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EXPLORING THE POTENTIAL OF GEOSPATIAL VIRTUAL REALITY IN FORENSIC CSI: AN OVERVIEW

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Abstract

This paper presents a discussion on the applicability of geospatial data sources such as laser scanners and photogrammetry integrated with VR so that crime scene investigation (CSI) can be improved in data management, time consumption, and user experience. CSI is a part of forensic science where physical measurement and evidence consist of objects connecting to the case are recorded in the crime scene. Traditionally, the method of acquiring information on the crime scene is using hand sketching and 2D photography. Even 3D models are used, but the display on the screen does not support full information of the data, making the presentation of the data visually limited. Geospatial method has the advantage of 3D information that is able to digitally measure dimensions and volumetric properties of physical objects. The geospatial surveying such as laser scanning, and photogrammetry can be used to preserve the evidence by recording the physical crime scene in the digital world. The scanning world known as point clouds are essentially used to calculate the angle, distance and dimensions, area, volume, and speed of objects as well. The point clouds can be optimised into virtual reality (VR) with realistic textured details making the user experience more intuitive.

Keywords: Crime scene investigation, geospatial, laser scanning, photogrammetry, point cloud, reconstruction, virtual reality

Abstrak

Kertas ini membincangkan keberkesanan data geospatial untuk kegunaan penyiasatan tempat kejadian jenayah (CSI) dalam menambahbaik pengurusan data, penggunaan masa dan pengalaman penggunannya. CSI merupakan salah satu cabang pekerjaan dalam bidang sains forensik yang melibatkan pengukuran dan pencarian bukti-bukti fizikal. Kaedah tradisional dalam kerja-kerja ini adalah dengan lakaran dan fotografi 2D. Walaupun model 3D digunakan, paparan pada skrin tidak menyokong maklumat lengkap mengenai data-data keperluan menyebabkan interpretasi visual terhad. Kaedah geospatial mempunyai kelebihan informasi 3D di mana ciri-ciri dimensi dan volumetrik dapat diukur secara digital. Teknik pengukuran geospatial seperti pengimbas laser dan fotogrametri boleh digunakan untuk menyimpan bukti dalam dunia digital. Data titik-titik awan itu boleh dimajukan ke realiti maya dengan butiran realistik.

Kata kunci: Siasatan tempat kejadian jenayah, geospatial, pengimbas laser, fotogrametri, titik awan, pembinaan, reality maya

1.0 INTRODUCTION

In Malaysia, crime scene documentation and recording involve a combination of conventional techniques and contemporary technologies. Law enforcement authorities typically gather preliminary information using photographs, sketching, and written notes. There is an increasing trend towards using digital tools like terrestrial laser scanners to produce detailed 3D reconstructions, which involve generating point clouds using terrestrial laser scanning. Furthermore, certain authorities are investigating drone technology for airborne photography and videography to provide a more comprehensive view of crime scenes. Despite recent progress, the utilization of photogrammetry methods, including aerial and close-range photogrammetry, is not fully exploited in Malaysia. This presents an opportunity for improving crime scene documentation standards.

Virtual reality (VR) shows great potential in documenting crime scenes. VR can enhance immersive experiences by enabling investigators to virtually revisit crime scenes and examine different viewpoints, which can assist in interpreting and analyzing evidence. VR simulations might be combined with real-time data from crime scenes to help investigators discover and evaluate evidence more efficiently. The employment of point cloud technology and VR systems to improve data management will help Malaysian law enforcement authorities stay ahead in crime scene recording and conduct more thorough and efficient investigations.

Although realistic point cloud simulations of crime scenes can be generated using 3D terrestrial laser scanning, the potential of VR technology has yet to be fully explored. Notwithstanding the presence of comprehensive point cloud data, Malaysia has yet to investigate the prospective expansion of this technology to encompass VR applications. In particular, the incorporation of point clouds into VR systems may facilitate the development of Geo-VR, or geospatial virtual reality, which is utilized in the reconstruction of crime scenes. Geo-VR presents a transformative approach in the visualization and analysis of crime scenes through the integration of immersive VR environments with geospatial data. The utilization of Geo-VR technology by Malaysian law enforcement agencies has the potential to improve their crime scene documentation procedures. This would grant investigators an unparalleled ability to examine crime scenes and acquire significant knowledge for the purposes of forensic analysis and investigations.

