



A Review of Crime Scene Investigations Through Augmented Reality

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Abstract. This paper discussed the background of crime scene investigations and reviewed a novel Augmented Reality Learning Environment for using HoloLens in crime scene investigation. It clarified the concepts of augmented reality (AR), and virtual reality (VR). With the advancement of technology, forensic investigation is compelled to adapt to corresponding changes and use them to its benefit. In addition, it reviews the extant literature on the use of HoloLens in crime scene investigation. Through this review, the research questions are being formulated for future perspectives of crime scene investigations through Augmented Reality.

Keywords: Crime scene · Forensics · Augmented Reality

1 Introduction

This paper is focused on investigating a novel Augmented Reality Learning Environment for the utilization of HoloLens to aid in crime scene investigation. Traditional forensic investigation commonly involves a considerable amount of time at the scene. However, inadequate time or resources, particularly limitation of time and geographical variations of colleagues, are often the case (Robey et al. 2000). The use of modern techniques to store, visualize, and manipulate evidence is necessary for the efficient utilization of investigative resources. This is specifically true since forensic investigation units tend to be highly-technological to enable small teams to obtain and record various types of data quickly. Considering this need to analyse and classify a range of data, virtual environment (VE) technology provides a user interface (Robey et al. 2000).

At present, law enforcement has broadly developed in solving crimes through the adoption of forensic techniques and processes. Currently, crimes can be solved by thoroughly examining the crime scene and analysing forensic evidence. Forensic scientists contribute largely not only to criminal investigation and prosecution but also to civil litigations, disasters, and global crimes (Inman and Rudin 2001). The success of crime scene investigation is based on a system of teamwork, investigative tools like GPS positioning, video imaging, mobile phones, data mining, and the like. Crime scene investigations have successfully utilised a tri-dimensional (3D) representation of objects. It is also

based on the capabilities to appropriately process a crime scene through the recognition, collection, and preservation of all significant physical evidence defined as any evidence that can give useful information for crime investigation (Gaensslen et al. 2008; Lee and Pagliaro 2013). If such physical evidence is not recognized, its forensic value might be lost forever. Despite the availability of current forensic technologies, the efficient use of physical evidence in solving a crime is only limited to the knowledge and integrity of the forensic personnel and the unbiased legal system supporting those functions. The successful outcome of the case relies on the physical evidence obtained from the crime scene. Yet, since some cases lack physical evidence, they remain unsolved. Conversely, some innocent individuals are made to answer for the crime which they did not commit because of witness misidentification or misused forensic evidence (Gianelli 2007; Lee and Pagliaro 2013).

2 The Features of Augmented/Mixed Reality

As this study deals with the use of HoloLens in crime scene investigation, reviewing some works that deal with its use would be of worthy attention. Mixed reality (MR) remote guidance, which combines reality with augmented reality, virtual reality, and augmented virtuality, can help in transitioning between these stages. Reality being enhanced with artificial images enables an easier performance of tasks, such as when individuals in different locations collaborate with each other. Assembly tasks can be carried out remotely, even if the people involved do not meet each other face-to-face (Ladwig and Geiger 2018). Similarly, Teo et al. (2019) described MR as a practical solution that can allow people to collaborate remotely through nonverbal communication. Their study focused on the integration of different forms of MR remote collaboration approaches, allowing a new assortment of remote collaboration to expand MR's features and user experience. Teo et al. presented a MR system that utilised 360 panorama images within 3D restructured scenes. A new technique was also introduced to interact with numerous 360 panorama fields within such restructured scenes. Through this, a remote user is able to switch between numerous 360 scenes, such as live, past, present, and so on, promoting improved understanding of space and interactivity. In Lehr (2018), the use of AR and MR as up-and-coming tools to fight criminality and terrorism was discussed. They even stressed the use of 'smart glasses' that can enable police officers to identify suspects by merely looking at them.

Similarly, a novel MR analysis device providing 3D reproductions of multiple users in a collaborative setting was introduced (Prilla and Ruhmann 2018). This analysis noted the importance of information on individuals' movements and behaviour, as well as how they interact with digital objects. The authors, recognizing the insufficiency of other means of analysis for this purpose, developed and applied a novel device showing users wearing head-mounted devices. Prilla and Ruhmann added that to their knowledge, the features of the MR device cannot be found in other tools, including the means for analysis.

Moreover, virtual environments (VE), VR, AR, and simulations can now be used widely because of recent advances in technology that made them become affordable and accessible to users, practitioners, and researchers alike. In Spain et al. (2018), identifying

the manner in which these applications can be developed and applied to enhance human lives across a range of contexts was identified as the main goal of human factors research. Brown and Prilla (2019) affirmed the availability and accessibility of AR devices, which Spain et al. (noted), wherein remote experts support people wearing these devices. 2D peripherals are usually worn by these experts in accessing video feeds of 3D head-mounted tools and augmenting them with verbal or digital information. Whether devices applied for these scenarios can also be applied for remote consultations is a relevant concern; hence, Brown and Prilla carried out a study aiming to re-evaluate this device, leading to findings that showed that despite the evenness of usability scores, participants noted clear preferences for certain settings.

