Seamless Crime Scene Reconstruction in Mixed Reality for Investigation Training: A Design and Evaluation Study

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***Abstract*— Investigation training in the real crime scene is a critical component of forensic science education. However, bringing young investigators to real crime scenes is costly and faces significant challenges. Mixed Reality (MR) is one of the most evolving technologies that provide unlimited possibilities for practical activities in the education sector. This paper aims to propose and evaluate a novel design of an MR system using Microsoft HoloLens 2.0 and it is tailored to work in a spatial 3D scanned and reconstructed crime scene. The system was designed to be a costly-effective experience that helps young Kuwait police officers to enhance their investigation skills. The proposed system has been evaluated through system usability, user interaction and performance metrics quantitatively via 44 young police officers, and qualitatively using the Think-aloud protocols via a group of experts. Both groups showed positive levels of usability, user interaction and overall satisfaction with minimal negative feedback. Based on the positive feedback, the system will be taken into the commercialisation stage in the future. Despite the high cost of the MR device, it was stated by experts that the system is needed to be provided as an essential tool for crime scene education and investigation practices.**

***Index Terms*— Crime Scene, Mixed Reality, Crime Investigation, Investigation Training, 3D Reconstruction, 3D Scanning, Photogrammetry, Usability**

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A video of the holographic training system is provided as a supplementary files. All procedures performed in studies involving human participants were in accordance with the ethical standards of Liverpool John Moores University and its later amendments or comparable ethical standards. Informed consent was obtained from all individual participants included in the study.

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I. INTRODUCTION

CRIME scene investigation practices aim to examine, discover, and secure traces of offenders. Police investigators and forensic professionals are involved in these procedures to collect clues and evidence in protected, secure and traceable ways for juridical purposes [1]. The lack of discovering and recognising the physical evidence in criminal cases can lead to losing forensic value, which, accordingly, leads to losing the link between the crime and the suspects [2]. The UK Home office reported that half of the cases were suspended due to the absence of supported evidence [3]. Therefore, expert forensics and investigators are trained using forensic tools proficiently to collect evidence from the crime scene, e.g. identifying and fixing fingerprints, gunpowder or blood droplets [4]. Tangible evidence had the major contributions –77.6% in homicide crimes and 90% in felony crimes – for connecting the suspect to the crime scenes [5].

In fact, training on these techniques for younger investigators on-site is significantly difficult as crime scenes have a sensitive nature and evidence can be easily damaged by curious trainees or careless handling by inexperienced investigators. These would lead to contaminating or tampering with the scene, and loss of evidence. Moreover, having many individuals at the crime scene makes it cumbersome to perform an effective investigation and it can increase the chance of trampling latent evidence [6]. Moreover, small crime scenes may not be able to accommodate students who may be in a wheelchair [7], thus limiting the accessibility of opportunities to these students to have hands-on experience. Furthermore, the National Forensic Science Technology Center emphasises that crime scene investigation is a complex process that requires specialised training and expertise, as allowing students to access crime scenes can compromise the integrity of the investigation process [8]. Some educational institutes provide crime scene facilities to provide practices for their students. However, it is impossible to offer individual investigation to the numerous numbers of students in three or four different levels with multiple scenarios in one single facility [7]. As a result, investigation and forensic training in police academies are still facing limitations in terms of contextual-based activities due to the number of trainees [9].

The main objective of this study is to design, implement and evaluate a novel training system that utilises mixed reality that reconstructs a scanned crime scene. The younger generation of investigators is likely to embrace technologies [10, 11], as considering the immersive technology part of the training programs would enhance interactivity and engagement.

The question which remains open is as follows: What is the impact of enhancing the crime scene investigation training systems if two methods of reconstructing scenes – 3D scanning and Photogrammetry are combined to produce a virtual crime scene mimicking the physical scenes and be integrated into a mixed reality system for training young investigators?

For responding to the previous research question, qualitative and quantitative research methods were conducted. The System Usability Scale (SUS) was the quantitative method, while the 'Think Aloud Protocol' was the qualitative method, which are interviews considering the adoption of this method in the study of Su et al [12]. Using mixed reality and 3D scanning technologies combined would help young investigators to superimpose and reconstruct crime scenes virtually on top of the environments they are living in, so they can learn investigation practicalities and interact with the scanned scene without the aforementioned limitations.

