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THE APPLICATION OF 3D VIRTUAL MODELS IN THE JUDICIAL INSPECTION OF INDOOR AND OUTDOOR CRIME SCENES

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ABSTRACT. The multidisciplinary approach has become an almost indispensable requirement in the examination of the *scena criminis*, especially in complex cases involving different professional profiles within the biomedical and forensic sciences. In recent times, innovative methods have been joined by the possibility of using three-dimensional laser scanners, capable of obtaining virtual reconstructions, very useful in analyzing outdoor or indoor crime scenes. In the present paper, three case studies regarding simulated indoor and outdoor crime scenes were analyzed, applying a virtual reconstruction based on a survey and acquisition of "point clouds" by using a laser scanner Leica BLK360, managed by means of the software Leica Cyclone. Victims were simulated by two hyper-realistic dummies produced by the Lifecast Body Simulation. The first crime scene regarded a suspect homicide case of a man found hanged to a metallic rod indoor, inside a room; the second crime scene regarded a homicide case of a woman, suspected to be victim of sexual assault, found indoor, on the floor of a corridor in a palace; the third scene regarded an outdoor place located in the hills of the Peloritani Mountains, simulating a crime scene where a homicide was committed. The advantages and disadvantages of virtual three-dimensional acquisitions in relation to forensic purposes were finally highlighted. The successful outcome of the scans proved the true-to-life reproducibility of virtual targets, with the possibility of easier interactions, the possibility to measure specific parameters, adequate simulations, and the essential "crystallization" of physical evidence. In the next future, it will be important improving the procedure in order to obtain protocols with high quality standards, able to ensure that the acquired data will be considered valid with evidentiary effect in judicial trials.

