressions, as 2D impressions (such as those in blood) can only lose detail from being portrayed in 3D.

A key detractor in the use of the Faro Freestyle was the almost complete loss of capture capability in sunlight, including when scanning too close to a window or open door while inside. However, repeating the scanning at night, or in very low light allowed the scanner to capture the scene, with the inbuilt flash activating when necessary. This could prove to be a serious issue when in use on a crime scene, as waiting to capture a scene until the evening or night may prove to be impossible, or cause considerable time to be wasted. Conversely, if this information is known and accounted for, the surveying team may be able to plan a visit to a scene in accordance with the best light conditions, and in doing so avoid the rush of other evidential collection. Photogrammetry is hampered by the opposing conditions, as much better lighting allows for more detailed photographs with which to feed into the software. Capturing images during the night may prove impossible, or complicated to supply appropriate lighting.

Scanning large areas such as the body or inside of the room proved especially problematic for the KBSS, which struggled to recognise similarities in the room and close loops in the model. This may have also been the cause for issues in accuracy of measurements, leading to the vastly greater standard deviations from the mean. A study in 2015 by González-Jorge *et al* [5] showed that in their crime scene scenario, the Kinect camera showed errors in measurement of between 2 and 10% at 3m range. The results from this study mostly showed the KBSS error within 10% of the actual measurement, however the outsole impression had an error rate of 22%. Compounded to this was the necessity for the output of the device to go through multiple file formats and programs to achieve a measurable model. The resulting models were measured in 3DS Max® rather than the intended

AutoCAD®, which proved to be far less reliable than AutoCAD® for distance measuring. The KBSS unit was also the only unit that failed to produce a coloured model. During the scanning, the models appeared to scan in colour, however could not be exported with the colour included. The KBSS unit in general did not perform particularly well: Not only were the scans poor quality, but on occasion the device would not register objects, and begin to melt everything in the field of view into a flat surface. In terms of time on scene, the KBSS unit took the longest total time to capture all the evidence possible.

The issues experienced using the KBSS are likely to be quite isolated, as there are multiple ways to build a KBSS. As there is no definitive software or algorithm with which to use, users are left in part to amalgamate code from other creators. Indeed, the eventual build of the KBSS unit used in this study differed from the planned build due to time constraint and encountered difficulties. Errors in the measurement of the distances on scene differed drastically to the other two technologies, with the length of the room being the largest error, 266mm greater than the actual distance, and the height of the body being measured 210mm shorter than the actual distance. This kind of error is far too great to be accepted in a court room as evidence, as the difference in height of greater than 20cm could confuse the victim's identity, or make it impossible to theorise for someone to have reached a distance with a certain weapon. This is major downside to the system, however for future studies, a more reliable workflow could be developed to avoid this problem. Due to these errors, and the relatively small sample size of measurements, the accuracy of the KBSS cannot properly be assessed by this research, and further study would be required to properly indicate its accuracy.

Reflective surfaces such as the beer can and bottle caused problems for all three scanners. The can of beer exhibit was placed in a low light environment, next to the body inside the room, but despite the low light and black colouring on the can, its highly reflective surface meant that it was not able to be picked up easily by any of the scanners. The reflective surfaces cause an issue as the scanners pick up the reflected image, and determine that the object is the reflection, thus confusing the resulting depth with a distorted image of something further away. The result from Photoscan is an extreme of the issue, showing simply an empty hole in the floor. The Freestyle and Kinect scanners showed some problems with defining the shape of the can as well, with the Kinect scanner performing worse due to its lower resolution, and the Freestyle able to define the cans shape, but showing small areas of it as empty. In the event of a crucial item of evidence being unable to be scanned (and if contamination is no longer an issue), a reflective surface can be sprayed with a matte paint or coating to remove the reflectivity barrier, or replaced with an evidence marker.

A common theme among all the technologies was that smooth flat surfaces such as painted walls posed an issue for recognition and tracking. The handheld scanners rely on certain visual features to be able to track their movement as part of the SLAM process. Without these features the systems are unable to determine any points from which to base the model. This is not an issue if the flat area is surrounded by features that fit within the scanners field of view, however if the entire view is filled with featureless wall, then little to no points will be recorded. When building the photogrammetry model of the interior scene, the walls appear to be very wavy and undulating due to the software being unable to determine any difference in depth of the flat surface from different angles. With many mid-range photos of a single wall (or of evidence on a wall such as blood spatter), the software is able to determine the walls flat shape more accurately, as visualised when the BPA and fingerprint photographed were integrated into the interior model. Though this problem can be overcome, if the wall is not important for the scene reconstruction, it would seem unnecessary to spend extra time to ensure the wall appears flat. When scanning with the Freestyle, an error would occur if too much of the featureless wall came into view, causing the scanner to lose tracking and occasionally require a restart of the scanning sequence.

