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Title: Geomatic techniques in forensic science: A review

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The purpose of this review paper is to highlight various geomatic techniques that crime scene reconstructionists or forensic practitioners can use to document different kinds of scenes, highlighting the advantages, disadvantages, and when best to use each technology. This paper explores geomatic techniques such as a total station, photogrammetry, laser scanners and structured light scanners and how they can be used to reconstruct crime scenes. The goal of this paper is not to discredit manual methods, as they are long standing and reliable, but instead to shed light on alternative methods that may produce equally or more accurate results with a more visually appealing final product. It is important for law enforcement and forensic professionals to understand the advantages and disadvantages of each technique, knowing when certain techniques should be used (and when they should not), and being able to revert to traditional methods if required.

Introduction

The most important aspect of any crime scene analysis is the ability to create an accurate reconstruction of the environment and the events that unfolded leading up to the criminal act being investigated. Crime scenes, by nature, present unstable and short-lived environments or circumstances [1,2]. This means that forensic investigators are tasked with extracting as much information as possible before the evidence begins to degrade [1–3]. The purpose of this review paper is to discuss the geomatic techniques available to law enforcement and forensic practitioners that will increase the amount of information gained from any given scene, when compared to traditional documentation techniques. This paper will explore techniques that are currently being used in crime scene documentation, including the total station and various forms of three-dimensional (3D) technologies, such as photogrammetry, laser scanning, and structured light scanning. This paper will provide forensic practitioners with a comprehensive review of the technology available for crime scene documentation. For the purposes of this paper, photogrammetry will be referred to as the process of taking photographs that are then meshed together to create a 3D model. Additionally, when the term accuracy is used, it refers to being as close to the “ground truth”, usually referring to measurements, and crime scene or evidence re-creations.

Traditional methods of crime scene documentation include handwritten notes, sketches, photographs, videos, and manual measurements [2–4]. Although these evidence types are accepted in a court of law, manual methods can incur errors, such as transcription, that could be negated with geomatic techniques [1,5]. The goal of this paper is not to discredit manual methods, as they have proven to be successful and reliable in the past, but to demonstrate how geomatic techniques may be useful and more beneficial in certain situations. Photography, and later videography, have been a staple in crime scene documentation for decades and will continue to be important because both techniques can easily and accurately capture a crime scene, demonstrating the location of evidence in relation to the scene itself, and to other pieces of evidence [2,5–8]. Crime scene photographs should consist of overall, midrange and close up images of the evidence recovered and of the scene itself [2,9]. Crime scene photography and videography techniques are reliable, inexpensive and can instantly capture the scene, which provides investigators and jurors with an idea of what the scene looked like to better understand the events that transcribed [2,4,6–8,10]. The issue however, is that photography takes a 2D image of a 3D scene/object which can result in a loss of information, such as depth, and can cause distortion, changing the overall view of the scene/evidence [6]. Similarly, although videography provides

a good overview of the scene, it lacks transparency as it only demonstrates the videographers point of view and is limited by what is looked at, potentially missing important areas of the scene [9].

For complete scene documentation, photographs and videos should be coupled with manual measurements of the scene, including the perimeter, large and small features within, and the accompanying evidence [2,4,11]. Taking measurements of a scene is vital to the documentation process, because it will allow the investigator to create a to-scale map of the scene, displaying the spatial distribution of the evidence, their relationship to the scene and each other [2,4,9,11,12]. Aside from photographs and videos, generating maps will help the jury members to better understand the scene and the events that transcribed [10]. For manual measurements, a tape measure is most commonly used because it is inexpensive, readily available and easy to use [4,11]. Although manual measurement techniques are a widely accepted practice, crime scene investigators should be aware of the disadvantages, including the extra time and effort required, and the potential for transcription errors [12]. Manual measurements may require multiple personnel, and depending on the size of the scene, could take a considerable amount of time [5,12]. The use of a tape measure incorporates the potential for human error, whether it be a misread of the measurement, of the unit, or a transcription error [1]. It should also be noted that the use of tape measures requires contact with or to be in close proximity to the evidence, incurring the risk of contamination or moving the evidence [12]. The apparent disadvantages to traditional crime scene documentation, and the constant need for improved efficiency and effectiveness, have paved the way for the use of geomatic techniques in crime scene documentation.