1. Introduction

The judicial inspection represents the complex scientific activities, whose purpose is the preservation of the state of the places, the search and insurance of things and traces pertinent to the crime, useful for the identification of the offender and/or the victim, as well as for the complete reconstruction of the dynamics of the events and the ascertainment of the circumstances in which crimes took place; so, as the first intervention at the crime scene, it often turns out to be decisive and crucial for the resolution of criminal cases. The inspection could be carried out in case of criminal or illegal acts, traffic accidents, accidents at work, domestic accidents, suicides, exposure to chemical or toxic agents, mass disasters, and other circumstances in which there is a hypothesis of serious crime (Carella Prada and Tancredi 2010). By virtue of the aims and purposes of the judicial inspection, it is intuitable how it constitutes an activity requiring collaboration between the investigating authority, judicial police, and experts of forensic medicine (Puccini 2003) and sciences. The forensic scientist may play several roles during inspection including those of judicial police auxiliary, expert witness, and technical adviser appointed by the judicial authority (Park *et al.* 2018; INTERPOL 2023). The activities carried out in surveying over the decades changed and evolved profoundly, introducing increasingly sophisticated techniques and methods over time. Between the end of the nineteenth century and the end of the twentieth century, the first schools of criminalistics began to flourish in Italy, France, and Switzerland. Indeed, in 1907, the doctor Salvatore Ottolenghi founded the corps of the "Scientific Police" in Italy. He believed that the methodological and scientific approach carried out during the inspection was the first task to perform, in order to ascertain the facts and allow the resolution of judicial cases. According to Ottolenghi, the judicial inspection represented the most important dossier of the judicial investigations carried out in criminalistics. He emphasized as well as the importance of applying a criminological approach to serious crimes, analyzing the psychological aspects related to criminal facts. A major contribution to the scientific techniques of forensic investigation was made by studies in anthropology, anthropometry, and the introduction of photography in the judicial field. On the wave of progress, technology and science brought countless innovations in the field of judicial inspection, enriching it with new scientific scenarios and making the multidisciplinary approach increasingly useful as reported in the cases presented in this volume (Byrd and Sutton 2023; Marra 2023; Marra, Di Silvestro, and Somma 2023; Morabito, F. Mondello, and Somma 2023; Morabito and Somma 2023; Somma 2023a,b,c; Somma *et al.* 2023a,b,c; Somma and Costa 2023; Somma and Maniscalco 2023; Somma *et al.* 2023d; Somma, Sutton, and Byrd 2023; Spoto 2023; Spoto, Barone, and Somma 2023; Tagliabue *et al.* 2023). Thanks to the multi-disciplinarity, forensic pathologists, geneticists, dentists, entomologists, biologists, anthropologists, archaeologists, geologists, chemists, engineers (among many other experts) were involved in teams of experts supporting the activities carried out by the forensic experts of the Judicial Police, laying the foundation for creating a multi-discipline approach that is increasingly established today (Cecchi *et al.* 2022). Especially in complex cases, the examination of the *scena criminis* by applying a multidisciplinary approach with different expertises, within the biomedical and forensic sciences, may be crucial (Saferstein 2017; C. Mondello *et al.* 2022; Baldino *et al.* 2023; Byrd and Sutton 2023). Unfortunately, in some circumstances due to various factors, both environmental and human, the inspection activities do not turn out to be carried out in the best possible way, and the primary objective, that is the preservation of the state of the places, the search and assurance of things, traces pertinent to the crime and evidence, may produce altered results with very serious consequences for the investigation in terms of contamination and loss of data. Today, in such cases, the possibility to use a modern approach based on the virtual acquisition of the crime scene by using three-dimensional (3D) laser scanners, makes possible the overcome of many of above-mentioned difficulties, unfortunately occurred in recent past during judicial inspections. In fact, this technology makes it possible to "capture" the configuration of the crime scenes and the elements contained therein, allowing to observe the “crystallized” crime scene with virtual models to other experts of various backgrounds, avoiding the complications inherent the fragility and lability of prints, stains, and evidence, and creating an undeniable advantage in the reproducibility and repeatability of the acquired data (Komar, Davy-Jow, and Decker 2012; Berezowski, Mallett, and Moffat 2020). The analysis of the event scenes and *scena criminis* reconstructed by laser scanner may be prioritized, allowing firstly a useful observation of the scenes from advantageous positions with an overall glance, and secondly of the details, making possible a better effective planning of the activities to carry out on the scenes. Furthermore, the use of these virtual models would also add the ability to manipulate, repeat dynamics, and restore crime scenes with the subjects and objects involved in the event (Jani and Johnson 2022). The use of 3D scanning technologies represents an innovative approach, complementing previous imaging methods (such as Computer Tomography and Magnetic Resonance Imaging), examinations already well integrated in forensic procedures, for a better definition and crystallization of the data as faithful to reality as possible. 3D scanning technology allows on-site scanning, unlike the previous methods used, bringing 3D resolutions and the possibility of making true-to-life models. Compared with photographic and two-dimensional data, three-dimensional reproduction is clearly more realistic, being scans able to simultaneously acquire data of both the victim’s body and the crime scene in 3D space and simulate interactions with it. It is definitely a gateway to future virtual realities and the innovative world of the “metaverse” that is beginning to affect technology research, including biomedical fields. The present paper aims to analyze possible advantages of using the aforementioned modern technology, which makes possible to create 3D virtual models allowing to reconstruct even the most complex crime scenes, making them dynamic environments in which different and virtual modes of interaction of the actors of the scene (victim, aggressor, witnesses) can be considered.

2. Materials and methods

The 3D virtual models of four targets were realized by means of the survey and acquisition of “point clouds” using the laser scanning technology. In two case studies, the indoor crime scene was simulated involving hyper-realistic dummies for victims. Two crime scenes were set up outdoor in the countryside.

2.1. Hyper-realistic dummies. Two hyper-realistic dummies (Flössel *et al.* 2021) produced by Lifecast Body Simulation were inserted as corpses in the simulated *scena criminis*. The models, being made on the basis of 3D scans and casts of a real man and woman, have extremely realistic details such as, hair, veins, skin folds, and small moles. They are also equipped with an airway and an articulated mouth for airway management since this type of manikin was created for medical simulation and therefore also allows the simulation of cardiopulmonary resuscitation techniques. As a matter of facts, data from the international scientific literature report their use precisely in the evaluation of the airway in relation to emergency (Lengua Hinojosa *et al.* 2021). The constitution of the manikins, used also in other training practice (Somma *et al.* 2023b), allowed to carry out totally realistic simulations and dynamics. Features of the manikins (Tables 1 and 2) were: Caucasian complexion; manually assessable eyelid and orbital structures with evidence of eyeball; presence of hand-worked hairline and somatic hair formations.

TABLE 1. Characteristics of the dummy of female sex.

Age (year)	24
Weight (kg)	32
Chest dimension (cm)	40
Hips (cm)	40
Shoes' number	39

TABLE 2. Characteristics of the dummy of male sex.