2.1 Collaboration Through Technology

Speicher et al. (2018) cited recent studies' pursuit to explore the potential of 360 videos for the collaboration of several users in remote settings. They furthered that these studies were able to identify some challenges with regard to 360 live streams, including out-of-sync views, amongst others. These challenges were dealt with by creating 360 anywhere, a video framework for multi-user collaboration, in which along with enabling users to view a 360 live stream, projected annotations in the 360 stream were supported. This allows a variety of collaborative AR applications which existing devices do not support.

Just like Speicher et al. (2018) who explored how multi-user collaboration in a remote setting may be undertaken through 360 videos, Kolkmeier et al. (2018) examined remote MR collaborative systems, which enable experts' real-time support., Kolkmeier et al. identified core design areas, such as the remote expert's independent viewpoint on the visitee's position and perception; the presentation technology's immersiveness; and the extent of having the visitor's body represented in the environment of the visitee.

In Ruhmann and Prilla's (2018) work, they emphasised that most studies had been allotted to AR glasses to finish tasks, with technology being recognised as having great potential for cooperative tasks. The authors presented a visual search experiment which was carried out in the context of a cooperative MR environment with Microsoft HoloLens tools. In their study of Microsoft's HoloLens AR head-mounted device, Heinonen (2018) presented a discussion of AR and described HoloLens as having two resolution screens and a 360-degree view field and twelve sensors that used for interacting with the environment. In addition, the device's performance can be compared to a sophisticated mobile device.

Similarly, Ruhmann et al. (2018) focused their study on mixed reality (MR) which can be used for cooperation support. They stated that most work conducted in this context has been focused on individuals. As the authors worked on collaboration support situations in MR, they came to recognise the need for insights into how technology may be used for working together. To examine this, they came up with a computer-generated 3D analysis tool for MR, which embodied interactive and collaborative support and was conducted with Microsoft HoloLens, demonstrating how hard-to-discover interaction can be carried out. The same scenario on the use of MR was examined in Poelman et al. (2012), this time presenting a new MR system developed for the collaboration of crime scene investigators with the remote support of expert colleagues. The head-mounted display can carry out map-making on a real-time basis in order for the investigators to

collaborate spatially. This is similar to the direction of Ruhmann et al. (2018) on their use of 3D analysis tool with interactive and collaborative support. In Poelman et al. (2012), a crime scene experiment was conducted to investigate the resulting system, whereby lay investigators collaborated to resolve a spatial problem with experts participating remotely. The findings revealed that the investigation of the physical scene through spatial collaboration with remote experts allowed current issues to be tackled at a distance.

Similar to Ruhmann et al. (2018) who focused on 3D animation for MR, Ma et al. (2010) also carried out 3D animation, this time, for accurate crime visualization, both for the audience and courtrooms. Using actual data as a basis, the scene was reproduced through forensic animations, showing the activity at various points in time. Computer techniques were used to reconstruct crime scenes, thereby replacing the traditional techniques in forensic investigation. The study explored the link between major types of crime in parallel forensic animations and acknowledged that animation with high levels of details and human characters is suitable for many types of crime and crime investigations although it can be used only on a limited basis in the courtroom.

2.2 The Use of Augmented Reality in Crime Scene Investigation

Lukosch et al. (2015a, b) described AR as a technology that enables viewing and interacting in real-time with superimposed virtual images over the real world. AR technology can enable the creation of unique collaborative experiences in such a way that co-located users can both interact with 3D virtual objects and see them. A live video can be annotated so that a remote user can collaborate with another user at a distance to enhance the face-to-face collaborative experience. Using AR technology to investigate crime scenes has been emphasised by many studies (e.g. Rice 2012; Sandvik and Waade 2008; Streefkerk et al. 2013). Recent studies revealed that augmented reality (AR) technology is capable of supporting distributed teams in an investigation of crime scenes (Datu et al. 2016b; Poelman et al. 2012; Ruhmann et al. 2018). Crime scene investigation is a cautiously planned systematic process that aims to acquire physical evidence to illuminate the physical reality of the crime and ultimately discover the identity of the criminal (Bostanci 2015). Sandvik (2010) particularly described the term crime scene as a model for understanding and augmenting places. It is a place that undergoes a specific state of transformation at a specific moment in time, where the place embodies the scene for some kind of criminal activity. Akman and Jonker (2012) specified that a crime scene investigation can position virtual objects such as found evidence in the scene, where two or more parties and their environment interact and collaborate through a head-mounted AR system. Such a system provides tools, direction, and information to users - on and off the site - to undertake their tasks autonomously and with each other.