2.0 RELATED WORKS

Research and development worldwide have focused on exploring improved technology for crime scene investigation. Studies have demonstrated digitalization in crime scene documentation driven by the geospatial-derived reconstruction methods such as terrestrial laser scanning, and photogrammetry offer a detailed and accurate representation. Research has shown that 3D terrestrial laser scanning, photogrammetry extended with the use of VR are useful in generating high-fidelity point cloud models that provide a detailed and accurate model of crime scenes. This technology is frequently used for its accuracy in gathering geographical data, allowing forensic experts to evaluate crime scenes more precisely and efficiently.

Virtual reality (VR) has the potential to be used in crime scene reconstruction, namely in a field known as Geo-VR, which is an advanced advancement in forensic science. Geo-VR combines geographical data with realistic VR settings, enabling policemen to explore and analyze crime scenes in a three-dimensional virtual space as if they were there in person. This novel method improves the clarity of crime scene information and promotes a more interactive and interesting investigation process.

The following tables provide an overview of key aspects related to the research background, methodology, and techniques used in the context of crime scene documentation and geospatial reconstruction.

Table 1 presents an outline of the research background, focusing on the identified issues and themes within the field. These themes serve as a foundation for understanding the challenges and developments in crime scene documentation. Table 2 shows the methodology and products utilized in previous research, highlighting the methods employed, the resulting products, geospatial optimization strategies, and their contributions to the industry. This table underscores the significance of utilizing geospatial-driven data, such as point clouds, in reconstructing crime scenes and its broader impact.

Lastly, Table 3 outlines the techniques employed across various reference papers, showcasing the advantages achieved in meeting specific objectives. However, it also identifies existing gaps in the current methodologies, providing insights into areas for further research and development. These tables are prepared based on an extensive review of relevant research papers, focusing on keywords such as crime scene documentation, geospatial reconstruction, terrestrial laser scanning, photogrammetry, virtual reality, and point clouds, to provide comprehensive insights into this evolving field.

Table 1 Research background

Title	Issue	Theme	Objective
Paper 1 3D Forensic Crime Scene Reconstruction Involving Immersive Technology: A Systematic Literature Review Author: Maneli and Isafiade [1]	Development of 3D crime scene reconstruction	SLR	To organize and summarize the significant existing pieces of evidence to guide future research in understanding the trend of developments in 3D crime scene reconstruction.
Paper 2 Virtual Crime Scene Author: Nelis, *et al.* [2]	Crime scene preservation	Simulation	To improve murder investigations using new technologies
Paper 3 Towards Autonomous Investigation of Crime Scene by using Drones Author: Araújo Jr, *et al.* [3]	Evidence searching	Evidence trajectory	To build an autonomous system for investigation of a crime scene using a drone images*. **not a photogrammetry surveying or reconstruction*
Paper 4 A Sketch based 3D Modelling Method for 3D Crime Scene Presentation Author: Ren, *et al.* [4]	Crime scene preservation	3D reconstruction	To develop a sketch-based retrieval algorithm for 3D modelling of a crime scene
Paper 5 Virtual Reality and Integrated Crime Scene Scanning for Immersive and Heterogeneous Crime Scene Reconstruction Author: Wang, *et al.* [5]	Ineffective of traditional methods of crime scene reconstruction	Simulation	To obtain potential evidence from a simulated crime scene in VR
Paper 6 Chapter 3 Taking LiDAR to Court: Mapping vapour evidence through Spatial Forensics Author: Formosa, *et al.* [6]	The scene or surrounding of the crime site which may be forgotten or vaporised due to environment	Simulation	To allow the crime scene to be revisited via digital 3D scene
Paper 7 What happened before the run over? Morphometric 3D reconstruction Author: Buck, *et al.* [7]	Difficulty to analyse superimposition of injuries – Pathology and accident investigation purpose	3D reconstruction	To reconstruct a morphometric model for injuries analysis caused by traffic accident
Paper 8 Toward 3D reconstruction of damaged vehicles for investigating traffic accidents in Thailand using a photogrammetric approach Author: Chidburee, *et al.* [8]	Forensic accident investigation – Limitations of manual inspection for collision trajectory	Evidence trajectory	To effectively assist a forensic investigation on collision trajectory using 3D point cloud simulation of vehicles – traffic accident reconstruction
Paper 9 Application 3D Forensic Science in a Criminal Investigation Author: Drofova, *et al.* [9]	The utilisation of photogrammetry and LiDAR scanning method for reliable 3D modelling of forensic evidence	3D reconstruction	To produce a 3D model of an object from photogrammetry and LiDAR based scanning for forensic analysis
Paper 10 3D Indoor Crime Scene Reconstruction from Micro UAV Photogrammetry Technique Author: Sazaly, *et al.* [10]	The issue raised by the author is the challenge of capturing accurate crime scene data within a short time frame using conventional methods.	3D reconstruction	To explore an alternative approach for rapid acquisition of crime scene data while preserving intricate details, ensuring efficiency without compromising accuracy