Age (year)	45
Weight (kg)	37
Chest dimension (cm)	52-54
Hips (cm)	52
Shoes' number	44

2.2. Laser Scanner. 3D laser scanners are among the most technologically advanced surveying systems and allow obtaining reliable and detailed 3D virtual models of specific targets (physical objects or places), offering a good graphic effect from the acquisition stage. This does not exclude that they require good planning of operations to make the best use of the instrumentation. The purpose of the laser scanner is to perform a massive survey of a set of points (point cloud) representing the study target (Barone, Paoli, and Razionale 2012; Naether *et al.* 2012; Olsen and Kayen 2012; Ebert *et al.* 2014; Cucinotta *et al.* 2018; Chias *et al.* 2019; Cucinotta, Raffaele, and Salmeri 2019; Luhmann *et al.* 2019; Ogawa and Hori 2019; Cucinotta, Raffaele, and Salmeri 2020; Puleio *et al.* 2020; Cucinotta, Raffaele, and Salmeri 2021; Barberi *et al.* 2022; Cucinotta *et al.* 2022; Lo Giudice *et al.* 2022; Barberi *et al.* 2023). Although it is a comprehensive and versatile tool, the laser scanner has a number of limitations. Firstly, the point to be acquired must be reachable from the signal; therefore, if a transient element (such as a passerby), or a permanent element (such as a tree) comes into the path of the signal, the laser will measure the distance to the first element reached, generating a blank area for the entire area equivalent to the shadow cast by the obstacle itself. In other words, the laser scanner acts as a kind of light source that, when placed in front of an object, casts its shadow in the area behind it; this shadow area, in practice, constitutes an unmeasured portion of the object (known as "occlusion spaces" or "occlusions"). Having ascertained that a single scan from a single position has a certain limitation into the acquisition of the area, it becomes evident that several scans sufficient to cover the entirety of an object or place are needed. Such multiple acquisitions, when merged together, will result in a complete 3D point cloud, describing the target in question in its entirety. These multiple scans are realized placing the laser scanner gradually at increasingly different points, variably spaced apart, which will constitute the "stations" of the final acquisition. If a particularly detailed outcome is required, it is advisable that the stations are not widely spaced; if excessive survey accuracy is not required, it is convenient to space the instruments further apart. Obviously, this choice depends maximally on the type of laser scanner used. The acquisitions presented in the present research were made with a Leica BLK360 laser scanner (Figure 1). It consists of a small instrument, weighing 1 kilogram and measuring 160 mm in height. The device emits a laser beam from a rotating mirror and acquires the "point clouds" taking advantage of a LiDAR (Light Detention And Ranging) system able to acquire 360,000 points per second with millimeter accuracy. Two types of 360° imagery may be obtained by means three integrated HDR cameras and thermal imaging: i) panoramic images, and ii) spherical images. The laser scanner performs, before the actual scanning, a photographic overview, and then begins to acquire the points through the laser beam.

FIGURE 1. Leica BLK360 laser scanner of the Department of Engineering of the University of Messina.

It has a range of 60 meters, with an accuracy of 6 millimeters at 10 meters. This indicates that the Leica BLK360 laser scan can acquire points up to a distance of 60 meters, with a margin of error per 10 meters of scanning that is 6 millimeters. It has a field of view of 360° x 300°, that is, it acquires a full round angle horizontally, and an angle equal to 300° vertically, and it can work in a temperature range of 5° to 40° Celsius. Some targets may show surfaces difficult to be scanned, such as those provided of high reflectivity (metals, glossy paints), high absorption (black color), and translucency (glass, water). Once started, the Leica BLK360 instrument performs a ten-second countdown before it begins scanning. Once the scan is done, the scanner will transfer by means wifi the raw data to a processing device to which it is connected, such as a tablet or PC. Users may select three different capture modes. Calibration, for guaranteeing the measurement precision, was performed prior to the data acquisitions. This calibration process ensured that the acquired data were directly comparable to the actual dimensions of the mannequins.

2.3. Clouds of points. A point cloud is a 3D digital representation of a specific target. It consists of millions of individual measurement points, each one provided of x, y, and z coordinates. Depending on the method used to capture the cloud and the sensors involved, each point may also include RGB color data or even intensity information, reflecting the return force of the laser pulse that generated the point.

Countless advantages are associated with this methodology, but one among them is represented by a significant reduction in acquisition time, ensuring an excellent and comprehensive result notwithstanding the short time.