It is important to capture the images and videos of the crime scene to analyze deeply the digital evidence for potential clues. Bostanci (2015) brought this idea further in order to utilise the obtained footage to draw the crime scene's 3D model. The results demonstrated that realistic reconstruction can be acquired through advanced computer vision techniques. This same purpose was embodied in the study of Streefkerk et al. (2013) who explored the use of AR annotation tools, whose relevance was grounded on the imperative for forensic professionals to gather crime evidence quickly and contamination-free. This tool enables forensic professionals to practically tag evidence clues at crime scenes

and review and shares this evidence. Using a qualitative method, Streefkerk et al. (2013) found that annotation could lead to enhanced crime scene orientation, rapid collection process, and reduced administrative pressures. Whilst existing annotation prototypes are technically limited because of time-consuming feature tracking, AR annotation is more promising, useful, and valuable in investigating crime scenes. This is affirmed by Rice (2012) who stressed the increased value and efficiency of forensic simulations and crime scene investigation in virtual environments using augmented reality tools. Through AR technology, along with useful tools and fast access to major databases, law enforcement, and investigation personnel can enable marking and highlighting evidence and running real-time tests.

On a similar scale, Sandvik and Waade (2008) examined how places are augmented through mediatisation, describing AR as something that represents processes of mediatisation that broaden and boost spatial experiences. These processes are embodied in users' active participation and forming of artificial operational environments which are entrenched in a variety of physical and virtual places. Thus, in another study, Sandvik (2010) used the concept of AR to examine the augmentation of places in different ways through various mediatisation strategies. AR denotes enhanced emotional character of places, including a crime scene, which is an encoded place embedded with certain actions and events that leave various traces to be interpreted and examined. For example, blood, nails, and hair are DNA-coded, in the same way, that gun powder and gun wounds are readable and traceable codes. As AR, the crime scene brings a narrative that is initially hidden and must be disclosed. The investigative process and the detective's ability to rationalise and construe enable the crime scene to be reconstructed from being a place into being a virtual space where the course of events is retold to solve the crime.

Similar to Sandvik (2010) and Sandvik and Waade (2008) who focused on mediatisation in AR, Lukosch et al. (2015a, b) described an interface-based mediated reality system that supports remote collaboration. In particular, the authors introduced a gesture-specific interface to investigate crime scenes, where through interviews and interactive sessions, such interface was shown to be effective, easy to use, and to learn. Datcu and Lukosch (2013) offered an even more innovative AR tool for crime scene investigation, and this is by using free-hand gestures for mobile AR applications. Proposing a computer vision-engineered model for hands-free interaction in AR, the authors emphasised that the project's novelty was the adoption of a hands-free interaction model, with a particular emphasis on the accuracy of a hand-specific pointing system for item selection. The results revealed high pointing accuracy and high viability of hands-free AR interaction. This same efficiency in AR has been earlier emphasised in Bostanci (2015), Rice (2012), and Streefkerk et al. (2013).

Just like other authors in this review, Lukosch et al. (2015a, b) recognised the usefulness of AR technology for operational teams in the field of security, given the capacity of this technology for quick and adequate exchange of context-related information. Information exchange allows the development of distributed situational awareness and collaboration facilitation. At present, operational teams rely on oral communication for information exchange, which can be ambiguous. Using both quantitative and qualitative assessment, Lukosch et al. (2015a, b) revealed that a team's distributed situation awareness can be improved through AR. This result was also the same as that of Datcu

et al. (2014a, b) where they compared situational awareness, amongst others, in AR and real-world environments in collaborative complex problem solving, such as a crime scene investigation. Whilst Datcu et al. (2016a) stressed the growth of AR into a mature field, the domains of situational awareness and presence of AR remained to be lacking in research topics. In order to examine various perceptions of situational awareness and presence in real-world and AR scenarios, a collaborative game was introduced in their study. The game was adopted in order to model collaborative complex problem solutions and was proved to be feasible, along with questionnaire design, in examining the various perceptions of situational awareness and presence in real-world and AR scenarios.

Alternatively, Gee et al. (2010) described an AR system designed for 3D annotation of physical environments and included an integration of absolute positioning technology and real-time computer image to produce a virtual 'incident' map. The map was collaboratively developed through the participation of operatives and a remote control hub. The study showed how the system may be utilised to aid forensic investigators in collecting and processing evidence in a crime scene, which was similar to Poelman et al. (2012) and Ruhmann et al. (2018).

Conversely, aiming to report on the development of handheld AR technology in situational attentiveness and collaborative investigation between teams and remote forensic investigators, Datcu et al. (2016b) examined the AR system by focusing on its stability and impact on situational attentiveness and quality of collaboration. It was found that the head-mounted AR system which Poelman et al. (2012) discussed in their study has certain limitations that are tackled by handheld AR technology. However, the divided attention between smartphone AR technology and the real environment affects situational attentiveness.

In another study, Buck et al. (2013) described a tool called GOMATOS, an optical 3D digital technique that is suitable for wound and whole body documentation for identifying injury-inflicting devices and reconstructing the event. These 3D data were integrated into the dead person's whole body model. Besides the findings of the body, a 3D documentation of the injury-inflicting devices and the incident was carried out. With this work, Buck et al. (2013) showed how 3D documentation and data integration helped address reconstructive issues concerning the development of patterned injuries and how this resulted in a real data-based crime scene reconstruction.

