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 SURVEY

# 3D Forensic Crime Scene Reconstruction Involving Immersive Technology: A Systematic Literature Review

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**ABSTRACT** Recreation of 3D crime scenes is critical for law enforcement in the investigation of serious crimes for criminal justice responses. This work presents a premier systematic literature review (SLR) that offers a structured, methodical, and rigorous approach to understanding the trend of research in 3D crime scene reconstruction as well as tools, technologies, methods, and techniques employed thereof in the last 17 years. Major credible scholarly database sources, Scopus, and Google Scholar, which index journals and conferences that are promoted by entities such as IEEE, ACM, Elsevier, and SpringerLink were explored as data sources. Of the initial 17, 912 papers that resulted from the first search string, 258 were found to be relevant to our research questions after implementing the inclusion and exclusion criteria. To summarize the existing efforts, we compared and analysed various classical 3D reconstruction approaches. This study presents the first comprehensive review of key milestones in the development of methods for 3D crime scene reconstruction, gaps for improvement and where immersive technology has been used to enhance crime scene findings. This study found that the implementation of light detection and ranging (LiDAR) scanners and immersive technologies, alongside traditional methods, has been beneficial in the recreation of crime scenes. The SLR is limited to existing applications with peer-reviewed papers published between 2005 and 2021. Results based on the analysed published data indicated that 20.2% of the articles implemented immersive technologies in crime scene reconstruction, of which Augmented Reality (AR) accounted for 15.3%, Virtual Reality (VR) accounted for 75%, Mixed reality (MR) accounted for 5.9% and VR and AR mixture accounted for 3.8%. Finally, we summarize the development trend of design and key technology prospects of crime scene recreation using immersive technology and provide insights into potential future research. To the best of the researchers' knowledge, this is the first survey that accomplishes such goals.

**INDEX TERMS** Crime scene, 3D reconstruction, forensic investigation, image forensic, immersive technology, augmented reality, virtual reality, systematic literature review (SLR).

## I. INTRODUCTION

Safety and security with a reliable justice system are essential factors in strengthening the economic development of a country. 3D crime scene recreation and analysis are critical for law enforcement in the investigation of serious crimes for reliable criminal justice responses [1]. A crime scene is the location where an offense has been committed and

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forensic evidence can be collected [2], [3]. Forensic investigation, analysis and evidence collection could involve a number of scenarios such as, blood pattern analysis [4], [5], [6], [7], post-mortem 3D full-body documentation [8], [9], [10], footwear impressions [11] and fingerprint analysis [12], [13], to mention a few. Expertise of forensic tools and services provides the investigator with the ability to identify and seize on evidence opportunities that would otherwise not be possible [14]. The evidence gathered are required for criminal justice response, among others. The derived evidence can also

assist in identifying crime committing trends and potential suspects, which is an important goal for crime intelligence and forensic analysts. The evidence is useful in various ways, which include:

- Identification of potential suspects
- Apprehension of prime suspects
- Fair and consistent sentencing by the jury
- Criminal profiling and discovery of serial crime
- Better attribution of past crimes
- Determination of mitigation priorities

Notably, 3D scanning is also used in many industry sectors or scenarios to design and manufacture products, among others. However, unlike other scenarios, forensic information needs to be collected within an acceptable time and with some level of precision, using credible measurement techniques [15], [16]. Furthermore, as presented in Table 1, such information should be non-invasive, complete, and compatible with digital storage for future access and utilization [17].

**TABLE 1. Comparison between attributes of forensic crime scene information and some other scenarios [18].**

Dimension	Forensic Crime Scene	Other Scenes
Timeliness	Very critical to capture details within an acceptable time frame before the evidence begin to degrade	May allow for some delay
Invasion	Zero tolerance for intrusion	Could perhaps be overlooked
Accuracy	Highly accurate details are required for thorough investigation	May or may not be critical. Some level of error may be tolerated
Completeness	Very critical, omission is not permitted. Every detail must be captured - no missing item.	May overlook some details

3D crime scene reconstruction is a very important component in the law enforcement process of serious crime investigation because it assists in gathering factual 3D information in order to solve crime issues. It is important to recognize that a forensic crime scene is relatively more sensitive to manage when compared to other scenes or scenarios. As highlighted in Table 1, some of the pertinent issues associated

with physically being at the scene are risk of contamination and destruction of evidence, which may hinder the criminal investigators to access or revisit the scene as often as required [15]. Therefore, it is expedient to visually capture the crime scene and any possible evidence to document and ensure the longevity of a crime scene, in order to aid crime investigation.

Traditional means of forensic and crime scene documentation include digital media (photography and videography), hand sketches, manual measurements, and paper documentation [19], [20], [21], [22]. However, traditional means of registering crime scene information fall short in achieving or maintaining the required integrity of crime information [23]. Hence, the evolution of crime scene reconstruction tools and techniques over the years in order to improve the efficiency, reliability and accuracy of the criminal justice system and further strengthen the security cluster. Furthermore, the advent of immersive technology such as AR [24], [25] and VR [26], [27] as well as advancement in the development of 3D sensor technologies [28], [29], [30], which are capable of obtaining 3D scans of crime scenes, have revolutionized forensic science and the ways in which crime scenes can be analysed. This development, together with the importance of forensic evidence in the criminal justice system, has motivated several forensic investigators and researchers to investigate and implement tools, methods, and approaches to reliable crime scene data collection.

In the past two decades, a lot of researchers have looked into 3D crime scene reconstruction using various methods and approaches [31], [32], [33]. There has also been further consideration for the implementation of immersive technology such as VR headsets to facilitate an immersive crime scene re-enactment [34], [35], integrating three-dimensional (3D) scanners to help generate 3D models for crime scenes [36], [37] and the capturing of crime scene video sequences to render 3D models [38]. Hence, a vast amount of literature has been produced and cited in the area of 3D forensic investigation and crime scene reconstruction, each having their potential merits and demerits. However, there is a shortage of comprehensive SLR on 3D crime scene reconstruction. Furthermore, the authors of the current research did not find a structured systematic survey of the existing research efforts in this domain of interest. This has motivated the need for a SLR on 3D scene reconstruction and forensic investigation.

This work provides a core foundation for SLR on 3D scene reconstruction and forensic investigation, while highlighting the developments, related challenges, and improvements to the accuracy of forensic applications and 3D scene reconstruction over the past 17 years. The aim is to organize and summarize the significant existing pieces of evidence so as to guide future research in understanding the trend of developments in 3D crime scene reconstruction as well as tools, technologies, methods, and techniques employed thereof in the last 17 years. This SLR aims to cover literature from Jan 2005 to December 2021. The primary contributions of this SLR are to answer five key research questions (RQ).

To accomplish the objective of the SLR, authors followed the guidelines set by Weidt *et al.* [39], and thus proposed several research questions that focus on systematizing and structuring the research on crime scene reconstruction application. In what follows, this work presents a comprehensive overview of 3D crime reconstruction and evaluates the following:

1. RQ1: What research areas have been explored with respect to crime scene reconstruction and forensic investigation? Which are the relevant publication channels and prevalent countries for 3D Scene reconstruction research?
2. RQ2: What are the traditional methods of gathering crime scene data? How have these methods evolved and supported crime scene reconstruction and forensic investigation over the years?
3. RQ3: What problems and limitations have been discovered while using the traditional methods? How have these limitations been improved upon over the years, and what tools, technologies and approaches have evolved over the years?
4. RQ4: How have immersive technologies improved 3D crime scene reconstruction and forensic investigation? Which of the technologies (augmented reality (AR), virtual reality (VR) or mixed reality (MR)) have mostly been used? What are the potential limitations or challenges identified with implementing this technology?
5. RQ5: What assessment methods have been employed to evaluate proposed methods of crime scene data gathering?

We present a first comprehensive review of the key milestones in the development of methods for 3D crime scene reconstruction with a focus on key tools, approaches, technologies, and challenges in crime scene reconstruction. The methodology of this SLR is adapted from established guidelines, [39], [40]. The remainder of this paper is structured as follows: Section 2 presents the related research and further justifies the novelty of our research. Section 3 provides details on the research methodology. Section 4 presents the results and detailed analysis, while Section 5 concludes the paper and provides future recommendations.

## II. RELATED WORK

This section discusses some of the previous research efforts that relate to review on 3D scene reconstruction or forensic investigation. It was found that most of the existing surveys have focused on a specific aspect of 3D scene reconstruction or scanning technologies, and none has presented a comprehensive methodical survey on trends of 3D scene reconstruction and forensic investigation with an exploration of immersive technology as done in this work.

A recent survey on geomatic techniques in forensic science by Berezowski *et al.* [18] presents various geomatic techniques that crime scene reconstructionists or forensic practitioners can use to document different kinds of scenes, while highlighting the merits, demerits, and ideal situation in which each technology can be used.

Galanakis *et al.* [41] present a study on the state of 3D digitization scanning technologies with a focus on crime prevention, crime investigation, and the education of law enforcement agencies (LEAs). Their work summarizes and analyses the state-of-the-art technologies in scene documentation and uses a multi-modal dataset from a hypothetical indoor crime scene to support their research. However, their research is different from the current effort in this study, which provides a structured and systematic summary on the trend of 3D scene reconstruction and forensic investigation in the last 17 years.

Costantino *et al.* [42] present an integrated survey methodology for crime scene reconstruction. The objective of their study was to evaluate the applicability of photogrammetry and laser scanner techniques both on forensic ballistic reports and on reproduction of crime scenes. Their survey however did not clearly describe trends of crime scene reconstruction but rather focused on two main technologies, which are photogrammetry and laser scanner techniques. Also, the authors did not conduct a systematic literature review.

Ropero-Miller *et al.* [43] present a landscape study on 3D terrestrial laser scanning technology based on input from industry, law enforcement, forensic, and criminal justice system communities, as part of their methodology. Their aim was to provide a comprehensive list of market participants, their products, and product features to enable better-informed decisions by end users. The comparisons of the capabilities of commercially available 3D laser scanning instruments were also presented. Similarly, Lewis [44] presents a study survey on 3D crime scene scanning devices, which more or less summarizes the work of J. Ropero-Miller *et al.*

This current work distinguishes itself from the aforementioned reviews and surveys by focusing on publication channels in 3D crime scene reconstruction and forensic investigation and presenting a comprehensive SLR that is focused on 3D crime scene reconstruction in the last 17 years, highlighting the trend of immersive technologies in crime scene reconstruction as well as various technologies and modalities considered in this domain of interest. Table 2 presents an overview of related research and an aspect-wise comparison of existing reviews with our review, which further justifies how this work differs from existing research and contributes to the body of knowledge in this domain of interest. This SLR found that most of the existing surveys are limited in scope and conducted in an informal manner, whereas our work used a systematic review approach with detailed analysis.

## III. RESEARCH METHOD

This work was grounded in a SLR framework of tools, technologies with methods and techniques used in 3D crime scene reconstruction by adopting guidelines provided by Weidt and Silva [39] and Torres-Carrion *et al.* [39] as models. These guidelines can be summarized into four major phases, which entails planning, conducting, assessment and reporting the review. The approach is further summarized in Figure 1 as implemented in this research.