However, the "point cloud" cannot automatically define the characteristics of the components of the study target, limiting itself to document only what the instrument may detect, *i.e.*, the external envelope of the investigated objects or places. After obtaining the "point cloud", the data have to be integrated and elaborated with dedicated computational systems, software, and artificial intelligence models in order to produce the virtual realities to be investigated.

Different types of management of the data related to the obtained virtual 3D model may allow:

i Exploration - It allows free navigation and 360° movements within the points' cloud.
ii Segmentation - It allows separation into different portions of the cloud, which identify the different components of the surveyed object. The only major limitation of segmentation is that it is not a fully automated process, but still requires human intervention. To address this aspect in the future, one could work on developing more advanced segmentation algorithms that can automate the process and minimize human intervention. This may include using deep learning techniques, such as convolutional neural networks, to automatically recognize and segment objects of interest. However, it is important to note that human intervention may still be necessary in some cases, especially when dealing with complex scenes or ambiguous interpretations; as a matter of facts, sometimes it could be an advantage since a human evaluation is essential in order to have a total understanding of the scanned object.
iii Extraction - It selects a part of the point cloud; the underlying geometry can be extracted in two dimensions, thus creating a corresponding drawing but in 2D dimensions.
iv Density evaluation - Each point cloud will be characterized by its own density, which will be directly proportional to the acquisition time of the object. Longer will be the scan time, more detailed will result the cloud with more points acquired and a greater density of the scan. In fact, some software allows to improve the performance of the program and the point cloud visualization itself by increasing or decreasing the density of the points.

- v Color attribution – It is able to apply different shades of colors to the point cloud to analyze features within the point cloud itself. For color attribution, Red, Green, Blue are usually used.

It should be emphasized that much of the results obtained still depends on the software used to elaborate the cloud. Among the main softwares on the market today (free and for a fee), some of the most popular and widely used, each one with its own interesting features, are: Cloud Compare, Autodesk Revit and Recap, Autocad Map and Civil 3D, 3DF Zephyr, Point Sense and FARO scenes, ArcGIS, and Leica (Cyclone, Cyclone 3DR and Register 360). Leica Register 360 was the software used to process the point clouds acquired by the Leica BLK360 instrument for the present research.

3. Case studies

In order to verify the available of the laser scanner technology applied to modern criminal investigation, simulated crime scenes were analyzed realizing the virtual 3D models by means laser scans of four indoor and outdoor crime scenes. The four simulated case studies are here presented.

3.1. Case study No. 1. The case study No. 1 reproduced a scene regarding the discovery of a dead body (simulated by a dummy) for an incomplete and atypical hanging (Figure 2a). The scene was carried out in an indoor place consisting of a room within the university campus. The dummy was dressed. The loop was made by means of an electric cable, with which the loop itself was secured by means of a slipknot; a simple knot secured the cable to the IV poles. The IV rods were placed at a height of 1.59 m and 1.53 m, respectively. The loop was placed at a distance of 1.10 m, starting from the top of the tallest rod. Once the dummy was prepared at the scene, the laser scanner was positioned in such a way to scan the subject from all possible angles. Therefore, four stations were identified in the place for the relevant scans, at varying distances from each other. The first station was placed in front of the dummy, to the right of the operator at a distance of 2.90 m (Figure 2a). The second station was placed, again in front of the dummy but to the left of the operator and at the same distance. The third station was placed behind the dummy at a distance of 5.09 m from the latter. The fourth station was placed 4.55 m from the previous station, in a clockwise circular direction. The four stations, viewed from above, thus formed an irregular quadrilateral, concentric to the position of the dummy. The first two scans (stations 1 and 2, located in front of the dummy) were made by fast recording lasting three minutes; the last two scans (stations 3 and 4, located behind the dummy) were made at high resolution by recording lasting six minutes each. The fast scans (3 minutes) allowed to acquire a point cloud with one to two million points approximately whereas the six-minute scans acquired a cloud with thirty-nine to forty million points.

FIGURE 2. Case study No. 1: Photographs of the dummy of male sex (Center for Simulation and Innovative Education, University of Messina).

3.2. Case study No. 2. The case study No. 2 reproduced a scene regarding the discovery of a dead body (simulated by a dummy), victim also of possible sexual assault (Figure 3a). The scene was carried out in an indoor place consisting of a walkway corridor within the university campus. The dummy was undressed to assess the direct effect of laser reflectance on shaded, potentially reverberating surfaces. Once the dummy was prepared at the scene, the laser scanner was positioned in such a way to scan the subject from all possible angles. In this case, the instrument was positioned in such a way to make three stations. The first station was placed near the wall of the corridor opposite to the dummy, slightly behind its head, on the same line, at a distance of 3.47 m. The second station was placed at 2.98 m from the previous one. The third station was realized slightly forward of the previous two (Figure 3b). The three scans were taken at high-resolution, each one lasting six minutes.