Geomatic techniques and their crime scene applications

Review table: The following table demonstrates the geomatic techniques discussed in this article. Please note that this is not an exhaustive list of all possible geomatic techniques. Specific brands are not specified in this table, as it is more of a general outline of the four different geomatic techniques. The factors below should be taken into account by forensic practitioners when deciding how to best document a crime scene Table 1.

Total station

A total station is a combined measuring and mapping tool that uses an electronic theodolite (to measure the angles) and an electronic distance meter [12–15]. Since the 1990s, the total station has been a reliable tool that allows crime scene analysts to take quick and easy measurements [12,14,16,17]. Even with the implementation of more advanced mapping techniques, the total station is still a widely used tool by many police agencies to document accident and outdoor crime scenes [16]. The price and ease of use of the total station are why it remains an attractive crime scene reconstruction tool [16]. Total stations can be used in two acquisition modes, prism offset and reflectorless, but use the same basic work principles which include, a measurement of the inclined distance to the object (slope), as well as two angles (vertical and horizontal) which generate the point coordinates [15,18].

Prism offset

A prism offset total station consists of two pieces of equipment, the total station itself and a target prism, and requires two individuals to operate [12,16]. The first individual aims the unit towards the prism, and the second individual holds the pole [12,16]. The individual holding the pole, does so over top or beside the piece of evidence or point being measured [12,16]. The operator aiming the unit, uses the eye piece to align the crosshairs with the prism [12,13]. Once they are aligned, the individual operating the unit presses a button and a measurement is taken [12,13]. The measurements taken are accurate if the prism is held steady and in the correct place [12]. Error is incurred when the individual holding the prism is not doing so in a steady manner [12]. In recent years, robotic total stations have become popular because it only requires one individual to operate, increasing the productivity of the point taking and measuring.

Prism offset total stations are beneficial for large outdoor scenes because they can be used for measurements well over 100 m, wherein employing manual methods would be impractical and rather time consuming [12]. A prism offset total station can also be used in small outdoor scenes, such as clandestine graves, but due to

the fragile nature of evidence in graves such as human remains, and the added difficulty of the change in depth, a reflectorless total station may be better suited.

Reflectorless

A reflectorless total station, also known as prism-less, consists of a single piece of equipment that is placed in or on the ground and remains unmoved while the points are being taken. This can be seen in Figure 1. A reflectorless total station sends out modulated laser signals to a point pre-determined by the user, which are then reflected back to the receiver [12,19]. The 3D position of the point can be calculated and reported back directly to the unit [12,14]. The data obtained is collected in spherical coordinates and automatically converted into 3D Cartesian, that can be used by any computer-aided design (CAD) program [12,14]. Similar to a prism offset total station, the user looks through the eye piece, aligns the point or object being measured with the cross hairs and by pressing a button, the machine takes the measurement.

The accuracy of a reflectorless total station is dependant on the intensity of the signal from the reflected surface [18,20]. The intensity is dependant on the distance from the total station, the reflectivity of the surfacing being reflected off, as well as the angle of inclination of the reflecting surface [18,20]. A larger distance between the unit and the point being measured will decrease the accuracy of the measurement [18,20]. Likewise, darker surfaces with weak reflectivity and increased angles of inclination will decrease the accuracy of the measurements [18,20].

Reflectorless total stations often have less range than a prism offset (500 m or less versus over 100 m) and are prone to greater error due to the method of measuring distance [12,14]. Scenes that would benefit most from the use of a reflectorless total station include indoor scenes, or small outdoor scenes such as clandestine graves [5,12]. A reflectorless total station also allows for measurements to be taken at elevated positions, which is helpful if there are large features such as poles, cabinets, or buildings in or around the scene [12].

Crime scene applications

Research has shown that a total station can achieve an error rate of less than 5 mm when used at an outdoor scene [17]. When compared to traditional measurement and mapping techniques, the total station is easier to use because it is semi-automated and eliminates the need for data entry [12]. Although the data generated is restricted to distance and positional data and shown as a table of points, these points can be exported to other computer programs that allow for creating 2D and 3D maps [12,14]. This eliminates the need for hand drawn maps done at the scene [12,17].