Congruent with the direction of Buck et al. (2011), Adamczyk et al. (2017a) presented a new 3D generation calculation approach for forensic documentation, whose purpose was to prepare a more insightful and objective forensic documentation. After conducting a series of interviews with technicians, their study suggested that the developed 3D calculation system had considerable potential for becoming a useful device for forensic technicians. In their other study, Adamczyk et al. (2017b) mentioned that 3D measurements are becoming a standard forensic process. Through the adoption of 3D measurement approaches, a more insightful investigation can be carried out, helping to demonstrate traces in the entire crime scene-setting. In their article, Adamczyk et al. (2017b) presented a hierarchical, 3D measurement system for the forensic documentation process. This system mirrored the particular standards in the forensic documentation process, as it was developed to conduct measurements in two documentation

phases. The first phase involved the use of a low-resolution scanner with a large measuring volume, which was used to document the whole scene. The second phase involved a more detailed but high-resolution scanner which was intended for areas requiring a more detailed approach. A software platform called CrimeView3D was used to supervise the documentation process.

3 Environmental Aspects of the Use of HoloLens

Rajeev et al. (2019) mentioned that the quality of the AR environment is based on high accuracy localisation and user positioning tracking. Developers are confronted with the challenge of localising the user based on visible environments. Currently, Global Positioning System (GPS) is largely used for tracking and orientations but its accuracy is only about 10 to 30 m. This is not accurate enough for AR as the precision required by AR should be in millimeters or smaller. Cyrus et al. (2019) noted that the HoloLens is highly accurate in terms of location information. In their study, Rajeev et al. (2019) proposed an AR-based vision indoor navigation system that can give accurate localisation and mapping in an environment where GPS is declined. By contrast, Cirulis (2019) stressed that a major disadvantage of a GPS-based AR system is inadequate accuracy in a virtual object.

Likewise, Cyrus et al. (2019) stressed that location information is typically used to precisely position holograms within the real environment in relation to the user. Since the information is accurate enough, it can be used to report the position. A range of experiments has been conducted to determine possible errors as a result of vibrations or other effects when the HoloLens is moved. An advantage of the HoloLens is that it can be readily positioned indoor without a need for additional infrastructure whilst its main disadvantage is its cost (Cyrus et al. 2019).

Moreover, Cirulis (2019) emphasised that changing from smartphone displays to HMD is important in AR, as this will enhance the immersion level of the environment. Although AR will increasingly become significant in the future, there are still factors that limit its use in various areas and industries. Some related problems arise, for which solutions are being developed. For example, it is inconvenient to use AR in outdoor conditions, but there are available solutions to address this, such as Pokemon Go and Sight Space. However, their inaccuracy is very high, preventing the user from moving freely in the augmented environment. Another example is the short-range in which AR systems can operationally reach. This is resolved by replacing marker-based solutions with depth cameras and spatial mapping (Cirulis 2019).

Cirulis furthered that the functionality for indoor and outdoor environments should be achieved for HoloLens, regardless of weather conditions and lighting. By calculating GDP coordinates, some AR solutions are available for outdoor use. However, in actuality, they have very high accuracy, which prevents the user from moving freely. Further projection can be calculated by putting a target 3D model in a fixed position and using data for internal sensors. Similar to Cirulis, Gee et al. (2010) performed a study of AR in a crime scene, in which a virtual map is made through the collaboration of many operatives and a remote control center. This system covered both indoor and outdoor environments and explained how forensic investigators may be helped by such a system in gathering and processing evidence at a crime scene.

Moreover, Blom (2018) conducted a series of experiments to examine the effects of various light levels on the functionality of a 3D holographic application that operates in HoloLens. He found that such functionality was not considerably affected, except when the surroundings are very dark. In contrast, the visibility of the hologram is affected by bright and muddled backgrounds. Therefore, the virtual content's visibility is reliant on the absence of bright light sources in the environment. This is specifically so in outdoor conditions where the weather conditions largely affect the application experience. However, the HoloLens system could decrease poor visibility in fairly dark environments since it has virtual content that gives its own light (Blom 2018). This is similar to the claims of other authors regarding the use of AR in both indoor and outdoor environments (e.g. Cirulis 2019; Gee et al. 2010).

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Comparing the Google Tango tablet and the Microsoft HoloLens together, Riedlinger et al. (2019) found that in terms of collaboration, users preferred the Google Tango tablet over Microsoft HoloLens because it felt more natural to interact using the tablet rather than the HoloLens, although the operation in HoloLens is hands-free and its tracking is stable. In addition, getting an overall impression is easier when the Tango tablet is used than the HoloLens. Riedlinger et al. also observed that users using Microsoft HoloLens found it difficult to position objects in similar surroundings with almost similar features. Since the position of the holographic model depends completely on the ability of the HoloLens to trace the position of pixels identified by cameras, changes in the environment would result in drift in the position of the holographic model. The causes of this error are people's movements, materials on site, and other elements that stop variations in lighting conditions (Jahn et al. 2019). These are similar to the results in Blom's (2018) study which described how a muddled and very bright environment affects the visibility of a hologram and how a very dark surrounding affects its functionality.

Alternatively, the study of Cyrus et al. (2019) found that the HoloLens' light detection and ranging (LIDAR) is typically used as a component of autonomous simultaneous localisation and mapping (SLAM). However, with the use of the LIDAR, the device's scanning of the surroundings usually involves just one plane and can be problematic with glass obstructions, such as a glass door. Along with the correct use of suitable software, the information that the LIDAR provides is accurate, given its high accuracy.