Further issues were created by the screwdriver exhibit being placed within a bed of long weeds/grass. Often exhibits are hidden or discarded in such a way on a crime scene, and all the scanning methods struggled to determine the object within the 'noise' of the vegetation. Almost any scanner will suffer in this scenario, given that the line of sight of the object is occluded from various angles. Dual return laser scanners however are able to gather information from the initially encountered vegetation, as well as the object hiding underneath, and in the future, this may be the best option for evidence in this situation.

Photogrammetry as a technique, and the Photoscan® software were relatively easy to use, requiring very little time to learn enough to produce a high quality scaled model. Forensic photography techniques are well known by forensic personnel, but it is not known whether the techniques used in this study could be perfected with more testing. The process of converting the photographs to a 3D model was relatively simple, requiring the knowledge of how to take the photos in a sequential run, and the small tweaks within the software. What may limit the practicality of photogrammetry for forensic use is the time it takes to process a high-quality model. To dedicate the use of a computer to process a single exhibit for potentially multiple days might not be feasible, however lower quality models can be produced in shorter time. This problem may prove to be a moot point however, as the 3D model may only be beneficial as a court room tool, and therefore may only need to be generated in cases that reach that far.

The Faro Freestyle was expected to be the easiest to use, considering it is an out of the box complete product, coming with an accompanying tablet and installed software. However, during its use, numerous errors and tracking issues hampered progress when scanning. While scanning, the unit is powered by the tablet via a USB cable, which allows for about 2 hours of scanning time before the tablet must be recharged. Two hours of scanning may not be enough on a complicated scene, meaning either lost time in charging, or increased cost in multiple batteries for the tablet. It is possible that as this study used a hire unit, it could have had issues that a new unit may not, although it is likely that the software still has issues that must be resolved. In processing the data, Faro's SCENE software was relatively complicated to learn in comparison to Photoscan, however the viewable models were still available and measurable without much effort. It is also likely that a more experienced user of Faro products may be able to gather better quality scanning data than what was collected in this study.

The KBSS was by far the most difficult to create, also proving to be the most difficult and disruptive while on-scene. Due to it being a custom-built system, it was complicated to manipulate physically, requiring an external power source (extension cord to power socket) to run. In a crime scene environment, it would be highly damaging to drag an extension cord around from room to room, and it would be assumed that a battery pack would be a necessity. Despite its difficulty, when compared to the Faro freestyle, it scanned individual objects much faster, and scanned more intuitively than the Faro Freestyle, which struggled to keep tracking and was extremely slow to scan.

A major barrier to the usage of photogrammetry to record 3D outsole impressions is its validity in court. Before such evidence can be presented, it must have rigid guidelines as to its collection method, including quality control. Further work must be done to determine best practice for photogrammetry collection of 3D impressions, including more in-depth testing against currently employed techniques. The photogrammetric results may only be indicative of the software used however, as multiple photogrammetry programs exist, and others such as Photomodeller® may provide a better result. Ideally this research would have also utilised a TLS to capture the area for comparison with the other technologies, especially given its usage by the Western Australia Police. However, limited funds and the costs of TLS units prohibited the comparison.

Conclusions

While the results of this study show that none of the technologies are ready to replace existing crime scene surveying tools, photogrammetry has demonstrated the capacity to deliver a clearly superior detail model of smaller exhibits, and to a lesser extent small rooms. Of particular use to forensic teams would be the generation of a high-quality 3D outsole impression, which can be captured on-scene in a time-scale equivalent to that already dedicated to a single impression. The market Faro Freestyle was reliably accurate, and easy to obtain, but delivers a sub-par overall result, and adds nothing to existing police capabilities. The KBSS unit proved to be unsuitable for professional use in its tested form, both due to its difficulty to assemble and use, as well as its accuracy. However this should not exclude the KBSS from further research, as it is relatively new technology that has lots of room to develop.

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