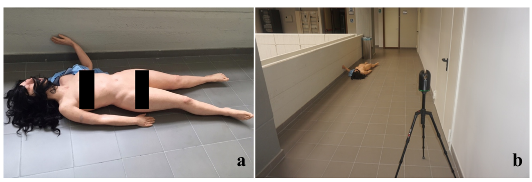

FIGURE 3. Case study No. 2: Photographs of the dummy of female sex (Center for Simulation and Innovative Education, University of Messina).

3.3. Case study No. 3. The case study No. 3 regarded an outdoor place located in the hills of the Peloritani Mountains, at Massa S. Nicola (about 16 km north to the city center of Messina) simulating an outdoor crime scene where a homicide was committed (Figure 4). The simulation was carried out after the removal of the body. In this case, five stations were set up, placed at a distance between each other of about 8 to 15 m. The first and second stations were placed at 12.15 m. The second and third stations were at a distance of 14.95 m. The third and fourth stations were located at a distance of 9.01 m. The fourth and fifth stations were at a distance of 11.76 m. The last station was in connection only with the third station from which it was 11.76 m away.

FIGURE 4. Case study No. 3: Cloud of points of the scene (Massa S. Nicola locality).

3.4. Case study No. 4. Case Study No. 4 reproduces a scene related to the concealment of a corpse in a clandestine closed grave, where a depression developed above (Figure 5). This depression was captured through the use of laser technology, with careful scan of the ground. Specifically, the target was scanned from multiple viewpoints in order to obtain a detailed three-dimensional image of the soil.

FIGURE 5. Case study No. 4: Appearance of the ground where a clandestine grave was simulated. The grave was concealed by a layer of leaves of oak (scientific campus at the University of Messina).

4. Results

The general outcome of the experimental trial was positive overall. In the case study No. 1, stations 1 and 2 (to the right of the reader, top and bottom, respectively) do not produce the gray halo because of the low resolution (Figure 6). The two high-resolution stations (to the left of the reader) produced gray halos highlighting an appropriate density of the point cloud (Figure 7). Two scans were performed at medium resolution, the reconstructed 3D virtual model still yielded a satisfactory result. The dummy material of the manikin responded positively to the laser, although there was a possibility that the dummy's skin emulating a kind of sweat (which gives the surface a slightly shiny appearance) could have created a noise or excessive inaccuracy in the scan result. The stations unfortunately left some occlusions suggesting that four stations were not sufficient to avoid the shadow areas. These occlusions were present in the area between the floor and the dummy's lower limbs (Figure 7b), being not reached by the laser penetrance. However, the same positive result did not occur for the IV rods, whose metal materials with hyper-reflective surface and shapes with a nearly elliptical transverse section were not ideal parameters for a laser scan. In fact, both of these characteristics were responsible for partial anomalous deflection of the laser beam, thus recreating an inaccurate result (Figure 7).

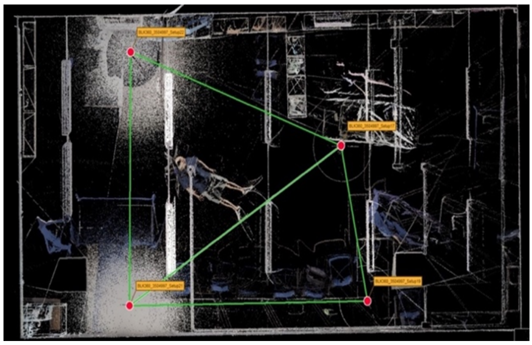

FIGURE 6. Case study No. 1: 2D map of the simulated crime scene with the position of the four scan stations, the station links (green line with error among 1 and 7 mm), and the gray halos for point clouds.

FIGURE 7. Case study No. 1: Two different views of the 3D virtual model.

In the case study No. 2, the dummy used also gave sufficiently comprehensive results, probably because all three scans taken in this case were performed at high resolution. The three gray halos highlighted an appropriate density of the point cloud acquired from each station (Figure 8).

The element that provided a not accurate result in the second simulation was the mannequin's hair, which was purposely disheveled on the face to make the scene more lifelike (Figure 9a).