4 Blood Spatter Analysis

Analysing the patterns of bloodstains is important in reconstructing the events of a crime scene and has become a domain of specialisation in Forensic Science (e.g. Albalooshi

and Eltabie 2015; Buck et al. 2011; Karger et al. 2008; Osborne et al. 2015). Pokupcic (2017) pointed out that blood is an important biological trace that is often left on the crime scene. It contains valuable information, making it an extremely important forensic tool. By analysing various aspects of bloodstains, the circumstances surrounding some violent crimes can be clarified. This critical information can direct criminal investigation in the proper direction towards solving the crime. It can also be used to legally determine criminal offenses which can result in a more accurate and appropriate judgment. Hence, determining the series of events surrounding a violent crime involving blood is very important.

Stringing - BPA's traditional method - involves appending a piece of string to every stain and allowing the string to stand for an estimation of the stain's flight path (Joris et al. 2015). Albeit stringing is used at length, there are several practical downsides that go with it (Joris et al. 2015). That is why various approaches have been employed to improve BPA. Wang et al. (2019) stated that traditional approaches cannot effectively reconstruct the entire crime scene, which is why they presented a portable system with a low-cost VR headset and other components to spatially collect data of crime scenes using a multi-directional 3D imaging technique. Their study analysed a real case to show the system's practical use and to confirm its feasibility and efficiency. The system can measure accurately and determine the relative location of blood sources and compare tools that can inflict injuries.

Gee et al. (2010) stressed that in the field of crime scene investigation, collecting data largely depends on manual recording, which is time-consuming, especially when many personnel is operating within several teams. Technologies like AR, which can make this process more efficient, would be a useful addition to the developments in crime scene investigation (Gee et al. 2010). Sandvik (2010) suggested that the forensic term crime scene may be used in understanding the concept of AR. The crime scene is an encoded space where readable and interpretable traces of crime are left, such as hair, nails, DNA codes, amongst others. Similar to the traces of gunpowder and bullet holes, these traces can be decrypted and deciphered. By reading and interpreting signs and traces in the crime scene, the crime scene becomes encoded (Sandvik 2009). The emergence of VR makes the work more efficient since it is now used for blood splatter analysis, forensic biology, and crime scene re-enactments, amongst others. An example to demonstrate this was the crash of Delta Flight 191 in 1985, which was recreated through a computer-based simulation, where some of its complex evidence was explained to the jury (Ticknor 2018).

Laan et al. (2015) mentioned that as a forensic discipline, BPA allows the determination of the position of victims on the crime scene with the shedding of blood. In order to find out the blood source, straight-line estimation for the trajectory is used, setting aside the effects of gravity and hence over-approximating the height of the source. Laan et al. (2015) ascertained the extent of accuracy of estimation of the origin's location when gravity and drag are included in the reconstruction of trajectory. Their study, therefore, allowed investigators to identify the victim's position and link the wounds to specific patterns, which is necessary for reconstructing the crime scene.

Osborne et al. (2015) mentioned that criminal investigations can utilise BPA to ascertain the events linked to blood depositions. However, it can also be potentially

vulnerable to contextual bias. Thus, when taking into account how to deal with the issue of contextual bias in analysis bloodstain patterns, it is necessary to pay attention to context management instead of context elimination. Similar to Albalooshi and Eltabie (2015), Buck et al. (2011) claimed that the pattern of bloodstains in crime scene investigation at the actual site is very important. The bloodstain pattern's morphology helps to identify the estimated locations of the blood source and the positioning of the victim. Through illustrative cases, the authors showed the advantages of 3D BPA, which includes the ballistic estimation of the trajectories of blood drops. In their study, 3D documentations were used for the crime scenes, creating accurate 3D models for the scenes, including bloodstain patterns and traces. In order to determine the areas in which the bloodstain pattern originated, their study analysed the trajectories in photogrammetry software. The ballistic aspect of the trajectories was determined using ballistic software. Buck et al. (2011) stressed that the crime scene investigation benefits from this method through non-contact calculation of the bloodstains and high accuracy of the analysis, amongst others. They emphasised that the accurate outcomes on the number of bloodstains and the position of their areas of origin should be anticipated with this method.

Below is a figure showing the shape of a well-defined blood spatter. The direction and the length of the axes of the elliptical bloodstain are shown in the figure. It also shows the calculation of the direction of the impact of the blood drop and the vertical flight path (Fig. 1).