Table 2 Methodology and product

Title	Method	Product	Geospatial data optimization	Contribution
Paper 1 Author: Maneli and Isafiade [1]	Review on previous 17 years studies (2005-2021)	Systematic literature review (SLR)	Discusses the practicality of LiDAR-based data to be extended to AR, VR and MR engines. Physical objects related to CSI can be optimised into virtual visualisation with good accuracy	Systematic review for crime scene documentation and reconstruction using LiDAR and immersive technologies i.e. augmented reality (AR), virtual reality (VR) and mixed reality (MR)
Paper 2 Author: Nelis, *et al*. [2]	Rendering for VR using LiDAR data and image data	Immersive VR of reconstructed crime scene	A 3D LiDAR scanner was utilised to reconstruct a crime scene. The data was extended into highly detailed evidence documentation like bullets which helpful for evidence trajectory	Introduces extensive 3D reconstruction for crime scene documentation method to the law authorities. The user experienced virtual environment of the reconstructed scene and this improves forensic analysis.
Paper 3 Author: Araújo Jr, *et al*. [3]	To build an autonomous system for investigation of a crime scene using a drone images*. **not a photogrammetry surveying or reconstruction*	Developing a mathematical formula to detect evidence around the captured (by drone) crime scene	The platform used was a drone. Point cloud or drone-based 3D data was not specifically mentioned. However, the drone was flown with the assist of Air-SSLAM and AirCSI which result a list of evidence, sketches, images, and videos.	The authors developed an autonomous system assisted by Air-SSLAM to detect evidence located at the crime scene. An AirCSI system was used to optimize the estimated the coordinates of the objects at the crime scene.
Paper 4 Author: Ren, *et al*. [4]	To develop a sketch-based retrieval algorithm for 3D modelling of a crime scene	Developing an algorithm for retrieving 3D models from 3D data sources e.g., laser scanner, photogrammetry, online library, open literature, and software modelling.	A mathematical model is presented that utilizes the discrete Fourier transform (DFT) and inverse discrete Fourier transform (IDFT) techniques to reconstruct images.	This study adds to the creation of new image reconstruction methods and algorithms that can be used in medical imaging and remote sensing i.e. image analysis, image improvement, and image compression.
Paper 5 Author: Wang, *et al*. [5]	To obtain potential evidence from a simulated crime scene in VR	Documenting a crime scene from a laser scanner and structured-light scanner. Analysing bloodstains pattern, footprint, and injuries through VR	Applies 3D scanning data and VR acquisition system to reconstruct injuries and evidence analysis	Improves traditional method by introducing 3D acquisition system consisting digital reconstruction and immersive visualisation for the usage of forensic analysis
Paper 6 Author: Formosa, *et al*. [6]	To allow the crime scene to be revisited via digital 3D scene	Reconstructing a crime scene from point clouds produced by photogrammetry and laser scanning and representing the reconstructed model in a VR – to be used by the court to revisit the crime scene digitally.	Focuses on the application of GIS and LiDAR technology in reconstructing crime scenes, particularly within the realm of spatial forensics.	Introduces the systematic procedures used in capturing, cleaning, analyzing, and presenting data in a legal setting. The theoretical framework of spatial forensics is examined, highlighting the importance of preserving evidence in a digital format to enable future investigations.