**TABLE 2.** Comparison with related research and justification for the novelty in our research.

Paper	Focus	Year span	Newest ref.	Survey approach	Aspects of 3D scene reconstruction trend				Targeted digital repositories
					Quality assessment scored	Datasets used	Explored Immersive technology	Potential gaps	
S. Colwill [45]	Applying low-cost 3D mapping to crime scene investigation and forensic evidence	13	2016	Informal	x	✓	x	✓	Not indicated
D. Costantino et al., [42]	Integrated Survey methodology on applicability of photogrammetry and laser scanner techniques on forensic ballistic reports and reproduction of crime scenes.	8	2016	Informal	x	✓	x	✓	Not indicated
J. Roper-Miller et al., [43]	Landscape Study on 3D terrestrial laser scanning technology	15	2016	Semi-formal	x	✓	x	✓	2
V. Berezowski et al., [18]	A review on Geomatic techniques in forensic science.	12	2020	Informal	x	x	x	✓	Not indicated
G. Galanakis et al., [41]	3D Digitisation Modalities for Crime Scene Investigation	6	2021	Informal	x	✓	✓	✓	Not indicated
This survey	Methodical approach to 3D Crime Scene Reconstruction modalities, evolving Immersive Technology	17	2022	Systematic search, snowballing and assessment	✓	✓	✓	✓	7

## A. SEARCH STRATEGY AND DATA SOURCES

### 1) SEARCH STRING AND KEYWORDS

Creating a good search string is critical in obtaining relevant results and publications needed for the study. This was done using a structured approach in terms of population, comparison, intervention, and outcome [39]. Relevant publications were identified by creating a search string that combined keywords guided by the research questions earlier established. Figure 2 presents the search keywords that were used to identify papers that were included in our knowledge base. The search operations were conducted by employing credible

and standard scholarly database indexes, such as Scopus and Google Scholar, as presented in Table 3. The search strings are “Crime investigation” OR “Forensic reconstruction” OR “Crime recreation” OR “Forensic investigation digitization” OR “3D crime scene tools and technologies” OR “Immersive crime scene reconstruction” OR “Forensic tools and technologies”.

### 2) DATA SOURCES

There are several academic databases and search engines. However, this study consulted two standard and credible

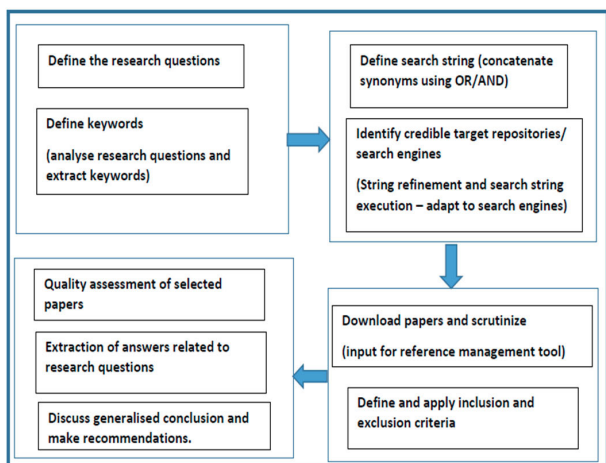


FIGURE 1. Guideline implemented when conducting the SLR in this work.

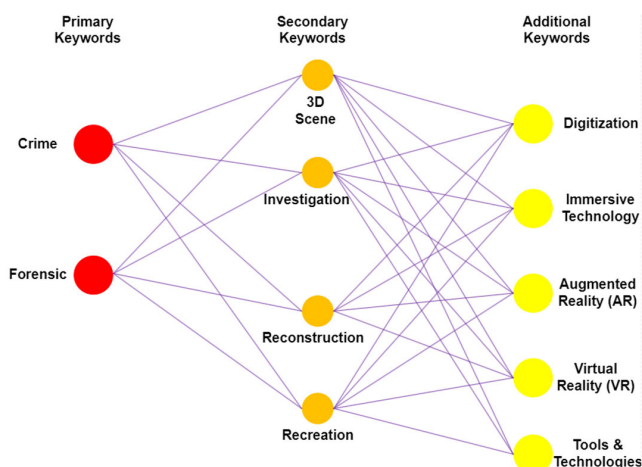


FIGURE 2. Search keywords used to identify relevant articles of interest.

scholarly database sources, which includes and promotes entities such as IEEE, ACM, ScienceDirect, and ResearchGate, among others. The main data sources are:

- a. Google Scholar<sup>1</sup>: Google Scholar is a freely accessible web search engine that indexes the full text or metadata of scholarly literature across an array of publishing formats and disciplines.
- b. Scopus<sup>2</sup>: This is a bibliographic database of research publications containing abstracts and citations for academic journal articles launched in 2004. Scopus uniquely combines a comprehensive, expertly curated abstract and citation database with enriched data and linked scholarly literature across a wide variety of disciplines. Scopus quickly finds relevant and authoritative research, identifies experts, and provides access to reliable data, metrics, and analytical tools.

<sup>1</sup><https://scholar.google.com/>

<sup>2</sup><https://www.scopus.com>

TABLE 3. Search strategy decisions.

<b>Utilized digital repositories</b>	Google Scholar, Scopus, IEEE Xplore, ACM digital library, ScienceDirect, ResearchGate, SpringerLink
<b>Searched paper types</b>	Conference papers, Journal papers, and Technical reports
<b>Search Applied On</b>	Research papers whose abstracts relate to 3D crime scene recreation or reconstruction; Papers that were written in source language English; Papers with an abstract or introduction that clearly states or describes the contribution of the work.
<b>Publication Period</b>	Since January 2005 - 2021 (17 years)

- c. IEEE Xplore<sup>3</sup>: This is a standard digital research library which provides access to more than five million full-text documents. It offers access to journal articles, conference proceedings, and technical standards on various scientific topics.
- d. ScienceDirect<sup>4</sup>: ScienceDirect is a subscription-based database which houses scientific and medical research. It contains the world’s largest electronic collection of full-text and bibliographic information on science, technology, and medicine. It contains more than 15 million scientific articles and is one of the subsidiaries of Elsevier, the world’s largest scientific publisher.
- e. ResearchGate<sup>5</sup>: ResearchGate is a professional social networking site for researchers and scientists. The platform helps researchers connect and make it easy for them to share and access scientific output, knowledge, and expertise
- f. ACM Digital Library<sup>6</sup>: This is one of the world’s most comprehensive databases, covering bibliographic literature in computing and information technology, among others.
- g. SpringerLink<sup>7</sup>: SpringerLink provides researchers with access to millions of scientific documents ranging from journals, books, series, protocols, reference works and proceedings.

**B. DATA RETRIEVAL AND STUDY SELECTION**

The search for most related articles and research was conducted in Google Scholar and Scopus since most of the high impact conferences and journal articles are indexed in these standard scholarly sources. The Boolean “OR” was used in

<sup>3</sup><https://ieeexplore.ieee.org>

<sup>4</sup><https://www.sciencedirect.com>

<sup>5</sup><https://www.researchgate.net/>

<sup>6</sup><https://www.acm.org>

<sup>7</sup><https://springer.com/link>

combining the search strings that were considered as earlier noted. A total of 17 912 articles were retrieved from the search exercise as shown in Table 4.

TABLE 4. First search string result.

	Scopus	Google Scholar	Total
Number of papers	412	17500	17 912

Further refinement was done by sifting the articles presented from the first search string as follows: (i) limiting the search to mainly journals, conferences, and technical reports; (ii) selecting forensics and computer science focal subject domains. From the initial search string that resulted in 17 912 papers, 15 676 papers were excluded resulting in 2233 papers (see Table 5).

TABLE 5. Second search string result.

	Scopus	Google Scholar	Total
Number of papers	83	2150	2233

1) INCLUSION CRITERIA

This study carefully selected relevant articles that promote the research objective using certain inclusion and exclusion criteria. The inclusion criteria entail: (i) Studies related to the research questions; (ii) Studies mostly published between 2005 and 2021; and (iii) Studies that can be found in credible scholarly databases. Papers published in peer conference proceedings, journals, technical symposiums, and workshops were included in the SLR.

TABLE 6. Final selection.

	Scopus	Google Scholar	Total
Number of papers	37	221	258

2) EXCLUSION CRITERIA

Papers that belong to the following categories were excluded from the selection as part of the primary study: (i) Papers whose abstract do not relate to 3D crime scene recreation or reconstruction; (ii) Papers that are written in source languages other than English; and (iii) Papers with an abstract or introduction that does not clearly state or describe the contribution of the work. Table 6 shows the final selection used.

C. QUALITY ASSESSMENT

Having finalized the paper selection process based on the inclusion and exclusion criteria, a 12-question quality assessment (QA) checklist was conducted to gauge the viability of

TABLE 7. Quality assessment checklist for the papers used.

S/N	Questions (Features Checklist)	Score
1.	Are the aims or objectives of the study clearly stated?	Y/N/P
2.	Does the paper mention/describe any 3D crime scene reconstruction or recreation methods?	Y/N/P
3.	Was the study planned to accomplish the stated aims and objectives?	Y/N/P
4.	Do the researchers conduct experimental work and was this described in sufficient details?	Y/N/P
5.	Do the proposed methodologies provide an advancement on traditional methods of data gathering?	Y/N/P
6.	Are the assessment methods or evaluation metrics reported clearly?	Y/N/P
7.	Does this paper consider any immersive technologies?	Y/N/P
8.	Are the data collection process, software and hardware tools used clearly described?	Y/N/P
9.	Do the researchers identify any relevant issues in their study?	Y/N/P
10.	Does the conclusion align with the experimental work and relevant state of the art research?	Y/N/P
11.	Do the authors provide any future recommendations?	Y/N/P
12.	Can research question(s) be answered in the study?	Y/N/P

the chosen papers. This was conducted in order to analyse and ensure that the studied papers align with the initial objectives that were set for the SLR, in order to achieve the end goal. Table 7 presents the customized QA system that was used in this SLR. In the QA checklist, a paper can receive a maximum rating of 12 points, which is based on the total number of features or questions evaluated. The point system is based on a yes (Y), no (N) and partially (P) system. Y represents a total mark of one (1) if the feature is fully present, N represents a total mark of zero (0) if the feature is absent, while P

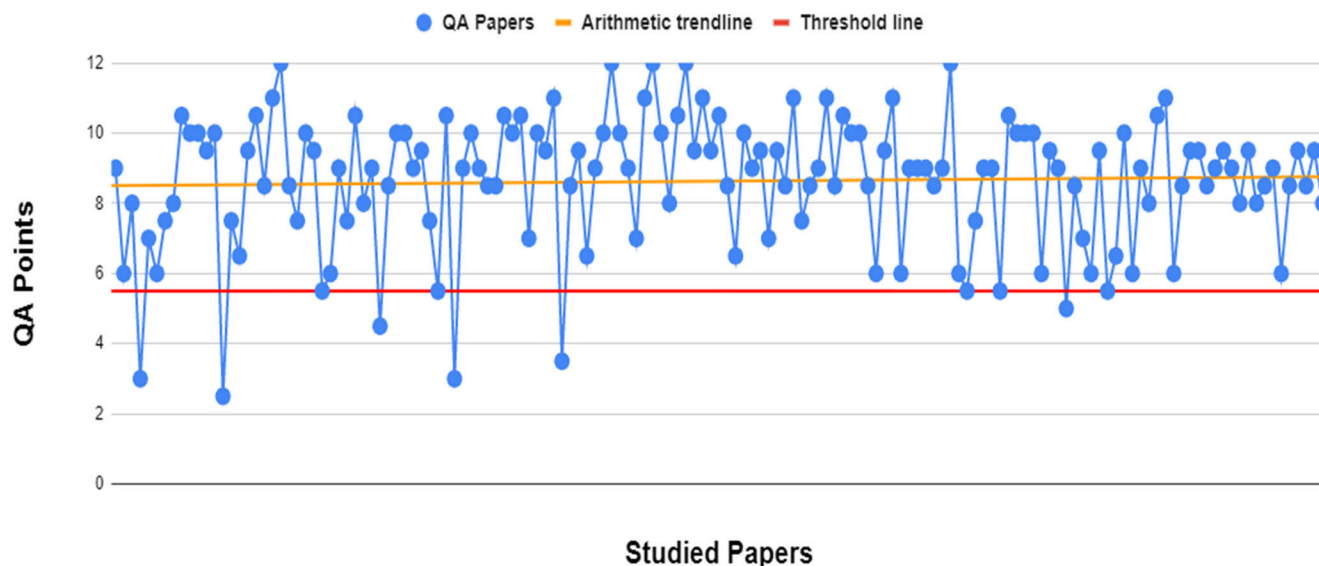


FIGURE 3. Line graph used to illustrate the trend and threshold for the QA point system.

represents a total mark of zero point five (0.5) if the feature is only partially absent or present. Strict guidelines are adhered to when considering whether a paper is scientifically sound based on the QA system. A randomly selected sample size comprising 142 papers ranging from 2005 to 2021 was used to foreshadow a glimpse of how our total paper size would fare in the QA as presented in Table 8. Figure 3 shows the distribution of the scores of the studied papers based on the QA. In order to establish the threshold line, the data points were sorted in ascending order and the first quartile formula was utilized (i.e.,  $(n+1)/4$ ), where  $n$  is the total number of sample data points. This equates to a position in the range of QA points that corresponds to point 5.5. Thus, the threshold line equates to 5.5 as seen in figure 3. Hence, a paper with a QA point above 5.5 and beyond is considered as a good candidate for the research. The arithmetic trend line is automatically derived from linear arithmetic averages as the paper count and points are calculated.