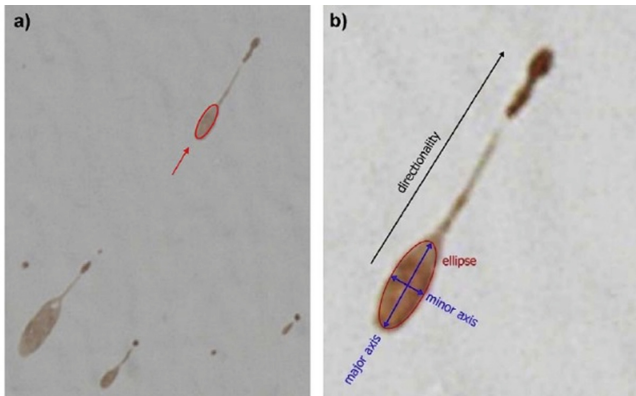


Fig. 1. The shape of a well-defined blood spatter (Source: Buck et al. 2011, p. 25)

Parallel to the study of Buck et al. (2011), Karger et al. (2008) stated that there is important information which the morphology of bloodstain distribution patterns for the reconstruction of the crime brings about. Karger et al. discussed a series of illustrative cases which allowed reconstructing the crime scene through BPA, confirmed by the offender himself. Different types of bloodstains were covered in the cases, such as smear stains, drop stains, splash stains, and arterial blood spatter. Karger et al. (2008) addressed the problems that are commonly encountered in practice, such as adverse environmental situations or mixtures of various bloodstain patterns. They also showed

that the morphology of bloodstain analysis can examine bloodstains individually by selecting a certain number of stains from a multifarious pattern for DNA analysis.

On a similar note, Aron and Northfield (2017) looked into how AR goggles can be used in forensic investigation and noted that the AR system helps users to tag objects found in the crime scene, like bullet holes and blood spatter. In addition, a police officer in a remote location can take the first look of the crime by merely watching the user's video stream. Related to this, Yen et al. (2003) stressed that there has been increasing knowledge on bloodstain pattern morphology, owing to a variety of experimental examinations in previous years. Moreover, a scenario in Dath's (2017) study showed how blood pattern analysis could be visualised in a VR environment. It pointed to where the action causing the blood spatter originated. As the visualisation is presented to the user, the user is able to understand how the act leading to the blood spatter trace took place and thus gains a holistic perspective of the crime. Similarly, Joris et al. (2015) recommended an automated and virtual method, in which digital images and fiducial markers were employed. Their findings showed that given the benefits of this proposed method, such as proper operation and other practical functions, it may be a valuable asset for BPA. Joris et al. presented the accompanying software called Hemo Vision to demonstrate its practical use in crime scene investigations.

On the other hand, cognitive robots were used in Acampora et al. (2015) study of BPA. They stressed that BPA is still basically based on manual methods, which lengthens the analysis of a crime scene. Aside from this, crime scene analysis becomes tedious and likely imperfect. Thus, Acampora et al. (2015) proposed a robotic framework for the automation of the BPA. Specifically, the robotic framework has a component that can navigate the crime scene, detect bloodstains, calculate the points of origin, and prepare a technical report that depicts the bloody scenario. Their objective of using the robotic framework is apparently similar to the goal of adopting VR in BPA.

Another attempt to improve BPA in crime scene investigation is Agosto et al.'s (2008) Fully Geomatic Approach. Their study involved the verification of the link between human walk paths and blood patterns, which required pictures taken by first-aid personnel. In general, crime-scene-related geomatic distortions affect those pictures. A range of GIS functionalities for the simulation of human walk movements served as the basis of the crime scene analysis.

Similarly, Wassom (2015) mentioned that blood patterns and other sensor-sensitive forensic data may be visualised using AR applications. Advanced imaging systems for visualising traumatic penetrating wounds can likewise contribute to the advancement of forensic pathology. Using a game simulation, Bahamon et al. (2014) noted that a user's main goal is to secure a photographic record of all physical evidence that could be found in a crime scene and preserve its integrity. This evidence includes blood spatter, broken glasses, weapons, bullets, and the like. This is meant to improve the analysis of crime scenes and solve the crime. Thus, both Wasson (2015) and Bahamon et al. (2014) noted the value of physical evidence in forensic investigation.

In Sauter's (2019) aim to reconstruct a crime scene in 3D, they stressed that developing an accurate 3D model was the first step. Photographs of the crime scene serve as image maps, which will be used to create a more realistic scene. The trajectories of blood spatter images can be accurately gauged when these images are used as models

and are placed in their precise location. By clicking the mouse on the blood or a strand of hair, a DNA report of the victim will be generated. All information about the case will be available to investigators since the 3D crime scene can be accessed online.

On a similar scale, Shen and Cipolla (2006) carried out comparative experiments regarding blood spatter stains using an image analysis algorithm, which can be used in crime scenes. This approach serves as an alternative to the labour-intensive technique of localising the blood's source in 2D. They concluded that the algorithm matched the accuracy expected from forensic investigation. Likewise, this creates a useful insight for the present study regarding how HoloLens can be used by localising the blood's origin in 3D.

5 The Use of Forensic DNA Databases

Each individual has a unique Deoxyribonucleic Acid (DNA) (except for identical twins) which does not change over time (except mutations), making it a viable tool for identification. DNA analysis is the source of every person's makeup, revolutionised forensic science and developed into becoming an important tool in forensic investigation (Frunkin et al. 2010). Owing to scientific developments, DNA databases have been created to serve different purposes, such as law enforcement. According to Roman-Santos (2010), the creation of DNA databases will enable law enforcers not to rely on subjective judgments in solving a crime and will help clear innocent people from being wrongly convicted. However, DNA databases are also critiqued for the potential that DNA might be used for the omission of materials that have a strong proof of the suspect's innocence. Roman-Santos concluded that whilst DNA is useful in fighting crimes, its potential allows it to be likely abused, which led him to infer that leaders should ensure that all DNA profiles should be used only for the limited purposed for which they were gathered and that they should be already destroyed once generated so that they cannot be used for purposes other than forensic identification. In order to expand DNA databases, several states in the United States have implemented laws that require DNA samples from people involved in murder, felony, burglary, and sex crimes (Roman-Santos 2010).