Title	Method	Product	Geospatial data optimization	Contribution
Paper 7 Author: Buck, *et al*. [7]	To reconstruct a morphometric model for injuries analysis caused by traffic accident	Point cloud reconstruction of human body and vehicle for accident reconstruction and pathology analysis – to determine physical damages and vehicle matching that causes the injuries.	Develops forensic 3D models from an interdisciplinary method called the Morphometric three-dimensional (3D) reconstruction involving forensic imaging, photogrammetry, 3D structured light, and laser scanning.	Conducts a thorough analysis of all evidence and marks to determine the source of injuries, categorize patterned injuries or transferred material, and reconstruct the event.
Paper 8 Author: Chidburee, *et al*. [8]	To effectively assist a forensic investigation on collision trajectory using 3D point cloud simulation of vehicles – traffic accident reconstruction	Point cloud reconstruction of vehicles involved in traffic accident using a low-cost mobile phone camera of photogrammetry	Reconstructs digital model of damaged vehicle caused by traffic accident using smart phone photogrammetry	Conducts coalition trajectory and damage inspection through visualisation from the generated photogrammetric model
Paper 9 Author: Drofova, *et al*. [9]	To produce a 3D model of an object from photogrammetry and LiDAR based scanning for forensic analysis	Photogrammetry and LiDAR scanning of an object	Presents image capture methods such as mobile phone photogrammetry and LiDAR scanning to produce highly detailed point clouds of small objects for forensic investigation	Point clouds-based model can extensively provide spatial information and realistic reconstruction to assist forensic CSI
Paper 10 Author: Sazaly, *et al*. [10]	Low-cost photogrammetry via micro unmanned aerial vehicle (UAV) and terrestrial laser scanning (TLS)	Geospatial-derived point cloud of a crime scene	Demonstrates forensic surveying and inspection of a crime scene involving evidence trajectory in indoor area. A micro-UAV photogrammetry and terrestrial laser scanning were utilized.	Micro-UAV and terrestrial laser scanning offer completeness and colour intensity as well as acceptable accuracy

Table 3 Technique used

Title	Ph.	Las.	VR	EVR	MET	ETS
Paper 1 Author: Maneli and Isafiade [1]	No	No	No	No	No	No
Paper 2 Author: Nelis, *et al*. [2]	Yes	Yes	Yes	Yes	No	No
Paper 3 Author: Araújo Jr, *et al*. [3]	No	No	No	No	Yes	No
Paper 4 Author: Ren, *et al*. [4]	Yes	Yes	Yes	No	No	No
Paper 5 Author: Wang, *et al*. [5]	No	Yes	Yes	Yes	No	No
Paper 6 Author: [6]	Yes	Yes	Yes	Yes	No	No
Paper 7 Author: Buck, *et al*. [7]	Yes	Yes	No	No	Yes	No
Paper 8 Author: Chidburee, *et al*. [8]	Yes	No	No	No	Yes	No
Paper 9 Author: Drofova, *et al*. [9]	Yes	Yes	No	No	No	No
Paper 10 Author: Sazaly, *et al*. [10]	Yes	Yes	No	No	Yes	No

Abbreviations used in Table 3
Ph. - Photogrammetry
Las. - Laser-based (point cloud generation)
VR - Virtual reality
EVR - Evidence trajectory via VR
MET - Manual evidence trajectory
ETS - Evidence trajectory system

3.0 CRIME SCENE DOCUMENTATION

3.1 Photogrammetry

From a 3D documentation perspective, photogrammetry is a part of the geomatics discipline, providing informative and highly dense spatial data on the captured object. For example, photogrammetry can be used to reconstruct close-range object [11] on the ground by using a handheld camera [12]. The acquired images are called two-dimensional (2D) closed-range photogrammetry (CRP) raw images which later are used to be processed into a 3D model using photogrammetric software [13].