**D. POTENTIAL STUDY LIMITATION: THREATS TO VALIDITY**

The potential threat to the validity of this SLR hinges on the fact that we have excluded papers that do not contain the highlighted keywords used in the search criteria. Hence, we may have overlooked some studies that have not specifically used these keywords but are somewhat related to research done in this domain of interest. However, the researchers concede that while this is possible the probability or impact of this threat should be minimal.

**IV. RESULTS AND DISCUSSIONS ON RESEARCH QUESTIONS**

The findings of the study are now presented with respect to the research questions that served as the guideline for the systematic literature review.

**A. RESEARCH QUESTION 1: WHAT RESEARCH AREAS HAVE BEEN EXPLORED WITH RESPECT TO CRIME SCENE RECONSTRUCTION AND FORENSIC INVESTIGATION? WHICH ARE THE RELEVANT PUBLICATION CHANNELS AND PREVALENT COUNTRIES FOR 3D SCENE RECONSTRUCTION RESEARCH?**

Identifying and understanding the trend of developments in forensic investigation and 3D crime scene reconstruction is critical for researchers and forensic investigators. In what follows, an insightful knowledge of publication trend, types, year, and geographical distribution of selected papers over the studied 17 years is presented.

Figure 4 shows the distribution of the selected paper count for each year. Evidently, the research on forensic investigation and 3D crime scene reconstruction over the studied years

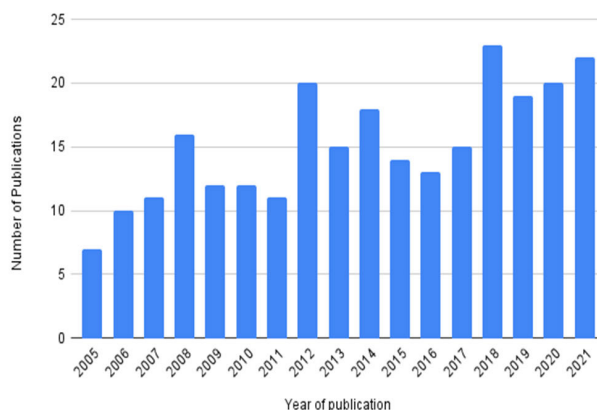


FIGURE 4. Timeline of forensic 3D scene reconstruction methods development (year-wise distribution of selected studies).

**TABLE 8.** Quality assessment (QA) criteria scoring.

Quality Assessment (QA)													
Study Ref.	QA1	QA2	QA3	QA4	QA5	QA6	QA7	QA8	QA9	QA10	QA11	QA12	Score (Y/N/P)
L. S. Wilk et al., [46]	Y	Y	Y	Y	P	Y	N	Y	Y	Y	N	P	9
A. Feola et al., [47]	N	Y	N	N	Y	Y	N	N	Y	Y	N	Y	6
K. Osman et al., [48]	Y	N	Y	N	Y	P	N	P	Y	Y	Y	Y	8
P. Thiruchelvam et al., [49]	P	Y	N	P	Y	P	N	Y	Y	Y	N	P	7
Singh et al., [4]	Y	N	Y	Y	N	N	N	P	P	Y	N	Y	6
Sieberth et al. [50]	P	Y	P	Y	P	N	Y	Y	Y	Y	N	N	7.5
McCleary et al., [51]	Y	N	Y	Y	P	Y	N	Y	N	Y	P	Y	8
Luchowski et al., [52]	Y	Y	Y	Y	Y	Y	P	Y	Y	Y	N	Y	10.5
Liscio et al., [53]	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	N	Y	10
Quang et al., [54]	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	N	Y	10
Larsen et al., [55]	Y	Y	Y	Y	Y	Y	N	Y	P	Y	N	Y	9.5
Kislov et al., [56]	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	N	Y	10



**TABLE 8.** (Continued.) Quality assessment (QA) criteria scoring.

Jegatheswaran et al., [57]	Y	Y	P	P	Y	N	Y	P	N	Y	N	Y	7.5
Jani et al., [58]	Y	Y	P	P	Y	N	N	Y	Y	P	N	N	6.5
G. Griffiths et al., [59]	Y	Y	Y	Y	P	Y	N	Y	Y	Y	N	Y	9.5
G. Galanakis et al., [41]	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	P	Y	10.5
R. Faflak et al., [60]	Y	N	Y	Y	Y	Y	N	Y	P	Y	N	Y	8.5
J. Desai et al., [61]	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	11
C. Reichherzer et al., [62]	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	12
M. A. Mat Amin et al., [63]	Y	Y	Y	Y	Y	Y	N	Y	N	Y	P	N	8.5
W. Baier et al., [64]	Y	Y	Y	P	Y	P	N	P	N	Y	N	Y	7.5
V. Berezowski et al., [18]	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	N	Y	10
U. Buck et al., [33]	Y	Y	Y	Y	Y	Y	N	Y	Y	P	N	Y	9.5
G. Dass et al., [65]	P	Y	Y	N	Y	N	N	P	Y	N	N	P	5.5
G. Jani et al., [66]	Y	Y	Y	N	Y	P	N	N	N	Y	N	P	6
S. N. Kader et al., [26]	Y	Y	P	P	Y	P	Y	N	Y	Y	Y	P	9

**TABLE 8.** (Continued.) Quality assessment (QA) criteria scoring.

A. Kovaleva et al., [67]	Y	Y	Y	N	Y	N	N	P	Y	Y	N	Y	<b>7.5</b>
R. Carew et al., [68]	Y	Y	Y	P	Y	Y	N	Y	Y	Y	Y	Y	<b>10.5</b>
C. Sautier et al., [69]	Y	Y	Y	P	Y	Y	N	P	Y	Y	N	N	<b>8</b>
O. Esaias et al., [70]	Y	N	Y	Y	Y	Y	N	Y	Y	Y	N	Y	<b>9</b>
A. Porzionato et al., [71]	Y	Y	Y	Y	Y	Y	N	P	N	Y	N	Y	<b>8.5</b>
G. Rusman et al., [72]	Y	Y	Y	Y	Y	P	Y	Y	N	Y	P	Y	<b>10</b>
K. Sheppard et al., [73]	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	N	Y	<b>10</b>
M. Walters et al., [74]	Y	N	Y	Y	Y	Y	N	Y	Y	Y	N	Y	<b>9</b>
I. Aquila et al., [32]	Y	Y	Y	Y	Y	P	N	Y	Y	Y	N	Y	<b>9.5</b>
P. M. Barone et al., [75]	Y	Y	Y	Y	Y	Y	N	P	P	N	N	P	<b>7.5</b>
U. Buck et al., [76]	N	Y	P	N	Y	N	N	P	Y	P	N	Y	<b>5.5</b>
K. Ponto et al., [77]	Y	Y	Y	Y	Y	Y	N	P	Y	Y	N	Y	<b>10.5</b>
H. Honsberger et al., [78]	Y	Y	Y	Y	Y	Y	N	Y	N	Y	N	Y	<b>9</b>

**TABLE 8.** (Continued.) Quality assessment (QA) criteria scoring.

Q. Le et al., [79]	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	N	Y	<b>10</b>
S. Liu, [80]	Y	Y	Y	Y	Y	N	N	Y	Y	Y	N	Y	<b>9</b>
X. Liu et al., [81]	Y	Y	Y	Y	Y	Y	N	Y	N	Y	N	P	<b>8.5</b>
V. Mach et al., [34]	Y	Y	Y	N	Y	P	Y	Y	N	Y	N	Y	<b>8.5</b>
T. Sieberth et al., [82]	Y	Y	P	P	Y	Y	Y	Y	Y	Y	P	Y	<b>10.5</b>
T. Sieberth et al., [83]	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	N	Y	<b>10</b>
M. Süncksen et al., [84]	Y	Y	Y	P	Y	Y	Y	Y	Y	Y	N	Y	<b>10.5</b>
M. Worring et al., [85]	Y	N	Y	P	Y	Y	Y	N	P	Y	N	N	<b>7</b>
R. Tredinnick et al., [28]	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	N	Y	<b>10</b>
J. Wang et al., [2]	Y	Y	Y	P	Y	Y	Y	Y	Y	P	N	Y	<b>9.5</b>
S. Becker et al., [86]	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	<b>11</b>
K. Rao et al., [87]	Y	Y	Y	Y	Y	Y	N	N	Y	P	Y	N	<b>8.5</b>
K. Lech et al., [88]	Y	Y	Y	Y	Y	P	N	Y	Y	Y	N	Y	<b>9.5</b>

**TABLE 8.** (Continued.) Quality assessment (QA) criteria scoring.

S. Bandyopadhyay, [89]	Y	N	Y	N	P	N	N	P	Y	Y	Y	P	<b>6.5</b>
C. Villa et al., [90]	Y	Y	Y	Y	Y	Y	N	Y	N	Y	N	Y	<b>9</b>
G. J. Edelman et al., [91]	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	N	Y	<b>10</b>
O. Komulainen et al., [92]	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	<b>12</b>
E. Liscio et al., [93]	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	N	Y	<b>10</b>
J. Nelis, [94]	Y	Y	Y	N	Y	P	Y	Y	Y	P	N	Y	<b>9</b>
T. Pollok, [95]	P	Y	P	N	Y	Y	N	Y	N	Y	N	Y	<b>7</b>
D. Raneri, [20]	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	<b>11</b>
C. Reichherzer et al., [96]	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	<b>12</b>
P. Ren et al., [97]	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	N	Y	<b>10</b>
J. Ševčík et al., [36]	Y	Y	P	N	Y	P	Y	Y	N	Y	N	Y	<b>8</b>
T. Sieberth et al., [98]	Y	Y	Y	Y	Y	Y	N	Y	P	Y	Y	Y	<b>10.5</b>
S. Singh, [99]	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	<b>12</b>