At present, DNA evidence is used for convicting or exonerating suspects of various types of crime (Frunkin et al. 2010). The tremendous power of DNA technology as a tool that can identify criminals had ushered a remarkable change in criminal justice (Panneerchelvam and Nozarmi 2003). Blood, hair, urine, saliva, and other evidence samples can be obtained in crime scene investigations, yielding DNA profiles. Blood from a suspect may be obtained to produce another DNA profile, which is then compared against crime scene evidence to find out whether a genetic match exists. On a similar scale, Hazel et al. (2018) also affirmed the fact that DNA is a very viable crime-solving tool. They pointed out that Kuwait, Saudi Arabia, and UK, amongst others, have been considering a universal DNA database populated by all people in the world. In their study, they discussed the likelihood for a universal database to be more useful and less discriminatory than what the current system fosters, given a correct implementation.

DNA evidence is important in crime scene investigation, and its relevance is that it can be linked to a suspect or can remove a suspect from suspicion. A comparison between properly collected DNA and known samples can be made to put the suspect

at the scene of the crime. In the absence of a suspect, a DNA profile gathered from the crime scene can be recorded into the Combined DNA Index System (CODIS) where a suspect can be identified anywhere in the United States or where serial crimes may be made to connect to each other (OVC 2012). The importance of physical evidence such as DNA codes in the crime scene and how AR may be used to make the process more efficient has been noted in several studies (e.g. Sauter 2019; Ticknor 2018; Werry 2011).

Bohannon et al. (2000) stated that developments in DNA sequencing technology enable inexpensive genetic tests; however, although the genetic information obtained from such tests is often valuable, serious concerns have been raised with regard to the privacy of such information, especially when it is gathered into databases. As they carried out an investigation into access control of forensic DNA databases, Bohannon et al. (2000) mainly observed that a target individual has an evidence sample in the form of blood or tissue obtained from a crime scene. They also demonstrated how forensic DNA databases may be carried out in a way that only legitimate concerns are feasible. For example, an individual with unrestricted access to the database will not be allowed to acquire information about another individual unless there is already known genetic information regarding that individual.

Relating to this, Benschop et al. (2017) discussed a particular software technology called SmartRank, developed to allow only relevant candidate suspects to a crime and rank them accordingly. They noted that a national DNA database with complex profiles commonly generates very huge variety of potential matches present several candidates which the forensic investigator needs to further study. When compared against CODIS, SmartRank was found to complement CODIS with regard to DNA database searches. Adopting the best practice principles, SmartRank also allows investigative leads to be obtained in criminal cases without as suspect.

In their study, Frumkin et al. (2010) showed that the present forensic procedure fails to differentiate between samples of blood, amongst others, with artificial DNA, and equivalent samples with natural DNA. In order to address this matter, Frumkin et al. designed an authentication essay, whose function is to differentiate natural DNA from artificial DNA. Forensic procedure uses an authentication essay to maintain the high credibility of DNA evidence in courts. DNA technology can be forensically applied in identifying potential suspects based on a match between their DNA and crime scene evidence, amongst other uses (Roman-Santos 2010).

Another technology which was developed for forensic DNA analysis was discussed in Liu et al. (2008), a real-time integrated system aimed at analysing short tandem repeat (STR). A mock crime scene using real-time STR investigation was conducted to assess the system's usefulness and compatibility with forensic investigation processes. In this mock crime scene, the suspect's blood samples were collected; his DNA was extracted, and the STR was analysed, as a successful CODIS hit was generated. This demonstration of STR analysis validated the potential of real-time DNA typing in determining the biological evidence at a crime scene. Similar to Benschop et al. (2017) and Liu et al. (2008), Greely et al. (2006) studied the scientific potential of DNA forensic technology by using DNA matches from crime scenes to identify the suspect from a pool of relatives who have DNA profiles in forensic databases.

On a similar fashion, Werry (2011) mentioned that photogrammetry, a forensic technique, is used by forensic scientists to create a VR crime scene. Numerous photographs are saved on a computer and combined into a 3D image, which the scientist can revisit anytime to look at the scene. These photographs can also be cross-checked against the statements of the witness or any new information that may arise. There are also databases of DNA, fingertips, and eye scans which can be readily accessed for crime scene investigation.

Furthermore, the implications and cost-efficiency of DNA evidence in the investigation of property crimes were studied in Roman et al. (2009). Aside from conducting traditional investigations, DNA processing was carried out in the treatment group. Since it is more expensive to conduct DNA-based investigations than non-DNA ones, significant investments will be necessary to increase the capacity of the police, crime laboratories, and prosecutors to effectively utilise this investigative tool. DNA Databases such as Combined DNA Index System (CODIS) speeds up the process (Norrgard 2008). In Claes et al. (2014), it was stressed that DNA left at a crime scene could be tested and used to thin down the collection of potential suspects.