Figure 1 (Top) Manual inspection of traffic accident damages (left) and digital inspection for forensic evidence trajectory through 3d point cloud (right) [8]. (Bottom) Collision trajectory using physical/traditional matching method (left) and digital/advanced 3D point cloud method (right) [8]

In addition, as shown in Figure 1, a simulation model in a 3D point cloud was produced to help the forensic investigator determine the affected area caused by the collision, and a matching process in which the damaged area is identical or not with the collided source can be performed. In general, image-based reconstruction technique such as CRP develops a 3D model by the approach of highly dense and true scaled image processing [14, 15]. The interesting part is that geomatics surveyors use the technique called "from photography to photogrammetry" which plain photographs are converted into 3D models [16, 17].

3.2 Laser Scanning

A laser scanner is a laser-based survey equipment that geodetically defines geographical and spatial information of the scanned object. The common laser scanner used in the geomatics industry is the terrestrial laser scanner (TLS). The survey method, terrestrial laser scanning records highly dense details including the sizes and shapes of the object [14]. Commonly, TLS is used for infrastructure and land development projects such as Building Information Modelling (BIM) [18], heritage modelling and preservation [19], drainage monitoring [20], forest inventory [21] and geographical information systems (GIS) [22]. Traditionally, a Light Detection and Ranging (LiDAR) system which TLS applies on its operation was applied in an airborne platform known as airborne LiDAR for the purpose of road design [23]. LiDAR is a sensor which transmits a signal to obtain distance from the sensor source to the Earth's surface. Its data has true colour attributes known as red, green and blue (RGB) colours which are commonly utilised for geographical study such as tree species classification [24]. The data are presented into true scaled representation in the form of millions of as-is coloured points called point clouds.

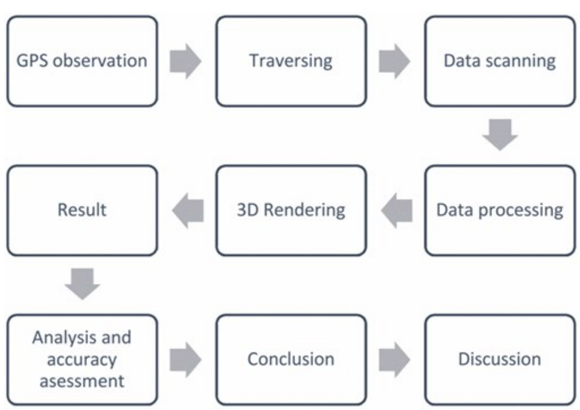

Figure 2 Simple flowchart of terrestrial laser scanning workflow for the development of a realistic 3D model of a building and its accuracy assessment [25]

Users are able to design models digitally that are as realistic as possible due to the data and features included in point clouds that have 3D coordinates of x, y, and z [26-29]. For example, a realistic 3D model of a building can be generated through 3D scanning using a TLS. This work is called building information modelling (BIM) as demonstrated in Figure 2.

The need for point clouds is 3D modelling which becomes the main data source. Without point clouds, 3D reconstruction does not mean anything because point clouds are 3D primitive. 3D reconstruction could be done without point clouds e.g. using 3D drawing software. However, drawing an object by imagining the physical shape of the object is not defining geospatial documentation. Geospatial documentation means the data has as-is attributes [14] e.g. dimension, position and colours where whatever seen on the scene is realistically translated into a 3D model.

With the advanced technology nowadays, tools become smaller and easy to carry. TLS is a terrestrial version of LiDAR [14] with no questions of its accuracy. Also, the LiDAR system is now been built into smartphones but the accuracy is questionable. At the same time, TLS or LiDAR-based tools can be also used in the non-geomatics application like robotic navigation [30] or 3D simulation. For instance, TLS has the potential to document crime scenes because of its advantage of preserving evidence on the crime scene [31]. Furthermore, crime scene investigation (CSI) requires high-quality visualisation for the authorities to study the forensic materials found on the crime scene. This might be helpful for the CSI officer because they could have cohesive records of the crime scene [5] without worrying about the evidence being demolished or removed after the site visit. Plus, this could be an improvement of the traditional method of CSI that uses 2D photographs which information cannot be obtained optimally by depending on such plain images.