**TABLE 8.** (Continued.) Quality assessment (QA) criteria scoring.

T. Wieczorek et al., [100]	Y	Y	Y	P	Y	Y	N	Y	Y	Y	N	Y	9.5
E. K. A. Zurgani, [101]	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	11
D. Abate et al., [102]	Y	Y	Y	Y	P	Y	N	Y	Y	Y	N	Y	9.5
C. Dath et al., [103]	Y	Y	Y	N	Y	P	Y	Y	Y	Y	Y	Y	10.5
M. de Gruijter et al., [104]	Y	Y	N	P	Y	Y	N	Y	Y	Y	N	Y	8.5
R. de Leeuwe, [105]	P	Y	P	Y	Y	N	N	N	P	Y	N	Y	6.5
S. Giancola et al., [106]	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	N	Y	10
K. Bahirat et al., [37]	Y	Y	N	Y	Y	Y	N	Y	Y	Y	N	Y	9
A. Leipner et al., [107]	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	N	P	9.5
J. Mai et al., [108]	Y	Y	Y	N	Y	Y	N	P	N	Y	N	P	7
A. Marcin et al., [109]	Y	Y	Y	Y	Y	Y	N	Y	P	Y	N	Y	9.5
P. Ren et al., [110]	Y	Y	P	N	Y	Y	Y	Y	N	Y	N	Y	8.5
R. Rider et al., [111]	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	11

**TABLE 8.** (Continued.) Quality assessment (QA) criteria scoring.

J. Sivanandan et al., [112]	Y	N	P	Y	P	Y	N	Y	P	Y	N	Y	<b>7.5</b>
C. Villa et al., [113]	Y	Y	Y	P	Y	P	N	Y	P	Y	N	Y	<b>8.5</b>
C. Villa, [114]	Y	Y	Y	Y	Y	Y	N	Y	N	Y	N	Y	<b>9</b>
S. Colwill et al., [45]	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	<b>11</b>
M. Wrona et al., [115]	<b>Y</b>	<b>Y</b>	<b>Y</b>	<b>Y</b>	<b>Y</b>	<b>Y</b>	<b>N</b>	<b>P</b>	<b>N</b>	<b>Y</b>	<b>N</b>	<b>Y</b>	<b>8.5</b>
D. Costantino et al., [42]	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	P	Y	<b>10.5</b>
E. Hołowko et al., [116]	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	N	Y	<b>10</b>
H. Liu et al., [31]	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	N	Y	<b>10</b>
Q. Milliet et al., [117]	Y	Y	Y	P	Y	Y	N	Y	N	Y	N	Y	<b>8.5</b>
G. Naveen et al., [118]	Y	N	Y	N	P	N	N	N	P	Y	Y	Y	<b>6</b>
M. R. Osman et al., [119]	Y	Y	Y	Y	Y	Y	N	P	N	Y	Y	Y	<b>9.5</b>
J. Pieszala et al., [120]	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	<b>11</b>
A. Shinde et al., [121]	P	N	Y	N	P	N	N	N	Y	Y	Y	Y	<b>6</b>

**TABLE 8.** (Continued.) Quality assessment (QA) criteria scoring.

M. Zheng et al., [122]	Y	Y	Y	N	Y	Y	N	Y	Y	Y	N	Y	<b>9</b>
G. Acampora et al., [123]	Y	N	Y	Y	Y	Y	N	Y	Y	Y	N	Y	<b>9</b>
N. Laan et al., [124]	<b>Y</b>	<b>P</b>	<b>Y</b>	<b>Y</b>	<b>Y</b>	<b>Y</b>	<b>N</b>	<b>P</b>	<b>Y</b>	<b>Y</b>	<b>N</b>	<b>Y</b>	<b>9</b>
J. I. Olszewska et al., [125]	Y	Y	Y	Y	Y	Y	N	P	N	Y	N	Y	<b>8.5</b>
P. Joris et al., [126]	Y	N	Y	P	Y	Y	N	P	Y	Y	Y	Y	<b>9</b>
A. Conway et al., [127]	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	<b>12</b>
S. K. Bandyopadhyay et al., [128]	Y	N	Y	N	Y	N	N	N	Y	Y	N	Y	<b>6</b>
A. Tajani, [129]	Y	N	Y	N	P	Y	N	Y	N	N	N	Y	<b>5.5</b>
N. M. M. Noor et al., [130]	<b>Y</b>	<b>P</b>	<b>Y</b>	<b>Y</b>	<b>Y</b>	<b>P</b>	<b>N</b>	<b>N</b>	<b>N</b>	<b>Y</b>	<b>N</b>	<b>N</b>	<b>6</b>
V. Mastronardi et al., [131]	Y	Y	Y	Y	Y	P	N	N	Y	P	N	Y	<b>7.5</b>
S. R. Bucheli et al., [30]	Y	Y	Y	Y	Y	Y	N	Y	N	Y	N	Y	<b>9</b>
K. Maksymowicz et al., [132]	P	Y	Y	P	Y	Y	N	Y	Y	Y	N	N	<b>9</b>
Q. Milliet et al., [133]	Y	N	Y	N	Y	P	N	N	Y	Y	N	N	<b>5.5</b>

**TABLE 8.** (Continued.) Quality assessment (QA) criteria scoring.

T. Booth et al., [134]	Y	Y	Y	Y	Y	P	P	P	Y	Y	Y	Y	<b>10.5</b>
L. C. Ebert et al., [135]	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	N	Y	<b>10</b>
J. Marques et al., [136]	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	N	Y	<b>10</b>
M. Hildebrandt et al., [137]	Y	N	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	<b>10</b>
B. Rai et al., [138]	Y	P	Y	N	Y	P	N	Y	N	Y	N	N	<b>6</b>
K. Tarrit et al., [139]	Y	Y	Y	P	Y	Y	N	Y	Y	Y	N	Y	<b>9.5</b>
W. Develter et al., [140]	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	N	N	<b>9</b>
K. Tonchev et al., [141]	Y	Y	Y	Y	Y	Y	N	N	P	Y	N	Y	<b>8.5</b>
T. Colard et al., [142]	Y	Y	Y	N	Y	Y	N	Y	N	Y	N	N	<b>7</b>
M. A. Sandholzer et al., [143]	Y	Y	P	N	Y	N	N	P	Y	Y	N	N	<b>6</b>
R. Ehigiator et al., [144]	Y	Y	Y	Y	Y	Y	N	P	Y	Y	N	Y	<b>9.5</b>
P. M. Puri et al., [145]	Y	Y	Y	N	Y	N	N	P	N	Y	N	N	<b>5.5</b>



**TABLE 8.** (Continued.) Quality assessment (QA) criteria scoring.

J. Huang et al., [146]	Y	N	Y	Y	P	Y	N	Y	N	Y	N	N	<b>6.5</b>
F. Andaló et al., [147]	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	N	Y	<b>10</b>
F. Ramsthaler et al., [148]	Y	N	Y	Y	P	Y	N	P	N	N	N	Y	<b>6</b>
M. A. Knox et al., [149]	Y	N	Y	Y	Y	Y	N	Y	Y	Y	N	Y	<b>9</b>
G. J. Edelman et al., [150]	Y	P	Y	Y	Y	Y	N	Y	N	Y	N	Y	<b>8</b>
S. Lukosch et al., [151]	<b>Y</b>	<b>Y</b>	<b>Y</b>	<b>P</b>	<b>Y</b>	<b>Y</b>	<b>Y</b>	<b>N</b>	<b>Y</b>	<b>Y</b>	<b>Y</b>	<b>Y</b>	<b>10.5</b>
P. M. Sauter, [152]	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	<b>11</b>
J. Larsen et al., [153]	P	N	Y	P	Y	Y	N	Y	Y	N	N	N	<b>6</b>
J. C. Bahamón et al., [154]	<b>Y</b>	<b>Y</b>	<b>Y</b>	<b>P</b>	<b>Y</b>	<b>N</b>	<b>Y</b>	<b>P</b>	<b>P</b>	<b>Y</b>	<b>N</b>	<b>Y</b>	<b>8.5</b>
F. Zhang et al., [155]	<b>Y</b>	<b>Y</b>	<b>Y</b>	<b>Y</b>	<b>Y</b>	<b>Y</b>	<b>N</b>	<b>P</b>	<b>Y</b>	<b>Y</b>	<b>N</b>	<b>Y</b>	<b>9.5</b>
A. K. Chong et al., [156]	<b>Y</b>	<b>P</b>	<b>Y</b>	<b>Y</b>	<b>Y</b>	<b>Y</b>	<b>N</b>	<b>Y</b>	<b>Y</b>	<b>Y</b>	<b>N</b>	<b>Y</b>	<b>9.5</b>
G. Edelman et al., [157]	P	Y	Y	Y	P	Y	N	P	Y	Y	N	Y	<b>8.5</b>

**TABLE 8.** (Continued.) Quality assessment (QA) criteria scoring.

U. Buck, [158]	Y	Y	Y	N	Y	P	P	Y	Y	Y	N	Y	9
F. Xu et al., [159]	P	P	Y	Y	Y	Y	Y	Y	P	Y	N	Y	9.5
D. de Angelis et al., [160]	Y	Y	Y	Y	Y	P	N	P	Y	Y	N	Y	9
G. Sansoni et al., [161]	P	Y	Y	N	Y	Y	N	P	Y	Y	N	Y	8
D. Gonzalez-Aguilera et al., [162]	Y	Y	Y	Y	Y	Y	N	Y	Y	P	N	Y	9.5
M. Wolff et al., [163]	Y	Y	Y	N	Y	Y	N	N	Y	Y	N	Y	8
B. Alefs et al., [164]	Y	Y	Y	Y	Y	P	N	N	Y	Y	N	Y	8.5
U. Buck et al., [165]	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	N	N	9
K. Franke et al., [166]	Y	Y	Y	N	N	P	N	P	P	Y	N	P	6
A. Ehlert et al., [167]	Y	Y	Y	N	Y	Y	N	P	Y	Y	N	Y	8.5
A. Brennecke et al., [168]	Y	Y	Y	P	Y	P	Y	P	Y	Y	Y	N	9.5
T. Dang et al., [169]	Y	Y	Y	Y	Y	Y	N	P	N	Y	N	Y	8.5
P. Fratini et al., [170]	Y	Y	Y	Y	Y	P	N	Y	Y	Y	N	Y	9.5
A. Cigada et al., [171]	Y	Y	Y	Y	Y	P	N	P	P	Y	N	P	8

have had a steady rise. Note that from 2005 to 2021 there has been an upward trend indicating that there is a growing need for research in crime scene reconstruction and forensic investigation. Furthermore, Figure 5 displays percentages of all the studied 258 papers ranging from 2005 to 2021, selected from Journals, Conferences, and Technical reports. Journals are generally considered far superior as opposed to the other categories. Hence, 60.8% of the papers selected for this study were derived from Journals. On the flip side, conference papers are also a great way to communicate, document new ideas, and introduce academic work to a wider audience of peers with shared interest. This accounts for the second largest value being 29.4%, and finally technical reports account for 9.8%. Figure 6 presents a continent-wise geographical distribution of researchers who have worked in this domain of interest. Researchers from Europe and North America combined accounts for 74.2%, which is almost three quarters (75%) of the SLR findings. Europe as a continent has a significant research contribution, while Africa and Antarctica tend to be in the lower end of the scale when compared to the other continents. Figure 7 further presents a graph illustrating the frequency of researchers across different countries. Researchers from the USA have contributed significantly to research in 3D scene reconstruction and forensic investigation, followed by Switzerland, Italy, England, and the Netherlands.

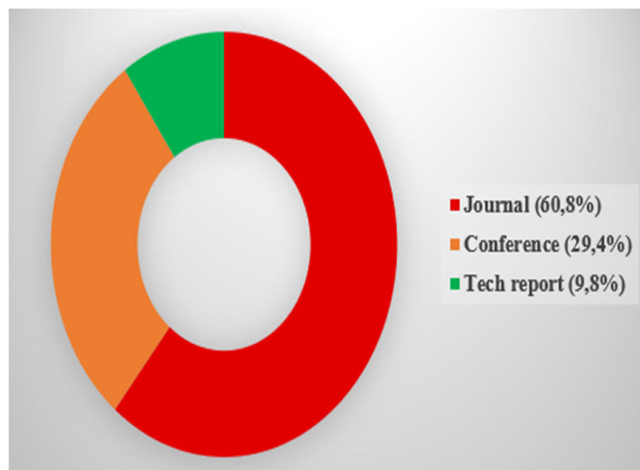


FIGURE 5. Percentage distribution of publication types of the 258 papers that were studied.