6 Forensic Toxicology Reports

According to Dinovo and Cravey (2007), forensic toxicology is defined as “a highly specialised area of forensic science which requires expertise in analytical chemistry, pharmacology, biochemistry, and forensic investigation. Isolating and identifying drugs and other poisonous chemicals from tissues, as well as interpreting the findings for legal authorities like the medical examiner, are the concerns of a forensic toxicologist. Drug cases may involve a clear and apparent overdose, often validated by a suicide note; or a drug-related pathological progression that results in an overall decline in health. Oftentimes, it is the homicide investigator who initially views the scene, and if given a proper training, he keeps the scene intact for the medical examiner whom he summons. The investigator, who carries the main burden of the investigation, is usually the sole member of the medical examiner’s staff to essentially look at the scene and talk to witnesses. The tasks that he must accomplish include collecting all information possible from the first officer on the scene, arranging for photographs of the scene, gathering and preserving all evidence, interviewing witnesses, and obtaining the victim’s medical history. On the other hand, the forensic pathologist carries out the autopsy, gathers the specific specimens to be analysed, and submits these to the forensic toxicologist, who serves as a crucial member of the team. As such, the evidence he collected must be taken into account, assessed, and clarified in the final assessment of the cause of death (Dinovo and Cravey 2007). Kilgus et al. (2014) stressed that during autopsy, today’s forensic pathologists largely depend on visible signs, tactile indications, and experience to identify the cause of death. Although computed tomography can be used for the corpses under examination, the lack of radiological work stations in the pathological site makes these data not used often. Through the data, the forensic pathologist may be prevented from damaging the evidence by enabling him to link, for example, external lesions to internal injuries. Thus, Kilgus et al. (2014) proposed a multi-modal approach to intuitively visualise forensic data and evaluate their feasibility.

Dinis-Oliveira et al. (2010) specified that forensic toxicology determines the relevance of the findings by the nature and integrity of the specimens. This denotes that selecting and gathering specimens, both for ante-mortem and post-mortem, is confronted by various challenges. Dinis-Oliveira et al. stressed that a potential bias may take place in interpreting toxicological results. Favretto et al. (2013) pointed out that the considerable ineffectiveness of the present approaches of toxicological screening to determine the new compounds that enter the market is one of these concerns. There is therefore an immediate need to enhance the screening capacities of toxicological laboratories. On the same note, Murray (2016) stated that whilst significant innovations in the domains of toxicology and DNA analysis have been emerging, most forensic procedures are still using 19th century techniques. Likewise, in Al-Kandari's (2012) study in Kuwaiti setting, a need for virtual autopsy and early DNA measurement in Kuwait was identified.

In order to produce a 3D documentation of findings which other experts can reassess when needed, the research project *Virtopsy* was introduced in Bolliger and Thali (2015). In this project, autopsy results and forensic imaging were combined together. This forensic imaging allows the findings to be objectively reassessed by other experts even when the body had been buried or cremated, or the victim healed of injuries. In Ebert et al. (2014), a range of 3D image modalities were used to reconstruct crime scenes but since they were presented in a 2D manner on computer screens and paper, they incurred loss of information. Hence, they applied immersive VR techniques and proposed a system that enables a crime scene to be viewed as though the investigators were there at the scene. Using a low-cost VR headset which was originally designed for computer gaming, Ebert et al. (2014) facilitated a 3D and interactive visualisation of the crime scene. Alternatively, Biwasaka et al. (2005) studied the usability of hologram in the 3D recording of forensic objects and the accuracy of restructured 3D images. The virtual holographic image documents the 3D data of the original object. They pointed out that holography can be a functional 3D recording method of forensic objects and found that it appears to function similarly with the computer graphic system; moreover, combining it with the digital technique would broaden its utility in superimposition.

On the other hand, forensic entomology comprises the study of insects found on a cadaver to approximate the time of death. This technique is the only available one for a huge post-mortem interval. However, relevant system complexities lead experts to give imperfect results. In their study, Veremme et al. (2012) described a decision support system (DSS) which was developed to consider the entire parameters of ecosystems and a considerable number of biological models. Similarly, in their study of virtual forensic entomology, Richards et al. (2012) showed how micro-computed tomography can be an effective means to describe internal and external changes in morphology by sampling pupae. This technique can be useful in estimating a minimum post-mortem interval for suspicious deaths, where pupae are shown to be the oldest stage of insect evidence gathered. Emerging technologies to improve forensic entomology may suggest that advancements like HoloLens can be possibly used in this field in the future.

7 Summary

This paper reviewed the literature on the subject under study. It specifically discussed the features of augmented/mixed reality and how collaboration in forensic investigation can

take place through technology. It then tackled the use of AR in crime scene investigation, the environmental aspects of the use of HoloLens, blood splatter analysis, and the use of DNA forensic databases. With its review of the literature, this study was able to validate the usefulness of HoloLens in elevating the level of crime scene investigation.

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