The case study of this research was conducted at a crime scene facility that is owned by the University of Winchester to be considered as a simulation for a real crime scene as it is equipped with the required facilities and materials for investigation practices. The process of building this new system is comprised of two stages. The first stage is capturing the crime scene and this stage involves the process of 3D scanning which not only includes the surfaces but also the textures, colours and forensic features of the scene. 3D scanning for indoors requires specific types of scanners that can detect walls, furniture and blind spots e.g. behind desks, under sofas and beds. Laser scanners are frequently used on external sites, but they were utilised to scan internal venues such as the scanned crime scene [13]. Moreover, laser scanners lack capturing textures, colours and features during the scanning; therefore, photogrammetry techniques were implemented to cover this lack and to provide high-quality images to be integrated into the process. The process introduced an efficient method of integrating the 3D scanning into the results of photogrammetry scans to form one single 3D model of the entire scene covered with needed textures and details. The output of this stage will be considered as content to be fed into the next stage.

The second stage is building the mixed reality system. The mixed reality application is designed to be run via Microsoft HoloLens 2.0 headset and it was built using the Mixed Reality Tool Kit (MRTK) 2.0. This tool kit provides a set of components and features to support app development. It also enables the device that has four cameras to scan the real-world environment to provide spatial awareness so it can support placing the scanned scene on top of the physical environment to ease the walking navigation for users [14]. Therefore, this kit was utilised in the design structure phases, followed by the development phase, which involved using the game engine Unity 3D that supports Microsoft HoloLens deployment. Then, the 3D scanned scene was fed to the project as 3D model after enhancing the textures and features. After that, the design of the system will be constructed, and all functions and training components will be ideated. The next phase is to incorporate MRTK 2.0 with its components to establish the functionality of the training stages. Moreover, the user interface will be built to enable the functions of the training stages and tested for usability purposes. The following phase is to deploy the app using Microsoft Visual Studio to the headset and it will be ready for testing and debugging for release.

II. Background and Related Work

Immersive technology is designed to blur the boundaries between the physical and virtual environments and add the sense and experience of being immersed [15]. Immersive technology takes different shapes, such as Augmented Reality (AR), Virtual Reality (VR) and Mixed Reality (MR) and all these technologies are becoming influential in everyday lives [16]. AR, VR and MR started to invade the learning and education sector. For example, several VR training applications developed in medical education [17, 18]. These applications provide haptic feedback and introduce safe environments for students to practice their practices and enhance their skills without affording the expenses of conducting these practices on humans or animals. In regard to the engineering field, AR played a significant role in providing safety training for electrical engineering students and this is by displaying animated instructions over the machines [19].

In recent years, researchers have started to utilise immersive technology to support crime scene investigation practices, particularly training. VR technologies provide opportunities for crime scene investigations that do not exist in the real world, as they can analyse the scene and measure its dimensions from sides and heights [20]. This expands the possibilities of acquiring more information about the scene under investigation [21].

Some immersive technology solutions were recently yielded for crime scene training, as a VR application contributed to support the crime scene practical skills by providing simulations to overcome the challenges of cost, accessibility and size limitations of real crime scenes [7]. Despite the efficiency of the VR application, the environments provided were created by computer graphics and not 3D scanned with realistic features, which does not the authenticity of the physical crime scene. This is in addition to the motion sickness experienced by users during the training. Another similar VR application used the game-based learning approach in artificial environments to teach criminal law [22]. A conceptual framework was developed to provide training on incident first responders for digital forensic investigators and interestingly, it can provide immediate performance feedback to each trainee [23].