The main limitation with using a total station is the slower capture time of points, as only one point can be captured at a time [12]. Once a point is chosen and measured, the user must redirect the unit to another point, re-focus and repeat [12]. In areas that are densely packed or on scenes with complex pieces of evidence, this may prove to be difficult and may not produce the most accurate results [12]. Other limitations include, scenes where the total station needs to be moved multiple times, as set up is time consuming, or smaller scenes with tight spaces [12].

Total stations have long been used for forensic anthropological and archaeological scenes. A recent research project, executed by Berezowski et al. [12] demonstrated the comparability of grave measurements between the total station, laser scanner and manual measurements. 14 landmarks were placed in the grave which resulted in 25 different measurements that were each taken manually with a measuring tape, and then electronically with a total station and a laser scanner [12]. This research found that when comparing manual measurements versus the total station and manual measurements versus the laser scanner, the average error was 10 mm [12]. When comparing the laser scanner to the total station, the average error was only 1 mm [12]. Although this research did not compare the three methods to a 'ground truth' measurement, the results highlight that electronic methods can generate less of an error when used correctly [12]. In an archaeological setting, McPherron [17] demonstrated the effectiveness of the total station on the Pech de l'Azé IV site in France. Despite to the complex and irregular nature of archaeological artefacts, the author found that the total

station was able to accurately document the orientation of each artefact which aided with questions of provenience and the ultimate question of how the site came to be [17].

Figure 1. Depiction of a total station in use at a crime scene.

Photogrammetry

Conventional photogrammetry

The basic principles of photogrammetry date back hundreds of years, however, due to unfamiliarity, it is considerably underused by accident reconstructionists [10]. The remote sensing and mapping industries have been using photogrammetry for decades, with the architecture, forensic, archaeology and film industries now following suit [10]. The relative simplicity and automated data processing make it an attractive technique to use for crime scene documentation [12,21,22]. Photogrammetry is the process of taking multiple overlapping photographs of the same object or area, which are then meshed together to make a 3D model [10,23]. Although each photogrammetry software application will construct the models in a slightly different way, the basis of model creation relies on similar principles. The camera positions and similar points between each image are identified by the software and aligned together [24]. From this alignment, the software creates a dense cloud, which provides the depth information from the 2D images [24]. From the dense cloud, the surface mesh is created from the 3D polygonal mesh [24]. Finally, the texture is reconstructed from the images themselves [24].

The process of taking photographs for photogrammetric models is slightly different than conventional photography [10]. To successfully create a 3D model from 2D images, there must be sufficient overlap of the object/area between each of the photographs [10,25]. Current literature states that there needs to be at least two photographs of the same image from two different perspectives [10,24]. Without the overlap, the resulting 3D models will have gaps and missing information. Photogrammetry models must also include a scale, which will allow for measurements to be taken [25]. This scale can be a ruler, a tape measure, or an object of known size.

There are many photogrammetry software applications that are available, that allow the user to import 2D images and then creates a 3D model. The software will find similar points between each photograph and mesh them together [26,27]. Certain software applications such as Agisoft PhotoScan [24,26], create the 3D model in three or four steps, including aligning the photographs, building the dense cloud, building the mesh, and adding the texture and colour [26,27]. This type of software does not automatically create the 3D model but relies on the user to initiate each step. The quality settings are also set by the user prior to initiating each step. Other software, such as 3DF Zephyr [28], will automatically create the 3D model in a single step, after the quality settings have been set by the user.

There are four criteria that must be satisfied to create an acceptable and usable photogrammetric 3D model [10]. Firstly, there must be multiple overlapping images of the same object or area from different camera angles [10,24]. This will ensure that all areas of the model are present without any gaps. Secondly, there must be some type of scale to ensure that accurate measurements can be taken [10,24]. Thirdly, the object being photographed must be in clear crisp focus in all photographs and should fill the frame as much as possible [10]. For example, if the object that is being imaged is a small blood stain off to the side of the photograph, accurate measurements cannot be generated from the photogrammetry model. Lastly, the photographs must be taken with the same camera with a constant focal length [10].

The accuracy of the measurements taken from a photogrammetry model are contingent on the number of images taken, and the quality of each image [10]. If the camera being used generates low quality photographs, then the resulting model will also be of low quality. Most law enforcement and forensic practitioners are equipped with a digital single-lens reflex (DSLR) camera capable of producing high quality, court appropriate photographs. This can result in high quality 3D models [21]. The quality of the model is also dependant on the size of the object within each of the photographs [10]. As mentioned above, if the object being modeled is small in the image, the resulting model will be of low quality and will produce inaccurate measurements [10].