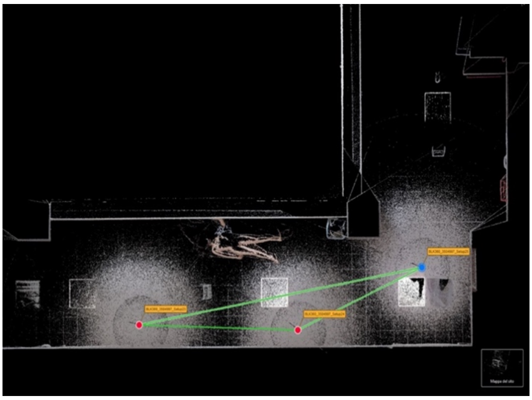

FIGURE 8. Case study No. 2: 2D map of the simulated crime scene with the position of the three scan stations, the station links (green line with error among 1 and 7 mm), and the gray halos for point clouds.

FIGURE 9. Case study No. 2: View of the 3D virtual model.

The manikin material, for which a less than comprehensive result was feared, responded sufficiently positively for the intended purposes. The stations, also in this case, unfortunately left some shaded areas suggesting that three stations were not sufficient to avoid the occlusions. The latter were present in the area between the legs and along the left side of the body, as they were not reached by the laser penetrance (Figure 9). Another station should have been required.
The case study No. 3, involving a simulated crime scene devoid of a dummy, also had

reliable results, despite carried out in an outdoor site (Figures 10 and 11). The meteo-climatic factors, present at the time of scanning, were found to be conducive to faithful reproducibility of the scene, guaranteeing a correct crystallization of the place. Moreover, the use of the extractable photographs, although panoramic and two-dimensional, allows to gain a clear and truthful picture of the sites, to better interpret the point cloud useful for supplementing the information provided by the point cloud, and understand its colors and relationships between the present elements.

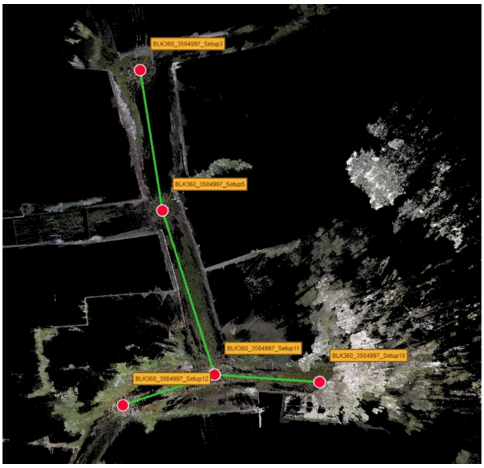

FIGURE 10. Case study No. 3: 2D map of the simulated crime scene with the position of the five scan stations and the station links (green line with error among 1 and 7 mm).

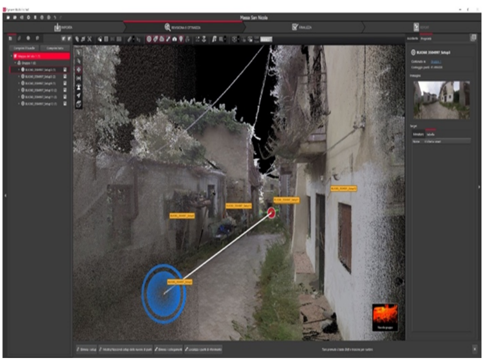

FIGURE 11. Case study No. 3: View of the 3D virtual model.

In the case study No. 4, the point clouds were superimposed and aligned thanks to the markers present. In total, 5,716,730 points were acquired, providing a detailed picture of the terrain.

Subsequently, the turf of interest, *i.e.* the area of the suspected inhumation, was isolated. Using the point triangulation technology, it was possible to obtain a 3D mesh of the area.

Using surface modeling software, a detailed graphical representation of the area was obtained, evidencing the presence of an anomalous depression, deep a few of centimeters, above the grave (Figure 12). This phenomenon may be related to the loss of volume depending on the decreasing porosity of the soil infilling the grave (as in this case) and the decomposition of the human remains (Byrd and Sutton 2023; Somma, Sutton, and Byrd 2023).