3.3 Representing Physical Crime Scene into Digital Point Cloud Data

Photogrammetry is the process of creating precise three-dimensional models from images of the crime scene captured from multiple angles using specialized software. By employing this methodology, investigators are capable of meticulously recording the spatial configuration of the incident site, encompassing crucial details such as gunshot trajectories, blood spatter patterns, and evidence placement. Photogrammetry facilitates the preservation of the scene in a digital format through the creation of intricate three-dimensional models [32, 33]. This allows investigators to meticulously revisit and analyze the evidence.

On the other hand, terrestrial laser scanning yields point cloud data that is exceptionally precise and comprehensive with respect to the crime scene. Laser scanners reproduce three-dimensional scenes, including objects, surfaces, and spatial relationships, with extreme accuracy by emitting laser pulses and measuring the time required for the light to return. This technology is especially advantageous in preserving realistic details [34, 35] that are vital for forensic analysis including tool marks, footprints, and tire tracks. Point cloud data and geospatial technologies are indispensable components of crime scene documentation, as they offer sophisticated instruments for the acquisition, examination, and presentation of evidence. Combining Geographic Information Systems (GIS) and Light Detection and Ranging (LiDAR) scanners with conventional crime scene investigation methods has been advantageous in correctly and comprehensively recreating crime scenes [36, 37].

Immersive technologies, such as virtual reality (VR), have transformed crime scene documentation by offering interactive and realistic simulations for training and analysis [38, 39]. These technologies improve comprehension of crime scenes and aid in visualizing intricate situations. Moreover, the utilization of 3D recording methods, such as point cloud data processing, has allowed investigators to meticulously capture, analyze, and display crime scenes with precision and detail. Statistical outlier removal (SOR) methods can clean point cloud data, improving the accuracy and dependability of the collected information [40].

4.0 VIRTUAL REALITY

4.1 Overview

Virtual reality (VR) refers to the use of technology to create a simulated, immersive environment that users can interact with through sensory experiences such as sight, hearing, and touch. VR usually involves wearing a headset with sensors that track the user's movements so that they can look around, sense, and interact with the virtual environment. By creating a fully immersive experience, VR can be used for a variety of applications, including gaming, education, training, therapy, and even virtual tourism.

Besides that, VR enables users to experience a computer-generated 3D environment that simulates a real or virtual environment. VR technology uses various devices such as head-mounted displays (HMDs), haptic devices, and motion sensors to provide users with a sense of presence and interactivity in the virtual environment [41-44]. VR technology has gained significant attention in various fields, including geospatial and forensic investigations [42-44]. It also has been used in urban planning to create immersive simulations of proposed developments, enabling stakeholders to visualise and explore the potential impacts of the development on the surrounding area [45].

In disaster response, VR technology enables first responders to plan their response, visualise potential risks and hazards, and identify areas that may need urgent attention [45]. In addition, VR technology has been used to create virtual reconstructions of historical events, such as accidents or disasters, enabling investigators to analyse the sequence of events and identify potential causes or contributing factors [46, 47].

4.2 Geo-VR

Geo-VR describes a three-dimensional (3D) model that is integrated with a geographical information which is then imported into VR software, where it can be further refined and enhanced with additional features such as textures and lighting effects [48]. Another approach involves using LiDAR (Light Detection and Ranging) technology to capture detailed 3D information about the environment, which can then be converted into point cloud data that can be visualised in VR [49]. Point cloud data can be used to create highly accurate and detailed models of the environment, enabling users to explore and interact with the data in a more immersive way [25]. The integration of geospatial data into VR platforms provides new opportunities for data visualisation, analysis, and exploration.

In the domain of crime scene investigations, VR has the potential to recreate and simulate crime scenes that can be explored from any angle, providing a more complete picture of the scene than traditional photographs or sketches often used in crime scene investigation in Malaysia. It has the opportunity to document and analyse crime scenes without the need for a physical location which can be particularly useful in situations where access to a real crime scene is limited or too dangerous. In short, VR could significantly improve the accuracy and efficiency of crime scene documentation.