A recent article by Sapirstein [21] reported the measurement errors on various photogrammetry models from multiple archaeological sites. In large buildings, 10–20 m in size, the resulting measurement errors were between 10 mm and 26 mm [21]. For small objects 2.5 m in size, the resulting measurement errors were 2 mm

[21]. Although the accuracy varies depending on the size of the items being measured, the precision remained consistent [21]. Sapirstein [21] reported that common local errors present after the photogrammetry mesh had been created include poor lens calibration and initial orientations, blurred photographs, a lack of high-contrast patterns on surfaces, the excess of small and thin objects such as vegetation, or oblique surfaces such as crevices and movement in the scene during photography. The errors reported by Sapirstein [21], although not as evident when used in smaller indoor scenes, or on individual objects, would be present in larger outdoor scenes where there is dense vegetation, buildings with monotonous finishes or numerous oblique surfaces.

Drone-based photogrammetry

Another avenue of photogrammetry used by crime scene analysts is drone-based surveying. In recent years, electronic companies have released relatively affordable drones (~\$2000 USD), which has sparked interest in the forensic science community [12,29]. Drone-based photogrammetry allows for the capture and subsequent model formation of entire scenes, instead of just a single item [12]. A project done by Berezowski et al. [12], demonstrated how drone-based photogrammetry can be used to capture the contents of a clandestine grave, showing in Figure 2. The scope of this research was not to obtain measurements from the generated models but did show that the images captured with the drone successfully created a visually appealing 3D model.

Drones are considered aircrafts, and according to Transport Canada, the individuals flying drones are considered pilots [30]. Although the specific rules for flying drones will vary by country, basic laws include no reckless or negligent flying, having the appropriate licensing, proper air-conduct and only flying in appropriate flight zones [30–33]. No pilot should fly a drone in a manner that is considered reckless, as to endanger aviation safety or any person [30–33]. No individual should operate a drone without having a registered drone pilots license [30–33]. Proper air-conduct means flying in a safe manner at all times as to avoid collisions and giving the right of way to motorized and heavier-than-air aircrafts, gliders and balloons [30–33]. No remotely operated drone should fly out of its country of origin, nor should it fly into any airspace that prohibits such aircrafts [30–33].

Figure 2. 3D model created from drone-based photography. Skeleton in grave is a plastic cast teaching skeleton.

Crime scene applications

De Reu et al. [34] utilized photogrammetry to capture and record an entire archaeological excavation at the Boudelo-2 site in Belgium. The authors generated the 3D models using high resolution photographs of the scene as well as three ground control points [34]. Ground control points are important for georeferencing, which allows for accurate measurements to be taken, and the computation and creation of orthophotos and digital surface models [34]. This research highlighted that although photogrammetry was used to document the scene, the method in which it was documented was the same as if it was recorded by traditional means [34]. The authors posited that although the inclusion of a 3D based imaging process brought new challenges, such as a change in workflow and post-excavation processing, the resulting 3D model allowed for a more objective analysis and allowed researchers to revisit the scene [34].

Buck et al. [35] re-created blood stain patterns from 2 mock scenarios and utilized both traditional stringing methods and newer 3D methods to identify the point of origin. Photogrammetry was one of the 3D methods used, wherein several pairs of photographs were taken from varying angles to ensure that each point was visible in a pair [35]. The authors found that the 3D methods allowed for a shorter preparation time and resulted in high accuracy and resolution of the blood droplets, even the smallest ones [35]. The addition of photogrammetry models allowed for a contactless method for documentation whereas the traditional stringing method does not [35]. Although the postprocessing portion required with photogrammetry model, is time consuming and requires a great deal of knowledge and experience, the area of origin calculation and the relevant forensic conclusions were heightened by the addition of photogrammetry [35].

Urbanova et al. [36] explored the benefits of low-cost unmanned aerial technology. Using recent forensic cases where individuals fell from a set height as reference, the researchers created three mock scenes where a dummy, skeletal remains and artificial blood was set up by an abandoned quarry [36]. The scene was documented using a DJI Phantom 2 drone with a GoPro attached using photogrammetric principles in order to create 3D models [36]. The researchers found that low-cost drone technology was in fact able to reproduce high-quality images that were appropriate to create 3D models of the mock scenes [36]. It was noted that if details of the deceased itself are necessary, a multi-resolution model that processes the aerial and ground view imagery separately should be employed, however, solely using the drone was able to show evidence such as blood stains, after being properly marked with crime scene equipment [36].