A. Mixed Reality

Mixed reality is described as an emerging technology that affords users with the maximum level of interaction with the real environment compared to other immersive technologies such as AR and VR [24]. Mixed reality interactive environments proved to offer better human performance in crime scene investigations, particularly in response to multimodal interactions [25]. Immersive technology took several shapes, such as 360-degree panorama of 3D scenes in a mixed reality experience to support remote collaboration among investigators [26]. Similar to the previous study of [26], other scholars built on this collaboration concept by adding a level of interaction using MR devices to recognise the viability of MR devices in this sector [27]. Several studies utilised augmented reality to achieve collaboration among remote forensic investigators to support team situational awareness [28, 29]. Researchers found that mediating immersive technology in crime scenes can enhance places through narratives and fiction [30].

Some key authors in immersive technologies considered MR and AR as interchangeable terms in some ways with consideration to MR as it allows more involvement with physical worlds and more interactions [31]. From this perspective, the literature extends to include AR studies that were yielded in crime scene training. However, the forthcoming AR studies were designed to run on smartphones and handheld gadgets. For instance, an AR pilot study was examined after adopting a gaming approach to enhance the forensic training experience [32]. Other AR applications were developed to support educational forensics, and they superimpose virtual objects for smartphone holders using AR tags [33]. Other recent studies used AR markerless applications [34, 35].

Some immersive tools were involved in crime scene investigation training and these tools are described as either distinguished AR headsets or mixed reality headsets as other researchers described, such as Microsoft HoloLens, and Magic Leap. These headsets use a transparent display, which permits light to go through the users' eyes while allowing the rendering to be visible on the displays. Very limited studies and industrial applications involved these tools in crime scene training [36]. However, these studies implemented a simulation of real cases using computer graphics and generated by 3D modelling, not by 3D scanned real crime scenes.

B. 3D Reconstruction

3D Reconstruction of crime scenes was one of the approaches that were involved in investigation training. Recently, 3D imaging techniques such as 3D scanners proved their efficiency for many forensic applications as they are non-invasive gadgets with rapid measurements in addition to a provision of high precision details. 3D scanners and structured light scanning have been yielded in forensic applications such as clinical forensic medicine [37, 38], face recognition [39] and reconstruction of crime incidents [40, 41].

Reconstruction in crime scenes took different shapes, such as the simulation approach, which involves creating the scene using computer graphics with the aid of game engines to be displayed using VR kit [4]. Other studies reconstructed crime scenes by integrating multiple technologies such as 3D animated graphics, motion tracking, natural language processing and computer vision to visualise the crime in courtrooms using VR kits [42]. More recent attempts to reconstruct pictures of crimes in transports using AR tags for the sake of forensic training [33].

Despite the efficiency of the 3D scanners and their advantage of reducing time consumption of surface scanning in crime scenes, the final result for visualisation has critical defects in terms of the quality of the surfaces. As it normally leaves holes and defects in the surfaces and textures, which means a significant loss of the crime scene features as displayed in scanned crime scenes in previous studies [43]. This is in addition to visualising the 3D models in two-dimensional screens, which does not show the capability of immersion in the 3D scanned scene. Several studies incorporated these laser scans with virtual reality applications; however, no study implemented the 3D scanned environments to a mixed reality headset with mobility privileges for the headset wearer.

This study introduces a seamless, comprehensive method that overcomes the scanning problems and defects in the walls and surfaces – particularly the indoor venues - resulting a realistic 3D scene. Moreover, the scanned scene will be optimised to be fed to a mixed reality system to train crime scene investigators.

Several police academies and educational institutions in different countries implement and develop VR simulations for crime scene investigation training [7, 44]. However, until now, there is no simulator in mixed reality technology implemented to provide a reconstruction of a real crime scene for trainees with the ability to move and walk safely and interact with the scanned scene and conduct the normal practices of investigations.

III. System Structure

This section articulates the MR training system structure – as depicted in Fig. 1 – and the two different stages of creating it, starting from Stage 1 Capturing a crime scene which comprises of 3D scanning process, photogrammetry, and post-processing. Then, the section continues to demonstrate designing of the system in Stage 2 Mixed reality holographic training system, which comprises of structure design, development cycle, getting models into the virtual scene, user interface using MRTK 2.0, application deployment to the headset, and testing and fixing bugs– stages of implementation depicted in Fig. 2. The system has been piloted on young police officers at the Kuwait Police Academy.