There are different applications of interest when considering 3D crime scene reconstruction and forensic investigation. The motivation for crime scene reconstruction is primarily to acquire geometric and qualitative information that could accurately describe the environment, victim(s), suspect, and pieces of evidence present on the scene. The research application areas on 3D crime scene reconstruction could range from a number of scenarios, depending on the motivation for the investigation. Major application domains identified in the studied years include bite-mark analysis ([172], [173], [174]), homicide scene reconstruction ([175], [176], [177]),

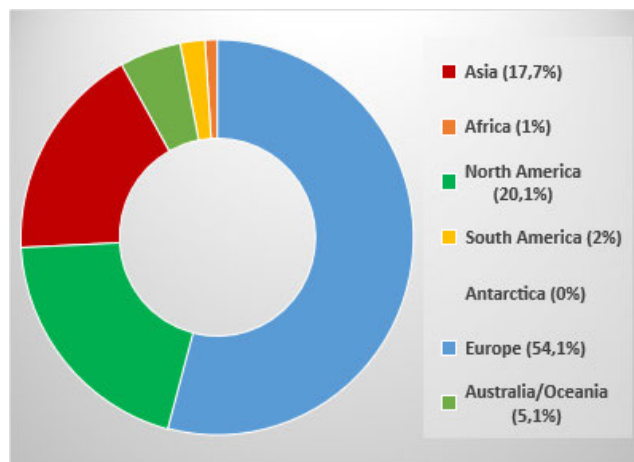


FIGURE 6. Frequency of paper distributions across all continents.

fingerprint analysis ([12], [178], [179]), footwear analysis ([11], [180], [181]), facial reconstruction ([141], [182], [183], [184], [185]), blood pattern analysis ([118], [186], [187], [188], [189]), Autopsy ([190], [191], [192], [193]) and bullet trajectory ([194], [195], [196]). Figure 8 summarizes the different sub-focus research areas that have been explored in this domain of interest and the frequency of paper distribution over the studied years.

**B. RESEARCH QUESTION 2: WHAT ARE THE TRADITIONAL METHODS OF GATHERING CRIME SCENE DATA? HOW HAVE THESE METHODS SUPPORTED CRIME SCENE RECONSTRUCTION AND FORENSIC INVESTIGATION OVER THE YEARS?**

Traditional methods of crime scene data gathering play a vital role in the law enforcement department; [20]. Figure 9 shows a sample hand-drawn image with its corresponding 2D computer generated scene and 3D image.

Over the studied years, traditional methods have generally been seen as not very efficient because they can only document information in 2D mode [23], [197]. These traditional methods of data capturing need to be precise and hold a level of reliability. Traditional methods of crime scene data gathering vary depending on which crime scene sub-focus is being documented (see Figure 8). Based on the papers that were reviewed in this study, there are four major categories of traditional methods of data collection, and these are:

1) **DIGITAL MEDIA (PHOTOGRAPHY AND VIDEOGRAPHY)**  
 Digital media, such as photography and videography, has been a staple in crime scene data gathering [18], [198]. This approach is readily available and inexpensive to implement. It allows investigators to capture visual evidence of what transpired within the crime scene and what the scene looked like, to better understand the events that transpired there [21], [199], [200], [201]. It allows for evidence to be revisited in the future and to stand as a pillar of justice in a jury [202], [203]. Investigators also are aware of the negative effect of

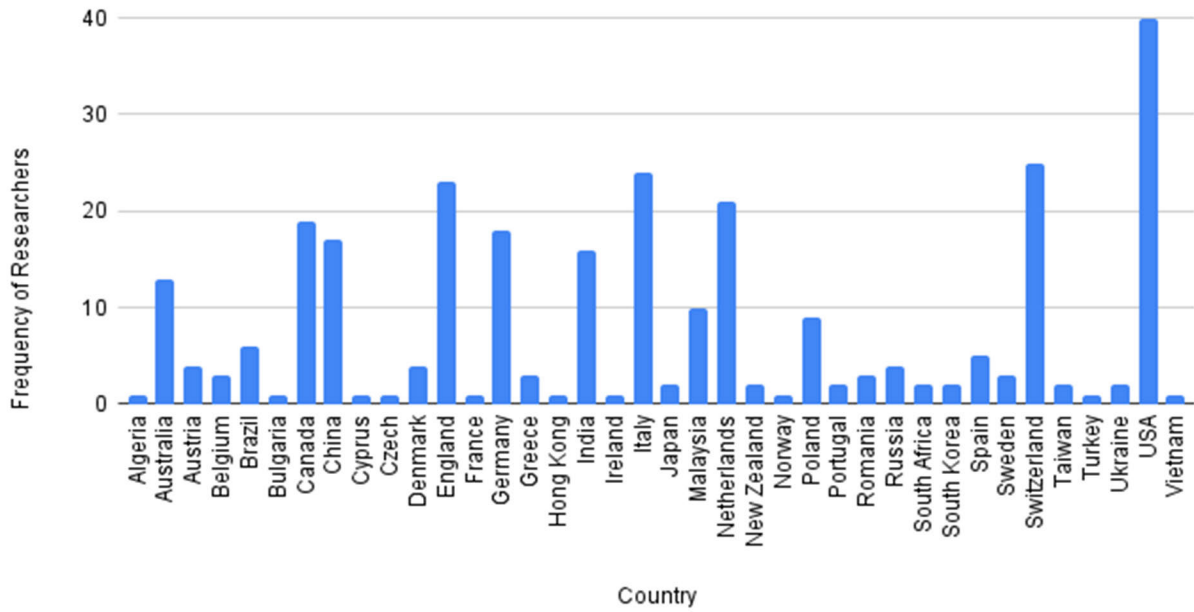


FIGURE 7. Frequency of researchers across different countries based on the studied papers.

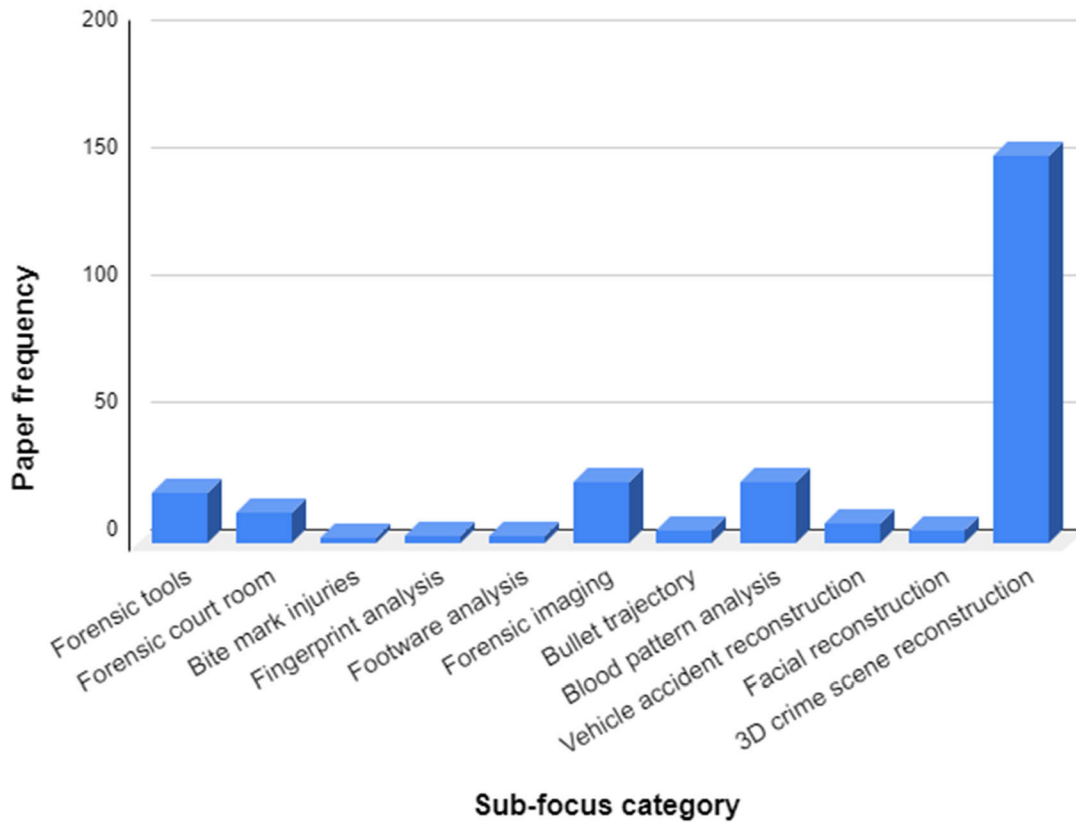


FIGURE 8. Distribution of the sub-focus forensic categories over the studied papers.

providing a single point of view for audience interpretation, hence they acquire multiple images shots to cater for that.

They also capture multiple images in the event of image distortion caused by lens warping [204], [205].

## 2) HAND SKETCHES

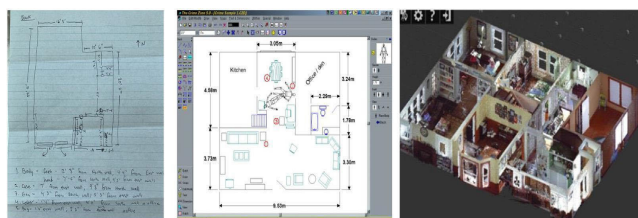
When considering basic low-cost data acquisition, pen and paper have always been the go-to option. Investigators are only provided with a finite window period for data capturing, otherwise they will risk what is called crime scene contamination [15], [206]. Hand sketches are used to quickly capture data within the crime scene, and they are also used to capture data which is not in a crime scene e.g. a perpetrator's face or visual body characteristics mentioned by witnesses.

## 3) MANUAL MEASUREMENTS

When gathering data, images and hand sketches are credible to an extent but they lack the ability gauge distances. Hence, hand sketches conducted and digital media captured need to be accompanied by their respective measurement scale (length, breadth, and height) [20], [110]. These manual measurements are normally conducted with either a tape measure, laser finder or a combination of the two.

## 4) PAPER DOCUMENTATION

Paper documentation primarily refers to manually jotting down relevant points of interest within a crime scene, which can then be used to refresh or help with an investigation [28]. Paper documentation is vital in providing substantial crime scene evidence as this evidence encompasses an investigator's observation and findings within a particular crime scene. [28], [207]. Investigating officers normally utilize pen and paper to jot down diagrams as shown in figure 9 (left).



**FIGURE 9.** An example of a 2D hand-drawn diagram with measurements done by a crime scene investigator (left). Example of 2D computer program for drawing crime scene diagrams and recording evidence locations (middle). An example resulting 3D diagram from a 3D scanned scene (right) [28].

### C. RESEARCH QUESTION 3: WHAT PROBLEMS AND LIMITATIONS HAVE BEEN DISCOVERED WHILE USING THESE TRADITIONAL METHODS? HOW HAVE THESE LIMITATIONS BEEN IMPROVED UPON OVER THE YEARS, AND WHAT TOOLS, TECHNOLOGIES AND APPROACHES HAVE EVOLVED OVER THE YEARS?