Laser scanning

3D laser scanning technology has been widely used in the engineering and construction industries for decades and has been more recently used in the forensic science domain [5]. 3D laser scanners work on the principles of Lidar (Light Detecting and Ranging) by emitting a laser pulse, which hits a target and subsequently returns to the sensor [5,12,16,23,37,38]. The distance from the sensor to the object is measured by the phase shift of the laser pulse or the time taken for the signal to return to the sensor [5,12,16,23]. A laser scanner can capture close to a million points per second as well as the accompanying photographs to provide texture and colour [12,38]. An example of a laser scanner being used a crime scene can be seen in Figure 3. The points that are captured are called a point cloud, which is then exported into laser scanning software that can create fully coloured 3D models that allow for point to point measurements and excellent visualization of the scene [5,12].

Figure 3. Demonstration of a laser scanner in use at a clandestine grave crime scene.

Using a laser scanner to capture a crime scene is beneficial because it is less time and personnel consuming, a laser scanner can be easier to operate, and the resulting measurements can be more accurate if the user has suitable training [5]. Compared to taking manual measurements of a scene, which is time consuming especially if it is a large scene, a laser scanner can complete a single scan, in as little as five minutes [5]. Multiple scans of the scene should be taken, to ensure complete visibility, therefore the scanning time is multiplied by the number of scans being taken [5]. Post-processing can be time consuming, however, with proper training it can be done well by a single individual [35]. Once a point cloud has been processed, point-to-point measurements can be taken from anywhere in the scene [5]. One of the biggest advantages of 3D laser scan data is the visually pleasing nature of the final product. This is especially helpful to the members of the jury/courtroom, as it will facilitate better understanding of the expert testimony [39,40]. Other advantages include the ability to navigate through the data in ways that may not be possible with 2D images, sketches and plan drawings, as well as eliminating the challenges related to ambient lighting with traditional photography [2].

3D scanning also has disadvantages as well, including the difficulty of capturing distant objects and the inability to image reflective surface [2,16]. Each manufacturer will publish the maximum distance that a scanner can reach [41]. This is computed by the time of flight or phase comparison between the inbound and outbound signals [41]. For example, the FARO Focus S350 can capture objects up to 350 m in the distance and in all directions, however, the measurement accuracy of those objects may be considerably less than the objects that are closer [12]. In a forensic context, important objects and areas should be no more than 60 m away from the scanner [16]. To accomplish this, multiple scans of a single scene, and even a single area should be taken to ensure that the important objects and areas are accurately captured [5].

A long-running issue with 3D laser scanners is the inability to capture shiny and reflective surfaces as the surface will likely reflect the signal away from the scanner [5,16]. In cases where there are windows, mirrors, or reflective cars, there is a higher chance that there will be missing data or associated noise artefacts which will increase the errors associated with the resulting measurements, and will impact the overall visualization of the scene [16,41]. In research settings, substances such as dry shampoo have been used over shiny surfaces to create a matte finish, however, this practice is not acceptable at crime scenes because it will contaminate the evidence. Recent research has found that complex bony surfaces may also be difficult to capture with a laser scanner, depending on the resolution of the scanner and the research question being asked [42]. For general size and shape related research questions, most hand-held and desktop laser scanners can capture enough detail for an accurate and detailed analysis, however, if specific smaller or texture based-features of the bone are being investigated, a 3D microscope or highly expensive laser scanners may be necessary [43,44].

Although 3D laser scanners can produce accurate and reproducible measurements, it requires extensive training and back-end computer work to take a point cloud from the scanner to a visually pleasing product in court [5,35]. There are courses available through the scanner manufacturers to become certified users, however, there is no set standard for crime scene analysts that ensure that their expert testimony will be admissible in court, aside from the steps taken to validate the technology and the standard operating procedures undertaken by all crime scene investigators at each crime scene [35]. This training may be an official certification from the manufacturer, or in-house training from a colleague [35]. Users must also receive rigorous training on how to take the point cloud and make it into a useable product on the computer [5,35]. This is arguably the most difficult part of working with 3D scanners because there are many steps involved and many areas where those steps can go wrong [12,16]. Even experienced users may run into problems that they have never seen before depending on the circumstances of the case [12,16]. Manufacturers will provide a user manual for their software, guiding users through the basic steps of registering the scans together and cleaning them up, however, it takes many working hours to become an expert [5].