VR presents the opportunity for collaboration between experts and investigators, creating the experience of being co-located on the scene [50]. This allows for crime scenes to be accessed by others virtually while important data could be transmitted among remote investigators, experts, and stakeholders for further inspection. Typical crime scene reconstructions often use two-dimensional representations in the form of static images. Although the use of laser scanning to create point clouds or three-dimensional image modalities of crime scenes, if viewed and presented on digital screens or printed mediums remains two-dimensional, which potentially suffers the loss of information (Ebert,2014). Hence by adopting immersive techniques such as VR, deeper understanding and interpretation can be achieved for crime scene investigation.

The use of VR should not be an ultimate solution nor the only tool. Research has shown that VR becomes the secondary method and among other multiple tools that are required for a comprehensive crime scene reconstruction and analysis [5]. In spite of this, VR methods and tools offer an immersive experience of the crime scenes, although virtual, with still images remaining to be used, particularly in Malaysia, the use of VR for crime scenes were proven to improve the understanding of spatial information and knowledge inquiry through cognitive memories

[51] thus support for a consistent decision making of the investigations [52]. Despite the advantage, using VR in crime scene investigation is inadequate and could be challenging for ethical reasons [53]. Nonetheless, the use of VR is a step forward in acquiring crime scene information that is more efficient and accurate, albeit as an alternative to the traditional and digital still images commonly used as must be accompanied by other tools.

5.0 GEO-VR IN CSI FORENSICS

When reconstructing a crime scene using point clouds derived from terrestrial laser scanning and photogrammetry, as well as virtual reality (VR), several limitations may arise. These obstacles include variations in viewpoint, the presence of noisy points, and uncertainty in scale due to the absence of control points for absolute orientation [54]. Additionally, it is essential not to overlook the necessity of Ground Control Points (GCPs) for image orientation, which ensures the overall accuracy of the reconstruction [55]. Moreover, the lack of depth information from RGB-D sensors can impose constraints on the completeness and accuracy of crime scene reconstruction [56]. Utilizing immersive technologies like VR for crime scene reconstruction can encounter challenges if the quality of the models used and the level of detail captured during scanning lacks spatial details, potentially diminishing the realism of the virtual environment. While VR technologies offer immersive experiences that enhance crime scene visualization, the effectiveness of VR in reconstructing crime scenes can be influenced by the quality of the reconstructions and the level of detail captured during scanning. Addressing ongoing concerns regarding the accuracy and completeness of reconstructions in VR is crucial to ensuring reliable forensic investigations. Although point cloud-based reconstruction and virtual reality have inherent limitations, they can greatly influence forensic investigations.

Table 4 presents a detailed summary of the components of Geo-VR that can have significant effects on CSI forensics, emphasizing the advantages of combining geospatial data with virtual reality technology. Table 5 displays crime scene simulations from previous studies, demonstrating the actual use and effectiveness of these methodologies in forensic analysis and investigations. The tables provide significant information on how point cloud-based reconstruction and virtual reality might enhance crime scene documentation and forensic investigations.

Table 4 Elements of Geo-VR in CSI Forensics

3D geospatial data	Refers to informative details on the captured scene to be used as a reconstructed model for decision-making. 3D point clouds from geospatial medium provide a greater knowledge of spatial and geometrical data, as well as a better comprehension and description of complex circumstances, scenes or scenarios [57].
Parametric model	Represents a geometric model, establishing a spatial relationship, shape and location of the model developed from a geospatial data source such as point clouds [58].
Semantic information	Graphic visual of scanned objects appears in 3D space in which volumetric properties consisting of area, dimension, and volume of an object shall be extracted. Geospatial data supports 3D rendering in which a model with a cleaned surface is reconstructed using modelling software. The features on the model are called semantic information which refers to the richness of details from the developed model [59]. This differs on point cloud where, in the visualization aspect, there is some inconsistency of data and the presence of noise, but the 3D semantic model is consistent in the data and noise-free. Tang, *et al*. [60] suggest that the output model's semantic information must be correct to maintain component attributes and associated information.
Multidirectional numerical information	This refers to how dense the features of scanned objects are geospatially defined into point cloud form. Aerial photogrammetry using a drone platform has an advantage where it is more accurate in horizontal positioning compared to terrestrial laser scanning [61]. Hence, multidirectional numerical information can be obtained through data fusion between the unmanned aerial vehicle (UAV)-photogrammetry and terrestrial laser scanning, providing a piece of optimum spatial information on the data.