Traditional methods of capturing crime scene data are considered lowly efficient due to their inability to accurately capture and represent crime scene data in 3D [18], [20], [82]. Most on-site records in traditional crime scene investigations rely on digital media, mainly photography and manual sketches [20], [28]. Such digital media and reported descriptions can thoroughly overwhelm lay people, such as the jury, in a court

setting. Furthermore, the traditional approaches are more susceptible to modification and alteration, potentially leading to the falsification of forensic evidence [2], [25]. Consequently, more objective, precise, and comprehensive solutions for crime scene documentation have emerged over the years [2]. Although, according to the literature, the fundamental skills of photography, sketching with manual measurements, which are often imperfect will likely always remain relevant and important, these are two-dimensional (2D) representations of the three-dimensional (3D) crime scene environment [20], [21], [175], [208].

In summary, there are a number of challenges and shortcomings that have been clearly identified with the traditional methods, these include:

1. **Human error:** Every crime scene investigator has an individual perspective, and even the most diligent will make mistakes at times, especially in a complex scenario [2]. Raneri *et al.*, [20] states that: "It would be remiss to ignore the human error of a fatigued operator recording their hundredth measurement in the early morning hours, with the potential to confuse the X and Y axes, write down a rangefinder reading incorrectly, or to quite simply overlook an item of evidence."
2. **Low precision:** To create a proper incident illustration, crime scene investigators must identify possible pieces of evidence and then hand-measure their location within a space, using a tape measure or laser rangefinder [28]. Doing so incorrectly can lead to the exclusion of an item of evidence, or extensive argument about its significance [20].
3. **Image distortion:** Capturing images of the complete scene can provide useful evidence [209], however, the images can be misleading due to the very nature of the image processing, and parameters such as perspective projection, lens distortions, and focal length can distort surroundings in respect to their objects or vice versa [20], [210].
4. **Potential data manipulation:** In recording the crime scene, it is very important to not erase, alter or contaminate evidence [15]. With traditional methods of data capturing such as digital media and sketches, it becomes almost impossible to securely store information about a particular crime scene [116]. It is very easy for gathered data to be manipulated via editing software or for data to get corrupted.
5. **Restricted time and cost** - Crime scene investigators have a finite time limit when it comes to capturing crime scene data and revisiting a crime scene [211]. Hand sketching items in a crime scene is labour intensive, also manually modelling a crime scene may result in non-realistic models [28], [210]. Furthermore, traditionally captured crime scene data needs to be prepared for 3D modelling and crime scene reconstruction, which is costly.
6. **Visual limitation-** Displays used as well as input devices (mouse and keyboard) work in 2D. These 2D devices lack

information and input capabilities, which are only present on a 3D viewport.

Traditional methods of crime scene data capturing and reconstruction have proven to be effective to a certain degree, but neglect a lot of details regarding capturing and visualizing entire 3D scene data accurately [82]. 3D imaging technologies are an extremely powerful method that enable an investigator to capture and later review crime scenes in precise detail [21]. This has led to the development of solutions such as the implementation of LiDAR scanning and the use of immersive technologies i.e., AR and VR. A LiDAR scanner consists of a laser and receiver, the laser works by means of transmitting pulsed rays on surfaces and creating 3D maps of those scanned surfaces [29], [45], [49]. The receiver calculates the time it takes for light to bounce off surfaces. The LiDAR scanner can then map out how objects look in 3D [37]. LiDAR allows for the collection of 3D data of a scene where the crime took place and to create the same scene graphically. [37], [212], [213].

Drawbacks from traditional methods of crime scene data gathering have been identified. Many researchers have looked towards beneficial methodologies which will help support or improve upon traditional means of data gathering.

- Dang *et al.* [214] suggested the semi-interactive panoramic image for indoor crime scenes to complement traditional methods of digital media capturing.
- Sansoni *et al.* [215] suggested a 3-dimensional optical digitizer for crime scene analysis. That way, more than one perspective can be captured while gathering digital media data.
- Maloney *et al.* [216] proposed the visualization of cast-off patterns using 3D modelling software to improve upon the traditional methods manual measurements, as well as digital media capturing and paper documentation by reducing the need for those methods.
- Breitbeck *et al.* [217] proposed a robot system for optical 3D scanning in forensic medicine. Their research complements the traditional methods of digital media, paper documentation and hand sketching.

Over the studied years, efforts to improve on traditional methods of crime scene reconstructions have seen a steady increase in the integration of immersive technologies for 3D interactive walkthrough visualizations [218], [219], [220]. Immersive technologies, such as AR, VR and MR, have improved upon traditional methods of crime scene data gathering, crime scene visitations and crime scene visualizations in terms of the overall cost effectiveness, visual integrity, precision, data integrity, time saved and mobility [221], [222], [169]. The use of immersive technologies alongside LiDAR scanners can be cost effective if similar capturing techniques are applied as shown by [110], [222], [223], since a user can be immersed into a crime scene environment for as long as needed. Visual integrity in the context of this paper refers to the assurance that data captured in a crime scene can be accurately visualized through digital means.

Traditional methods of crime scene data gathering capture data in 2D e.g., photography, thus can be considered as lacking visual integrity due to the fact that captured 2D data is incorrectly used as a representation of 3D data. Immersive technologies alongside LiDAR scanners have the ability to 3D map entire crime scenes, thus ensuring visual integrity and crucial evidence is not overlooked [28]. Precision is the ability to accurately calculate distances between two points repeatedly. Traditional methods have a degree of inaccuracy in this regard [20]. Immersive technologies could easily cater for this with the integration of a LiDAR scanner. To promote data integrity, scanned crime scene data could easily be synced across multiple devices and stored on a database, thus ensuring safety. With conventional methods of data capturing, where hand sketches are made on paper, paper-based hand sketches can easily suffer unfortunate fates such as tearing, water immersion, fires etc. Also, hand sketching items in a crime scene is time consuming. A LiDAR scanner could mitigate this restraint by capturing entire scenes in shorter time spans. Investigators also have a limited visitation time within a crime scene; 3D scanning technology allows for the rapid acquisition of highly detailed 3D meshes of a physical environment [24], [224]. AR annotations can be implemented within an already 3D scanned crime scene, which will also speed up the time taken for investigators to identify useful points of interest [15]). Considering P2P file sharing, normally one investigator works on an investigation thus only providing one perspective [2]. AR and VR-enabled 3D crime scene reconstructions could enable multiple investigators to work on a single case to help solve crimes quicker. Mobility, in this context refers to the ability to move around without carrying encumbering equipment. Most crime scene investigators arrive at crime scenes with a lot of equipment for data gathering, equipment such as sketch pads, pens, cameras, tape measures, laser finders etc. The implementation of AR, VR and a portable LiDAR scanner such as the one housed in the 2020 iPad Pro as opposed to a bulky professional 3D scanner, which is not portable enough to be easily taken into the field, would improve mobility [225]. However, the LiDAR scanner housed in the 2020 iPad currently has some limitations with respect to accuracy [250].

Over the studied years (i.e., 2005 to 2021), multiple methodologies such as 3D imaging, 3D scanning with laser scanning and structured light scanning have been utilized in many forensic applications [2], [8], [90], [226], [227], [228]. These applications include face recognition [229], clinical forensic, incident scene reconstruction [14], [20], [175], [207], and bite mark analysis [172], [193].

There have been a number of research efforts, which try to support or complement traditional methods of data collection. Table 9 summarises the research that has been conducted throughout the studied years, with their intended traditional method replacement or enhancement and the types of tools utilized to capture and process crime scene data.

TABLE 9. Summary of proposed research on crime scene data gathering over the studied years (i.e., 2005 to 2021).

Reference	Research focus	Replaced methods				Future Recommendations	Tools	
		Digital media	Manual measurements	Paper documentations	Hand sketches		Hardware	Software
G. Galanakis et al., [41]	3D digitisation modalities for crime scene Investigation	✓	✓	✓	✓	N/A	Kinect v2 RGB-D sensor FARO Focus LS120 scanner FARO Focus S350 Gom ATOS Compact Scan 5M Go!Scan 50 Leica P40 Z + F Imager 5010X	FARO Zone 3D software Autodesk Recap Unity 3D game engine
L. Luchowski et al., [52]	Multimodal imagery in forensic incident scene documentation	✓	✓	X	✓	N/A	Faro X 130 scanner Z+F 5010C scanner	N/A
R. Jegatheswaran et al., [57]	Implementation of virtual reality in solving crime scene investigation	✓	X	✓	X	N/A	3-D laser scanner HTC Vive virtual reality headset	Unreal Development Kit
G. Dass et al., [65]	3D crime scene investigation	✓	✓	X	X	N/A	Multiple cameras Smart phones Computers	3D-Hawk
T. Sieberth et al., [83]	Applying virtual reality in forensic crime scenes	✓	X	✓	X	N/A	HTC Vive VR-ready gaming laptop Projector Screen Lighthouse Camera	Unity 3D
T. Wiczorek et al., [100]	Analysis of the accuracy of crime scene mapping using 3D laser scanners	✓	✓	X	X	N/A	N/A	N/A
P. Ren et al., [110]	Sketch based modelling and immersive display techniques for indoor crime	X	✓	✓	✓	N/A	Hand-held laser scanner HandySCAN 700 HTC Vive Desktop	Sweet Home 3D Visual Studio Unity3D

**TABLE 9. (Continued.) Summary of proposed research on crime scene data gathering over the studied years (i.e., 2005 to 2021).**

	scene presentation								
M. Zheng et al., [122]	3D crime scene reconstruction with handheld cameras	✓	✓	X	X	N/A	LiDAR Smart3D Capture	N/A	
J. Noond et al., [230]	Utilizing simulation tool for crime scene analysis visualization	✓	✓	✓	✓	N/A	N/A	N/A	
U. Buck et al., [175]	Virtual crime scene reconstruction using 3D methods for accidents or homicides	✓	X	✓	X	N/A	GOM TRITOP/ATOS system 3D laser scanner Desktop	3ds max	
F. Andaló et al., [147]	Computer methods applicable to forensic science	✓	✓	✓	✓	N/A	Camera 3D scanner	N/A	
N. Flor et al., [232]	Virtual crime scene reconstruction	✓	✓	✓	✓	N/A	LiDAR	Blender	
A. Gee et al., [233]	Integrating augmented reality annotations in forensic investigations	X	X	✓	X	N/A	GPS UWB positioning Handheld visual SLAM sensor Ad-hoc wireless LAN	N/A	
M. van Iersel et al., [234]	3D crime scene modelling with thermal information	✓	✓	X	✓	N/A	FLIR Titanium 560M camera Vosskuhler IRC-300 camera Canon EOS 450D Point Grey Bumblebee XB35 stereo camera	N/A	
A. Topol et al., [235]	Generating semantic information from 3D scans of crime scenes	✓	✓	✓	X	N/A	Instant Scene Modeler Visible light sensor Stereo camera	N/A	
M. Biocchi, [236]	Integrating technology with crime	✓	X	✓	X	With further research, immersive imaging may be found to have other uses in crime scene investigations	N/A	Autodesk 3D Studio Max Autodesk AutoCAD iWitness Crime Zone	



**TABLE 9.** (Continued.) Summary of proposed research on crime scene data gathering over the studied years (i.e., 2005 to 2021).

S. Se et al., [237]	Photo realistic 3D model reconstruction	✓	✓	✓	X	N/A	Instant Scene Modeler Model Camera Time-of-flight scanning laser rangefinder Auto Synchronous laser scanners	N/A
S. Se et al., [223]	3D modelling for crime scene reconstruction	✓	X	X	✓	External sensors such as an orientation sensor can be incorporated to augment the visual motion estimation.	Instant Scene Modeler Hand-held stereo camera Computer	N/A

Table 9 presents a summary of how these proposed methods have evolved and supported crime scene reconstruction over the years. The common denominator amongst these proposed methodologies is that they complement or support most of, if not all, the points that the traditional methods of crime scene data gathering lack. Each of the four major methods of traditional crime scene data gathering, which has been improved upon by the corresponding research, has been indicated with a tick symbol (“✓”) on table 9. This confirms whether they complement or improve traditional methods of crime scene data gathering. Methods which contain an “X” in the sub-headers of the main header (“Replaced methods”) mean that those distinct methodologies did not support one of the four major points of traditional crime scene data gathering. From the observed study, it is also noted that only a few studies also gave potential future research recommendations as indicated in Table 9.