The accuracy of the digital measurements produced by a 3D laser scanner is contingent on the software, the user, and the environment being scanned. Most scanners have their own software programs, created by the manufacturer, that allow users to register and analyze the scans [12]. The possibility of a software glitch or inability to complete a task due to a lack of software development cannot be overlooked. Secondly, scenes that are scanned multiple times must be registered together in the software to create one single scan of the

entire scene [12]. This incurs the possibility of user error as the process is not always completely automated and relies on the user's discretion.

Lastly, in areas of dense vegetation or highly repetitive surroundings such as long roadways, the software may have difficulty with scan registration. To improve the accuracy of the registration process, it is highly beneficial to utilize targets during capture [16]. A target is an object, usually a sphere or square checkerboard, that is placed throughout the scene and captured by the scanner to help with registration [16]. As an unofficial rule, each scan should have at least three overlapping targets present from the previous scan. Targets must remain in the exact same place for the entirety of the scans and cannot be moved even a few millimetres [16]. This is because the registration process relies on the placement of these targets to orient and register the scans together and if moved, the scans may not mesh together correctly. This can cause inaccurate measurements to be taken or an inaccurate representation of the scene [12,16]. Although targets are helpful with the registration process, it is not commonly utilized amongst forensic practitioners. Instead, cloud to cloud registration is used, which means that the software aligns each scan based on the similar points within [16]. It should be noted here that a visually pleasing final product capable of producing accurate measurements can be generated with both target based and cloud to cloud registration [12].

Crime scene applications

Raneri [5] presented two different case studies in which 3D technology was used to document crime scenes. Firstly, a shooting was captured on video by multiple witnesses standing in different locations demonstrating when the first shot was fired [5]. Using a 3D laser scan of the scene, the position of the witness videographer was mapped into the laser scan data to demonstrate where each person of interest was standing and the distance between them, as well as being able to be fully reconstructed in virtual 3D [5].

In a case where a large fire burned down a commercial building, 3D laser scanning was used to quickly and efficiently capture the scene without putting any officers in harms way, as fire can cause the structural integrity of a building to deteriorate [5]. As the search for evidence continued, the scene was continually scanned, and more rubble was eliminated [5]. The 3D scans of the burned building were coupled with the city plans which allowed investigators to reconstruct the building [5]. This allowed for an accurate account of how individuals may have gotten trapped, or how evidenced ended up where it did [5].

A research study conducted by Holowko et al. [45] highlighted the benefits of using 3D laser scanners in the documentation of blood stain patterns. The researchers devised a scanning protocol that was based off of the top-down approach used in traditional crime scene photography, which stipulated that the entire scene would be assessed using midrange and close-up scans integrated for the documentation of bloodstain clusters, and singular blood stains [45]. A mock crime scene was created to test the scanning protocol, which found that the addition of 3D scanning to blood stain pattern analysis was highly beneficial, as the multi-resolution scans enabled virtual exploration, accurate scene measurements, and was easier to capture than traditional methods of blood stain pattern analysis [45]. The positive results towards the addition of 3D laser scanning to blood stain pattern analysis was also voiced by Buck et al. [35] as mentioned above in the photogrammetry section. The authors utilized photogrammetry, a total station and a laser scanner to document the scene and subsequently calculate the area of origin [35].

Liscio [46] conducted a research project that created and compared the 3D models of 20 shovel impressions and to the 3D models of the back side of five round-tipped shovels. Only the tip of the shovel model was used for comparison, as the author noted that the centre of the shovel distorts during the digging process [46]. A 3D deviation analysis was performed on both the impression models and the shovel models to indicate how much deviation was present between the two in the hopes of being able to match an impression to a model and distinguish between the five shovels [46]. The results demonstrated that the deviation analysis was able to successfully match the impression to the shovel and distinguish between the different shovels [46]. Although the author reported positive results, it is important to note that the method is not ready for actual crime scene situations and requires further research [46].