Forensic geologists may usually apply several geological, geomorphological, geophysical, and geochemical methods to search for clandestine graves (Murray and Tedrow 1975; Palenik 1982; Tindall 1994; Lombardi 1999; Bull *et al.* 2004; Murray 2004a,b; Pye and Croft 2004; Bull, Morgan, and Dunkerley 2005; Pye 2005; Ruffell and McKinley 2005; McKinley and Ruffell 2007; Morgan and Bull 2007; Pye 2007; Fitzpatrick, Raven, and Forrester 2009; Pirrie 2009; Ruffell and McKinley 2009; Ruffell 2010; Ruffell and McKinley 2014; Pirrie, Dawson, and Graham 2017; Werner *et al.* 2019; Donnelly *et al.* 2021; Fitzpatrick and Donnelly 2021). The approach, based on the use of laser scanner, allowing to evidence the possible occurrence of a clandestine burial, may represent a new method to consider in case of searches for clandestine graves. This method was applied a few years ago by law enforcements for the search of a suspect burial, but the identified depression was related to a case of a positive false.

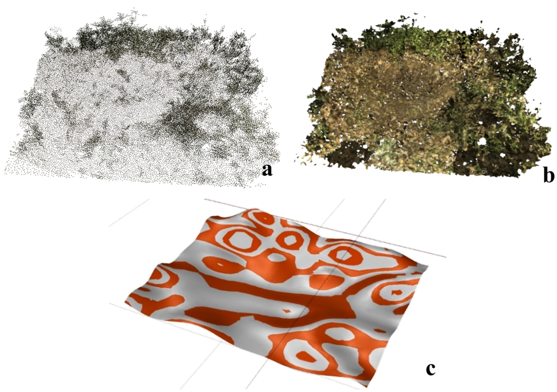

FIGURE 12. Case study No. 4: Different views of the 3D virtual model of the clandestine grave (with mesh: b, c; and without, a). The reconstruction shows the depression developed on the ground above the grave due to the loss of volume related to the soil porosity acquired during the reworking of the soil during excavation and infilling of the grave.

5. Discussion

The 3D virtual model obtained in case study No. 1 (Figure 7) regarding the simulated indoor crime scene allowed to ascertain the assessment of the suicidal circumstance, studying its plausibility and compatibility between the subject, his characteristics, and the dynamics of hanging. The 3D virtual reproduction allowed the quantitative analysis of several key parameters including the height of the knot, loop of the noose, and other features, which guide in a differential diagnosis between suicidal hanging and corpse suspension in an otherwise possible homicidal context.

The 3D virtual model obtained in the case study No. 2 (Figure 9) regarding the simulated indoor crime scene allowed to obtain a faithful reproduction of the crime scene for the evaluation and search of several elements, present in a site, frequented by multiple individuals, where sexual assault and homicide took place. Such elements, including clothing of the victim, drag marks, traces of blood, *etc.*, could lead to the suspicion that the place of discovery was a secondary crime scene and not corresponding to the place where the crime took place.

This procedure could prove to be viable, with its countless advantages, in the case further opinions of other experts may be necessary or in cases regarding the telemedicine. In this latter case, it is not surprisingly that the use of virtual models is increasingly emerging with its innumerable advantages, when a close relationship between traditional and digital medicine is indispensable, revolutionizing the relationship between experts.

The appropriate result of the 3D virtual model obtained in the case study No. 3 (Figure 11) regarding the simulated outdoor crime scene depended strongly by the weather conditions. In such cases, the main disadvantages may consist in the constant motion of the vegetation due to the wind or other environmental factors. The wind, during the scans, was responsible for the formation of a noise in the scan results. The noise may be reduced with appropriate procedures in the case of outdoor simulations, the advantages are represented by the possibility to characterize the geomorphological and geological features of the territory and its planimetric pattern (Somma *et al.* 2023a).

Therefore, the acquisition by 3D methods rather than 2D classical standard photography allows sophisticated and appropriate assessments in better defining the characteristics of the targets also in quantitative terms, the dynamics of events, and the injuries found on the corpse, in terms of compatibility.

The three examined cases showed that the robustness value of the achieved investigation, being equal to 90%, was highly satisfactory. The maximum error encountered during measures was 0.011 m with an overlap between point clouds equal to 24%.

In addition, the 3D scanning of the outdoor places allows the constant faithful reproducibility of the space, even at a distance of time after the finding of the corpse, avoiding to scan the targets when the atmospheric phenomena are not appropriate for the measures.

The experiment conducted in case study No. 4 also emphasized how more detailed, close, and precise scans of an area can reveal details not visible to an immediate human eye and can make even remote consultations between various professionals in forensics easier.