From the studies used in this SLR, it was observed that the prominently used tools in 3D scene reconstruction are the Instant Scene Modeler [223], [235], [238], LiDAR scanner [29], [232] and the FARO X 130 [52]. This is due to the exceptionally high accuracy of these tools. However, there are limitations that have been identified in the literature with the utilization of these mentioned tools. These identified limitations are as follows:

- 1. Technology cost:** While the mentioned 3D reconstruction tools, such as FARO X 130 and Instant Scene Modeler, have proven to be exceptionally accurate, they come at a very high cost. Thus, the unfortunate obstacle regarding wide adoption of these tools in crime scene investigations is the overall cost [27]. It is anticipated that the advancement in technology will lead to further proliferation of devices that are capable and at an affordable price point for crime scene investigation units. [41].
- 2. Environmental influence on data validity:** If taken in an environment with poor ambient lighting or hard to reach

areas, LiDAR scanned data can easily be misinterpreted. Important scene elements that are higher than human reach may be missed and cannot be scanned unless a drone is utilized [41], [239]. LiDAR scanners find it particularly challenging mainly with highly reflective surfaces, which may pose problems and artifacts on the images that can be misinterpreted or misidentified [225]. Figure 10 provides an illustration of what is meant by image artifacting, where the car’s windows appear to be shattered which is not the case. Inaccurately recorded data can easily jeopardize the integrity of a court case [240].



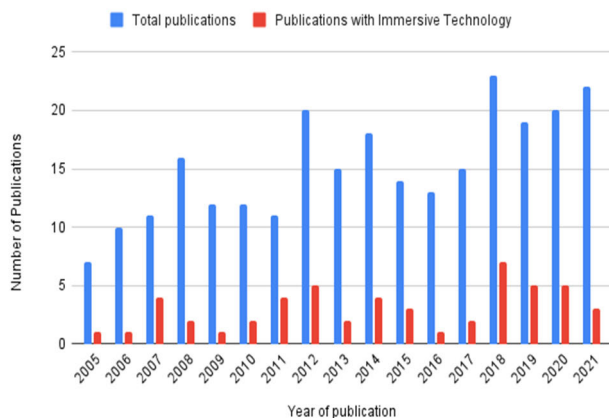
**FIGURE 10.** LiDAR scanned structure. This figure illustrates image artifacting caused by a reflective surface image obtained from D.S. Dima et al. [241].

- 3. Error margin deviation:** Different LiDAR scanners from different manufacturers each have their own margin of error calibration regarding accuracy, varying from different ranges [41]. These slightly miscalculated deviations may range from as little as a few tenths of a millimetre to tens of millimetres, depending on what is being calculated or scanned from various distances e.g., blood spatter to as large as a few meters when dealing with vast area targets such as ground global targets [6].

**D. RESEARCH QUESTION 4: HOW HAVE IMMERSIVE TECHNOLOGIES IMPROVED 3D CRIME SCENE RECONSTRUCTION AND FORENSIC INVESTIGATION? WHICH OF THE TECHNOLOGIES (AUGMENTED, VIRTUAL OR MIXED REALITY) HAVE MOSTLY BEEN USED? WHAT ARE THE POTENTIAL LIMITATIONS OR CHALLENGES IDENTIFIED WITH IMPLEMENTING THIS TECHNOLOGY?**

Immersive technologies, such as AR used in [242], VR used in [243] and MR used in [233], have further revolutionized 3D crime reconstruction and forensic investigation. These technologies can provide information overlay and allow the jury to interact with the crime scene as if being there in person [197], [240]. Furthermore, the technologies help broaden crime scene investigations by enabling multiple investigators to work on the same crime scene at once, thus reducing the backlog on other unsolved cases.

Figure 11 shows a distribution of immersive technology research over the published papers in the entire studied years in this SLR. This trend shows that while there is yet to be a proportionate increase in corresponding use of these technologies, there has been a steady upward trend of their adoption and implementation in 3D scene reconstruction and forensic investigation in recent years.



**FIGURE 11.** Distribution of crime scene reconstruction research with Immersive Technology trend. This figure displays the trend of the total published papers in the studies compared to papers published with an implementation of Immersive Technology.

AR in its essence is a technology which can superimpose digital perceptual information in the real world. This technology, in crime scene investigations, can help by providing information overlay and enhancements for law enforcement crime investigation processes [25], [233]. Some tools that are peculiar to AR are the Magic Leap, Microsoft HoloLens, Varjo XR-1 and ZED Mini. The Magic Leap and Microsoft HoloLens utilize a transparent display that allows light to pass through for the users' eyes, whilst also allowing rendering on the displays. However, the Varjo XR-1 and ZED Mini use cameras to record their surroundings and display both the real world and virtual objects with conventional displays [244].

On the other hand, VR can generate computer 3D environments based on the real world [245], [246], [247]. This technology has the capability to facilitate revisiting a crime scene by immersing the investigator in a computer-generated environment. Some of the tools used in VR, which were also mentioned in the studied literature, are the HTC Vive [92], [110], and Oculus Rift [92], [248].

MR is the merging of the digital environment and the physical world to produce new environments and visualizations. In crime scene reconstructions, MR provides investigators with the ability to revisit a virtual crime scene and interact with relevant points of interest within the virtual crime scene, without the fear of contamination or time constraints [240].

There are several benefits that can be identified through the combination of a LiDAR scanner, immersive technology, and traditional methods of crime scene data capturing and reconstruction, these include:

- A. **Cost effectiveness** – Immersive technology has the potential to immerse an investigator into a crime scene without the need to travel to the scene. Furthermore, the use of a handheld LiDAR scanner such as the one housed in the 2020 iPad Pro, and immersive technology could assist crime scene investigation with a low cost solution in investigator training [249], [250]. As highlighted by a recent study [250], a LiDAR-enabled iPad could be used to capture entire 3D crime scene data at the expense of higher margins or errors and relative inaccuracies compared to industrial 3D scanning solutions. A LiDAR-enabled iPad could be used in several crime scenes related data, generating semantic information from 3D scans of crime scene capturing and reconstruction. However, the data might require a lot of post-processing to be carried out in order for it to be useful in this domain of interest.
- B. **Visual integrity** - Even the most diligent crime scene investigators tend to make mistakes by overlooking “irrelevant information” as information that has been missed can easily be altered, contaminated, or removed [2]. With the utilization of a LiDAR scanner for data capturing (e.g., room measurements), missing relevant information and human error could be minimized [20]. Alongside the 3D LiDAR scans, 3D crime scene reconstructions implementing AR annotations and VR will help assist investigators with courtroom visualization presentations with greater realism of physical landmarks [240], [251], [252].
- C. **Precision** - Information captured by hand sketches or manual measurements conducted by tape measures are not very accurate, particularly in challenging situations [20], [28]. Manual measurement techniques are susceptible to multiple vulnerabilities, such as the flexing of a tape measure across large distances to the difficulties of perfectly rolling a trundle wheel in a straight line. [20]. The utilization of the LiDAR enabled iPad could within reason mitigate this issue, especially for indoor cramped spaces where minute measurements are important.

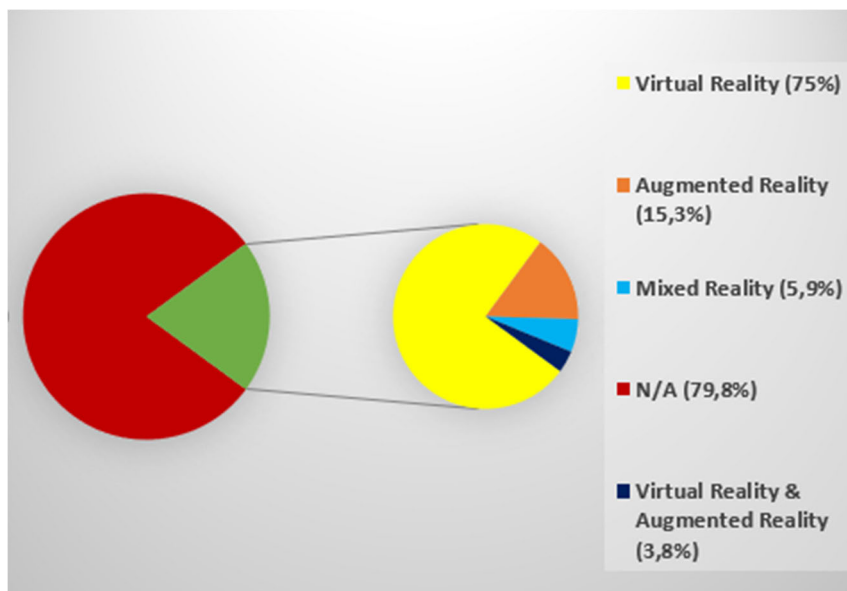


FIGURE 12. Immersive technologies distribution adopted in the studied papers.

- D. **Time saved** - Forensic 3D visualizations are processor intensive and may require a lot of time to produce. The use of immersive technology in forensic visualization would cut costs by reducing the amount of 3D modelling required and facilitating revisiting of crime scenes virtually. This would promote realistic immersion due to the use of real-world elements [252]. Applying AR annotations to forensics may accelerate investigation while avoiding interference with evidence by virtually highlighting relevant items or points of interest [15]. Accurately hand sketching items in a crime scene is time consuming, a LiDAR scanner could mitigate this restraint by capturing crime scene elements in a shorter time span [253]. Investigators also have a limited visitation time within a crime scene; 3D scanning technology allows for the rapid acquisition of highly detailed 3D models of a physical environment [28].
- E. **Visual quality** - An investigator reviewing gathered crime scene data will not be limited to a 2D viewport [2], [20], [83]. Investigators will be able to interact with 3D superimposed digital perceptual information provided by immersive technology in the real world [25], [176].
- F. **Mobility** - Most investigators arrive on scene with multiple data capturing equipment. Carrying multiple data capturing equipment at once causes a mobility issue, whereby an investigator has limited range of movement. Investigators could reduce the need for bulky equipment such as industrial 3D scanning solutions, which require external power sources such as car adapters [225], for power efficient 3D scanners which do not require external power. However, this could sometimes be at the expense of higher error margins and inaccuracies compared to industrial 3D scanning solutions [250].

Figure 12 presents the distribution of immersive technologies implementation and adoption over the studied years of crime scene reconstruction. 258 papers in total were analysed, from those paper distributions, 206 papers (79.8%) did not deal with any form of immersive technology and 52 papers (20.2%) distinctively dealt with crime scene reconstruction with immersive technologies. Similarities can be drawn from these papers, yet they each implement a method of problem solving in their respective manner. The main findings can be drawn as follows, based on the 20.2% which implement a form of immersive technology. The 20.2% of the papers that utilized immersive technologies can be categorized into four groups: (i) group one is AR, which accounts for 15.3%; (ii) group two is VR, which accounts for 75%; (iii) MR is the third group, which accounts for 5.9%; and finally (iv) group four is a combination of VR and AR, which accounts for 3.8%. The reason why group four (4) exists, and is not classified as MR, is because while some papers mentioned both AR and VR in a single document, they never combined the two technologies to form MR. Thus, such papers are not segmented or split up into various groups, but put into a new group, hence group four. The popularity of VR over AR is conspicuous across various research efforts in the studied papers.