Table 5 Example of types of simulation of crime scene generated by geospatial data and virtual reality

Simulation	Insights
Virtual reality reconstruction	Using the Dundee Ground Truth Imaging technique Yu, *et al*. [62] describes a way to keep records of indoor crime scenes . The goal of this procedure is to make it easier to reconstruct crime scenes in virtual reality by giving accurate measurements and placing objects in a three-dimensional space. It likely explains how to record evidence, take pictures of crime scenes, and record the paths of evidence in order to make the information from image tools more accurate and complete.
Geo-forensics reconstruction	Ruffell, *et al*. [63] stress how important it is to combine geoforensic methods with traditional forensic methods to improve the investigation, documentation, and analysis of crime scenes. Incorporating geoscience applications into forensic investigations helps the investigators find, record, and keep evidence better, which ultimately leads to the successful resolution of criminal cases.
3D scanning reconstruction	Baier, *et al*. [64] explores a detailed multiscale approach for utilizing 3D scanning technologies in accident reconstruction. The study focuses on documenting pedestrian accidents, fractures, bone injuries, and their applications in forensic medicine. The increasing use of three-dimensional documentation in forensic radiology and imaging highlights the need of modern technology in capturing and reconstructing accident scenes for investigative and legal purposes.
Virtual reality reconstruction	Kader, *et al*. [38] explores how immersive virtual reality technology might enhance forensic science chemistry instruction by allowing students to interact with realistic crime scenes. The authors describe the creation of a virtual reality crime scene activity using WebVR software. This allows students to participate in investigating virtual crime scenes, collecting evidence, and doing crime scene reconstructions.
Virtual reality reconstruction	Jeevitha [65] discusses new methods for capturing crime scenes, tracing evidence paths, and recording evidence with Virtual Reality technology and advanced data storage systems. Integrating Virtual Reality and cloud-based technology in crime scene investigation can improve the documentation process and strengthen evidence preservation for forensic analysis and judicial proceedings.

6.0 CONCLUSION

This paper highlights the evolving landscape of forensic science and crime scene investigation, where the rapid advancement of technology plays a pivotal role in improving investigative processes. Laser scanning and photogrammetry not only offer practical solutions for documenting crime scenes but also present opportunities for real-time data capture and analysis, expediting the investigative timeline. By leveraging these technologies, forensic practitioners can ensure a more thorough and comprehensive documentation of evidence, minimizing the risk of crucial information being overlooked or lost.

Furthermore, the integration of virtual reality (VR) engines revolutionizes the way crime scenes are visualized and analyzed, providing immersive experiences that enhance understanding and decision-making capabilities for investigators and legal professionals. The ability to virtually reconstruct crime scenes in 3D environments not only aids in evidence interpretation but also facilitates effective communication of complex forensic findings to juries and other stakeholders during legal proceedings.
Moreover, the multi-application nature of geospatial-VR techniques in forensic CSI extends beyond crime scene reconstruction to various forensic disciplines, including pathology, bullet trajectory analysis, and evidence searching. This versatility underscores the potential for geospatial-VR to become a cornerstone of modern forensic investigations, offering holistic solutions that address a wide range of investigative challenges. Additionally, the development of automated systems for evidence trajectory tracking represents a significant advancement in forensic CSI practices. By harnessing the power of artificial intelligence and machine learning algorithms, these systems can analyze vast amounts of data to identify and track relevant objects, streamlining the investigative process and providing valuable insights into case dynamics.

In conclusion, the implications of this scenario emphasize the transformative impact of technology on forensic science and crime scene investigation. By embracing innovative tools and methodologies such as laser scanning, photogrammetry, virtual reality, and automated tracking systems, forensic practitioners can enhance their capabilities, ultimately leading to more effective and efficient investigative outcomes and ensuring justice is served.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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