A technology such as laser scanning effectively allows the scene to be crystallized and reproduced as faithfully as possible with excellent results also in terms of quantitative measures of specific evidence.

6. Conclusions

In light of the results of the experimental research accomplished for the four case studies here presented, the positive results indicate that the judicial inspection may benefit of an innovative approach through the application of new technologies, such as the 3D laser scanning, for assisting the forensic experts and the judicial authority to reconstruct historical facts and discriminate among different criminal hypotheses regarding complex criminal cases occurred in indoor and outdoor places. This method, originally born for geological applications (Monti *et al.* 1999; Telling *et al.* 2017), and references therein and successively applied by Italian police forces to reconstruct crime scenes, revealed to be very useful for medico-legal activities as it may support cadaveric findings, and in particular the reconstruction of the event dynamics occurred in the crime scenes, always diriment in defining the compatibility between injuries and criminal hypotheses. The technology illustrated, however not free of possible bias mostly due to weather conditions, was successfully applied for a recent criminal case related to two outdoor scenes where human remains were found. The 3D virtual models were carefully reconstructed at high-resolution allowing the reconstruction of 2D representations of the slope with topographic map and sections (through Autocad software), diriment in defining the dynamics of the events (Somma *et al.* 2023a). Recent criminal investigation for a case of kidnapping, occurred outdoor in the countryside and carried out in team by some of the authors, as advisors or police assistants of the judicial authority, demonstrated as a multidisciplinary approach (involving engineering, geology, botany, among many others) was successful for the event dynamic reconstruction, revealing very productive and harbinger of important contributions to forensic sciences, criminalistics, and criminology (Somma 2023c). Technologies provided by experts in engineering (Olsen and Kayen 2012; Park *et al.* 2018; Somma *et al.* 2023a,b,c,d), principles and methods provided by other discipline such as geology (Lombardi 1999; Somma *et al.* 2018; Spoto, Somma, and Crea 2021; Somma 2022; Somma and Costa 2022), botany (Caccianiga *et al.* 2021), palaeontology, entomology (Byrd and Sutton 2023) and other natural sciences could be crucial in directing the investigation especially in cases occurred outdoor in the countryside. This multidisciplinary approach, which is increasingly appearing in the Italian panorama of the biomedical and forensic sciences (Picozzi and Intini 2009), could allow a better reconstruction of events, getting as close as possible to the actual dynamics that happened. The successful outcome of the scans, applied in simulated and real cases, proved the true-to-life reproducibility of virtual places, with the possibility of easier interactions, quantification of certain parameters, and the necessary "crystallization" of evidence sources. Considering that the judicial inspection should be performed in all its phases in a comprehensive, organized, and methodical manner to minimize procedural errors, maximize forensic medical performance, and other criminalistic implications, and that nothing should be overlooked or left to chance, the compilation of guidelines and protocols would facilitate the duties of the forensic experts in the activities in laboratory and outdoor places. In future, it will be important to improve the procedure to obtain more precise protocols with high quality standards that can ensure that the methods are valid with evidentiary effect in judicial trials. So therefore, it is desirable in the next future the introduction of a protocol for regulating such procedures. In such a way, the results obtained by means of laser scanner will be not only objective and validated, but also usable in routine quality standards for court. The ethical implications of using 3D laser scanning in crime scene investigations may include privacy concerns and the potential for misuse of the technology. For example, collecting detailed data on the crime scene could lead to the inadvertent disclosure of private information about victims or suspects. To mitigate these risks, it is important to establish clear guidelines on the use of scanning technologies and ensure that the data collected are used only for legitimate purposes and in compliance with privacy laws. Additionally, training forensic professionals and implementing accountability mechanisms can help to prevent the misuse of scanning technologies.

Author Contributions

Conceptualization, G.B., D.S., R.S.; methodology, A.Al., A.As., G.B., V.F., D.S., R.S., E.V.S.; software, A.Al., M.R., F.S.; validation, A.Al., G.B., D.S., R.S., E.V.S.; formal analysis, A.Al., M.R., F.S.; investigation, G.B., D.S., R.S.; resources, A.Al., V.F., M.R., F.S., R.S.; data curation, G.B., D.S., R.S.; writing original draft preparation, G.B., D.S., M.R., F.S., R.S.; writing review and editing, G.B., D.S., R.S.; visualization, G.B., D.S., R.S.; supervision, A.As. All authors have read and agreed to the published version of the manuscript.

Competing interests

The authors declare no conflict of interest.

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