While the implementation of AR could sometimes be economical, the use cases of AR and VR differ, and they both have their limitations. VR is better suited for visualizing 3D scene environments as the devices are generally more powerful and can fully immerse the user into the scene. VR could be process intensive, usually requiring multiple devices and higher expertise of knowledge to operate. AR, on the other hand, augments your surroundings by superimposing digital elements (images, texts, sounds) over a

real-world environment. Hence, leveraging the strengths of these two technologies could offer a great advantage in crime scene investigation.

Figures 11 and 12 confirm that there is limited research on the use and adoption of immersive technologies in 3D scene reconstruction and forensic investigation. These technologies have not been widely adopted in this domain of interest, possibly due to their relative newness. Immersive technologies are still at a stage of exploration, and not too many people are aware of the game changer immersive technologies can have in the crime scene reconstruction field. The following are the potential limitations or challenges that have been identified with the implementation of these technologies and their tools:

- I. Motion sickness - The VR headset mentioned by Ebert *et al.*, [248] allows an investigator to navigate around a virtual crime scene whilst physically not moving around in the real world. This causes a synchronous disconnect between the two which could lead to confusion and eventually sickness [254].
- II. Dizziness - An output device which houses a low refresh rate, lower than the brain's processing rate may result in dizziness [254].
- III. Disorientation - Like motion sickness, disorientation occurs due to a user's brain struggling to differentiate between virtual and physical spatial movements [258].
- IV. AR drift- There are various issues to be investigated, which are related to performance, alignment, and gesture interaction [255].
- V. Security - There are often no strong security features in this technology [255]. However, the incorporation of artificial intelligence and blockchain technology could assist in this regard.
- VI. The Microsoft HoloLens manual identifies potential side effects such as nausea, motion sickness, dizziness, disorientation, headache, fatigue, eye strain, dry eyes, and seizures [256], [257].

#### **E. RESEARCH QUESTION 5: WHAT ASSESSMENT METHODS HAVE BEEN EMPLOYED TO EVALUATE PROPOSED METHODS OF CRIME SCENE DATA GATHERING?**

Several assessment methods have been employed to evaluate the different methods of crime scene data gathering proposed in the literature. Each of these evaluation methods can be categorized into two: (i) formal evaluation; and (ii) informal evaluation. Formal evaluation refers to a testing method which has a grading system or metric to gauge how well or how badly a method performs. An informal evaluation refers to an assessment which does not necessarily conform to any evaluation criteria or standards. We summarize some of the assessment methods in the following studies.

- Galanakis *et al.*, [41] proposed the 3D digitization modalities for crime scene investigation method which aimed to advance the traditional methods of crime scene data gathering. The methodology was formally

evaluated via a qualitative analysis method, the findings showed that measurements obtained from the reconstructions of the terrestrial laser scanner were significantly diverse from corresponding real sizes. It also confirmed that the used scanner is not ideal for small objects but rather for big objects and structures.

- Se *et al.*, [223] proposed an approach of 3D modelling of crime scene reconstructions using a camera. The approach aimed at improving upon traditional methods of picture taking and hand sketching. This methodology was assessed and formally evaluated by means of testing with an Instant Scene Modeler hand-held stereo camera at different distances relative to the item being scanned. Experimental results show that scanned scenes within three (3) meters from the camera had an accuracy error margin within two centimetres.
- Sieberth *et al.*, [83] proposed the application of VR in forensics, which allow for a walkthrough of the crime scene. This approach also improved upon paper documentation and image taking. The developed system was formally evaluated by means of it being used in three practical homicide cases.
- Sünksen *et al.*, [84] proposed an approach of preparing and guiding forensic crime scene inspections in VR. This method aims at improving on traditional picture taking and manual measurements. The informal evaluation process of this methodology involved twelve (12) students assuming roles as spectators in individual sessions with a moderator. The usefulness of the proposed approach for presenting crime scene reconstructions and its applicability for information propagation in a courtroom were both assessed with an arithmetic mean of 4.75 on a 5-point Likert scale.
- Reichherzer *et al.*, [96] proposed the application of virtual crime scene reconstructions in courtrooms. The paper compares two currently employed methods used in court. Method one being the use of photographs in court and method two being real world visitations. This comparison aimed at gauging narrative and spatial memory presented in the context of viewing real and virtual copies of a simulated crime scene. Narrative memory was assessed in this study by means of formal evaluation. This evaluation featured experiments that compared three viewing conditions: VR, photographs, and physical viewing (PV) of a crime scene; the findings indicated that viewings done in VR were superior to those done with photographs, and in most cases were equivalent to PV. In rare viewing cases, PV was superior compared to VR.
- Abate *et al.*, [102] proposed using a low-cost panoramic camera for 3D documentation of contaminated crime scenes, which aimed to improve the traditional image taking and paper documentation. The formal evaluation of the methodology involved determining the final quality produced by the low-cost panoramic camera in terms of visually inspecting the number of details that

could be generated by the dense reconstruction step and performing local comparisons with known reference shapes. Findings illustrate that both approaches can match points on small objects (like a gun, bottle, can, and vase), providing for a 3D documentation of the location and shapes of these artifacts. However, both 3D reconstruction procedures fail when dealing with smaller objects (e.g., the packet of cigarettes and the lighter).

- Liu *et al.* [80] proposed the use of an unmanned aerial vehicle (UAV) photogrammetry for traffic accident scene reconstruction. This approach aimed at improving traditional methods of digital media (2D images and videos) gathering by means of reconstructing 3D models from 2D UAV sequential images. This method was formally evaluated by means of experimental case study work and reconstruction quality assessments. Findings within the methodology showed that the 3D reconstructions proved to be effective.
- Carew *et al.*, [260] proposed an approach of integrating 3D printing into forensic crime scene investigations. This method aimed at complementing traditional methods of digital media data acquisitions by means of capturing 3D content, and then physically reproducing 3D crime scene evidence captured on scene. Findings within the methodology indicate that even though the approach is beneficial for crime scene investigations, there are limitations. An example of the limitation includes bone replicas, which do not imitate exact bone density when printed.

In summary, considering the evaluated papers observed in the literature, different types of evaluation schemes have been employed, depending on the nature of the methodology and solutions implemented. The studies show that most of the methodologies that have been suggested have undergone formal evaluation and a minority of the papers have been informally evaluated.

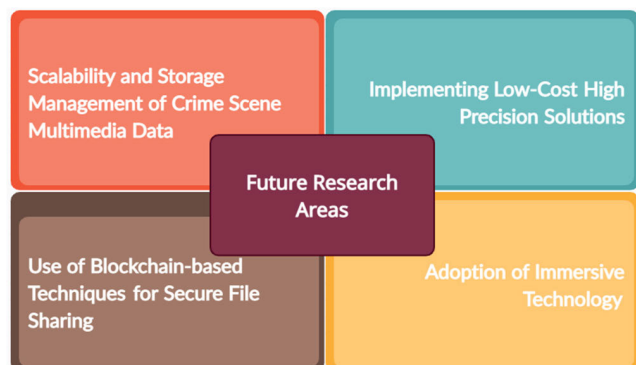


FIGURE 13. Potential areas for future research.

Throughout the studied 258 papers ranging from 2005 to 2021 in this SLR, some prominent aspects of importance were overlooked. These prominent aspects of importance are “Scalability and Storage Management of Crime Scene

Multimedia Data”, “Implementing Low-Cost and High Precision Solutions”, “Use of Blockchain-Based and Artificial Intelligence techniques for Secure File Sharing” [259] and “Adoption of Immersive Technology”. Scalability and storage management of crime scene multimedia data relates to where and how crucial crime scene digital data gets stored and managed for later use. This is crucial because reconstructions can be presented as a point cloud or as meshes, and both have their benefits and drawbacks. There is a need for developing more reliable low-cost solutions for 3D crime scene reconstruction as the literature has revealed that high-end devices tend to produce more accurate results, however these devices can be costly. Furthermore, promoting data sharing during crime investigation is critical for law enforcement and forensic experts [260], and this begs the question: how secure are the files being shared to avoid or minimize alteration or falsification of evidence? These are some of the potential research areas that still need to be explored.

## V. SUMMARY AND CONCLUSION

This work has provided a systematic and critical analysis of 258 papers that have been published in the past 17 years (2005 to 2021) in the field of 3D crime scene reconstruction and forensic investigation for the first time, by following the guidelines provided by Weidt *et al.*, [39] and Torres-Carrion *et al.*, [40]. The selected papers, which spanned 17 years of research in this domain of interest, have resulted in several advancements in forensic investigation and 3D crime scene reconstruction for criminal justice response. Thus, providing key insights on tools, technologies, and techniques that can help researchers and crime specialists keep up with recent developments in this domain of interest. To the best of the researchers’ knowledge, this is the only SLR that systematically summarizes and organizes the scattered shreds of evidence in the area of 3D crime scene reconstruction in the past 17 years. Researchers can further use the review to identify, justify, filter, and refine hypotheses, recognize and avoid pitfalls of previous work.

Our study found that while 3D reconstruction of pertinent crime scenes has already been explored as a complementary tool in investigation channels, such technology is still not widely investigated or accepted. For example, there is relatively little evidence of the adoption of the technology in the African continent, when compared to the advanced parts of the world, as seen in Figure 6. This could be due to the expensive and specialized digitization equipment that is available so far. While high-quality scanning equipment gives the much desirable precision accuracy, the downside is their increased cost. Hence, low-cost devices and high-precision technology capable of scanning scenes or objects in 3D will promote adaptability as a reliable alternative to their counterparts. Also, as a way of compensating for technical limitations, this SLR research also notes that some approaches utilize more than one scanning device or modality, e.g., pairing photogrammetry with laser scanning. Hence, integration of

multiple technologies and methods could lead to extremely accurate and complete 3D reconstruction of crime scenes.

Furthermore, the advantages offered by immersive technologies have compelled researchers and forensic investigators to consider integrating these technologies into crime scene reconstruction. Immersive technologies have proven to recreate scenes with a great level of detail, whilst being relatively cost effective as it can facilitate the visit of the crime scene without needing to travel. Traditional methods of hand sketching, picture taking, and inaccurate manual measurements tend to still dominate in data capturing and crime scene reconstruction. The studied papers in this SLR indicate that traditional methods are lacking and that there is always room for improvement. The findings in this SLR have shown that the implementation of immersive technologies coupled with traditional methods offer crime scene investigators an edge on crime scene reconstruction and investigation. This research would recommend exploring more use cases, and applications of LiDAR scanner and immersive technology, specifically leveraging the strengths of AR and VR for crime scene reconstruction and investigation. This would provide information overlay and enhancement for law enforcement crime investigation processes, and provide reliable information for their investigations. The adoption of this technology will intentionally enhance, provide clarity, and foreshadow in detail as to how particular events transpired in a given crime scene. Furthermore, the potential benefits of bringing in a LiDAR scanner and immersive technology in crime scene reconstruction are that 3D crime scene reconstructions will be more accurate, allow for mobility, and human error will be reduced during data capturing. Furthermore, peer-to-peer (P2P) file sharing will be promoted, allowing more than one investigator to work on a single crime scene. Lastly, data captured will have depth i.e., 3D as opposed to the 2D used in traditional methods of data capturing.

This SLR concludes that 3D crime scene reconstruction is critical for forensic investigations and needs further exploration and investigation by researchers. Notably also, the consumerization of 3D scanning technologies will birth more and more devices, hence more low-cost devices should emerge. Several important research efforts are discovered and analysed in this SLR, which will help researchers, scientists, and forensic investigators to build more robust solutions in this domain of interest. In addition, research efforts should be geared towards developing scalable frameworks and approaches that will accommodate crime scene multimedia data as scanned data can be excessively large, and potential parallelization issues that may emerge from the need for collaborative file sharing among multiple investigators. This also includes privacy and security issues relating to the credibility of shared forensic evidence.

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