Structured light scanning

Structured Light Scanners, both hand-held and desktop are excellent tools to create 3D models [47]. These scanners project bi-dimensional patterns of non-coherent light onto objects to obtain the size, shape, and distance information [23,47]. Structured light scanners can be beneficial in cases where there are small pieces of evidence which would benefit from a 3D analysis, including human remains, archaeological finds or objects with enhanced latent prints. Handheld scanners are especially useful because they are small, and portable and can completely image an object in a short amount of time (in minutes). This is shown in Figure 4.

Figure 4. Depiction of a handheld structured light scanner in use at a crime scene. Skeleton in image in a plastic cast teaching skeleton.

Similar to laser scan data, if multiple scans are taken of an object, those scans must be meshed together. This can be done both automatically by the software or manually by the user within the software [48]. Once all the scans of the same object have been properly meshed together, accurate and reproducible measurements can be taken [47]. Additionally, the final product of the hand-held scanners are visually pleasing which will facilitate a better understanding of the case in court [10,40,47].

Crime scene applications

A research study conducted by Niven et al. [48] utilized a structured light scanner to scan various faunal elements, including those from a horse, a gazelle, and a reindeer. The purpose of this study was to create a virtual library of faunal remains, as comparative faunal skeletons are often difficult to find, and are dispersed around the world [48]. The benefits of creating a virtual library include the absence of fragility, the ability to share easily with other researchers and the possibility of creating a 3D print of the faunal elements [48]. This research can be easily applied to human remains, and useful in scenes involving clandestine graves or scattered human skeletal remains.

Komar et al. [2], discuss how 3D techniques such as a structured light scanner, could be useful in mass graves and human rights investigations. The scanners can be used to capture important evidence such as tire impressions, bucket teeth and other impressions associated with the heavy equipment used to create the mass graves, as well as smaller evidence such as blindfolds, ligatures, personal belongings and evidence of violence towards the victims, such as a gunshot wound to the skull [2]. 3D techniques allowed for the entire mass grave and all the associated evidence to be documented in situ, providing investigators with more information about the victims and how they became a part of the mass grave [2].

Discussion

The application of geomatic techniques to forensic cases, although still new to the field, can be highly beneficial to many types of crime scene documentation and analysis. This review has demonstrated how technologies such as the total station, photogrammetry, laser scanner, and structured light scanner, can increase the amount of information obtained from a scene, and the accuracy at which it is collected. Each technique will have its own advantages and disadvantages, however, geomatic techniques in general can be easier to operate, in comparison to traditional manual methods, facilitate a better understanding of the scene by jurors and other court members, and enable future research or the ability to virtually return to a scene. Disadvantages include that geomatic techniques can be expensive, require high levels of training to obtain accurate results, and techniques must be able to pass admissibility standards applied to evidence used in court.

The ability to capture a scene in a short amount of time is highly beneficial to crime scene reconstructionists because of the temporary nature of crime scenes [2]. 3D scanners, terrestrial or handheld, can allow for the quick and accurate capture and subsequent virtual visualization of the crime scene [16]. Research has shown that large outdoor scenes can be accurately captured quickly, averaging at five minutes per scan multiplied by the number of scans, as opposed to manual documentation which could take multiple hours or even multiple days, depending on the size of the scene [5,12]. Although the capture time for 3D documentation is mostly shorter than manual documentation or the use of a total station, the post-processing time can be quite time consuming. It is important that the investigator decides whether using 3D methods will be more beneficial and yield more, and more accurate information than manual documentation.

Other benefits include that most 3D capture methods can be performed by a single user, whereas manual methods require multiple personnel [12]. The final product of some of these geomatic techniques are fully coloured 3D models and allow for the viewer to navigate in any way or at any angle and to visit any part of the scene. This is especially important for the jurors and other members of the court, as it will allow them to better understand the expert testimony [10,40]. As the verdict of the accused is held in their hands, it is important that it is based off an educated decision [10,40]. With both manual and 3D methods, once the information is captured at the scene, investigators are unable to return to obtain any new information. The

application of 3D methods, however, allows for a more interactive investigation and the potential for further analysis if new leads arise in the future. The creation of 3D models also facilitates future research projects if necessary.

Geomatic technologies can also be very expensive which could be a problem for agencies or individuals who are not granted funding for their equipment [2]. 3D laser scanners can be bought for as low as \$25,000 to upwards of \$100,000. There are less expensive technologies available however, such as a total station (approximately \$1000), and various low-end 3D capture methods such as the drone or handheld scanners (anywhere between \$1500 and \$5000+). It is important to note that although the initial cost of certain geomatic techniques can be rather high, the invaluable information they provide to a crime scene investigation may be worth the expenditure. Finally, although geomatic techniques can be easy to operate, there is a substantial amount of training involved, on both the equipment and the computer software [35]. Users must be trained on the equipment as well as the accompanying software to be able to utilize for forensic purposes [35].

Perhaps the most pertinent question in relation to the use of 3D technologies for forensic purposes is whether the results are accurate, and if they will be admissible in a court of law. As the use of geomatic technologies is relatively recent, there is a lack of research on the accuracy of these techniques. Each technology will have its own accuracy rate, which should always be presented in court. At a basic level, the accuracy of any geomatic technique will rely on the instrument and the user [1]. This is important to note because an instrument that is well calibrated and accurate can achieve poor results if the user is untrained. Likewise, a skilled user can achieve low accuracy rates if the instrument is not well calibrated. Although there is some variability with the error rates of these geomatic techniques, the total station can achieve accuracy rates of less than 5 mm, and the laser scanner and structured light scanner can take measurements with millimetre accuracy [16,17,50]. Due to the insurgence of research being published on the use of geomatic techniques for forensic purposes, the possibility of being deemed inadmissible in court has lessened, as members of the court and jury personnel are more informed on the advantages and disadvantages of each technique and understand that the geomatic techniques can produce the same or more accurate analyses [12].

It is important to note that not all scenes will be suitable for the application of geomatic techniques. When using a total station, the instrument cannot move while measurements are being taken [12,16]. In scenes where the ground is sloped or uneven, and adverse weather conditions cause the equipment to shake, there will be errors associated with the capture and subsequent analysis. Although these scene conditions are completely hypothetical, the unknown and diverse circumstances of crime scenes may inhibit the use of geomatic techniques, wherein investigators must rely on manual methods of capture and documentation. In some cases, investigators could benefit from using both manual and geomatic techniques.

A study done by Sheppard et al. [1] that compared the measurements taken via photogrammetric 3D models versus a tape measure, found that the differences between the two groups were negligible with only a few millimeters difference. Participants measured ten fixed and ten non-fixed items using both methods, which were compared to the control measurements that were taken with a laser distance measure [1]. The measurements taken with the photogrammetry software applications were highly affected by the user, most likely attributed to the lack of knowledge of the software, whereas the manual measurements taken with a tape measure were affected by transcription errors [1]. Sheppard et al. [1] found that the digital measurements from the photogrammetric models were more reproducible than the manual measurements, however, the size and complexity of the object being measured was a factor [1]. This research project highlighted the importance of utilizing multiple documentation techniques depending on the circumstances of the case.

Conclusion

The geomatic techniques presented in this paper provide forensic professionals with a wide variety of tools for capturing and documenting crime scenes. Due to the temporary nature of crime scenes, it is beneficial for crime scene investigators to be able to document a scene in a short amount of time [2]. It is up to the forensic professionals to determine which technique will be best suited for the scene. Research has shown that total stations are beneficial for large scenes, as the distance measured can be well over 100 m [12,16]. The use of

a laser scanner is beneficial for indoor scenes where blood stains are present and the need for an area of origin calculation is necessary, as well as smaller outdoor scenes, such as those associated with clandestine graves and shooting reconstructions in cars [12,35,39,45]. Conventional photogrammetry and structured light scanners should be used when there are smaller pieces of evidence to image, such as bone, whereas drone-based photogrammetry is better suited for larger scenes where an overall capture is necessary [21,27,29,33,34,36,44,47,48].

Recent research has demonstrated that the use of multiple techniques is highly beneficial to crime scene documentation and can optimize the amount of information obtained from the scene [1]. This includes the use of manual methods as well, as they have proven to be simple to use, cost effective and produce court appropriate results [12]. It is important to note that manual methods can be used in tandem with 3D methods as they may compliment modern technological solutions. Regardless of the technique used to document a crime scene, each scene must be approached with the ultimate goal of creating an accurate and admissible reconstruction of events.

Declaration of Competing Interest

There are no conflicts of interest or funding sources to disclose. There is no affiliation or sponsorship between the authors and the technology brands showcased in this paper – the technology brands used were solely based on availability.

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