A. Part 1 - Capturing crime scene.

Expecting realistic results from 3D scanning of a physical environment is quite cumbersome particularly if it features forensics such as blood droplets or wall marks [45]. Despite several attempts to reconstruct interior crime scenes, capturing blind spots in narrow rooms proved to be the most challenging, resulting in incomplete scenes [43]. Therefore, a series of scanning techniques for indoor spaces were reviewed in similar cases in the cultural heritage field. Moreover, a series of consultations with experts in 3D scanning in the cultural heritage field were conducted, and then a number of techniques of 3D point cloud laser scanners were shortlisted to achieve the high level of detail required. Eventually, FARO point cloud 3D scanner X130 was chosen to perform the capturing due to its efficiency in reconstructing exterior and interior scenes and its ability to generate coloured textures in previous studies [46, 47].

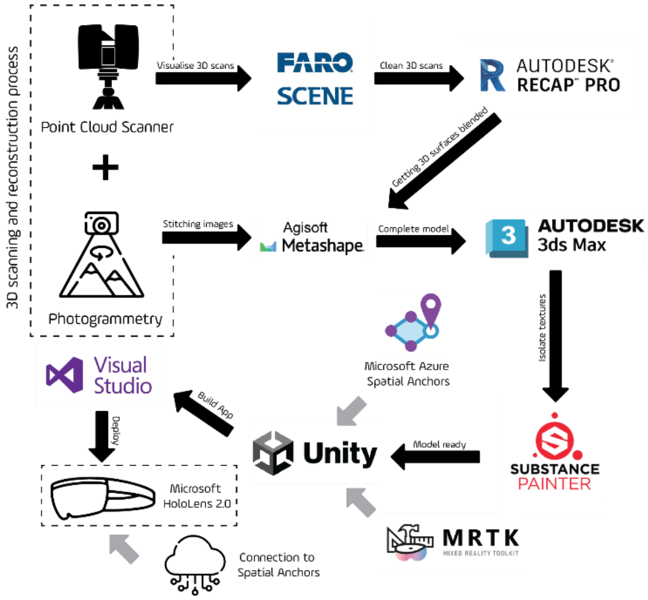

Fig. 1. System architecture

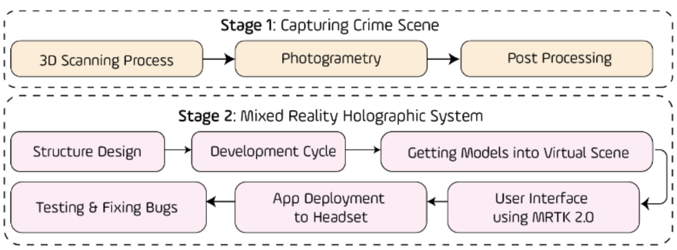

Fig. 2. Stages of implementation

3D scanning process – Finding an actual crime scene to use as a case study is quite complicated due to the restrictions regarding police permissions, privacy constraints and the timing for conducting it after the incident. Therefore, using the 'Winchester University Crime Lab Facility' was the most feasible solution. The facility has two floors, and the top floor has two bedrooms, which have been set to simulate a murder crime for two individual victims represented as male and female mannequins in each room. Both rooms have been set to be captured in terms of the lighting conditions, such as light balancing and enlightening the dark areas with extra light sources. Blind spots have been covered via defining nine positions of the FARO scanner to be placed in both rooms to be able to capture these spots and to avoid neglecting essential parts of the scanned scene - as depicted with a top view in Fig. 3 (b). This is in addition to checkerboard patterns fitted to walls to support registration of the resulting scans in the post-processing stage– as depicted in Fig. 3.

After several failed attempts, the scene was captured successfully through nine positions with different heights and the scanner settings were adjusted to be indoors mode with resolution ¼, scan size [Pt] 5120 x 2205, 11.3 Million Points (MPts), and with a 4x quality level. This was in addition to nine different panoramic images generated to overlay the point cloud with textures.

After the completion of the scanning, registrations of the nine scans [Scan 00 – Scan 08], were performed using FARO SCENE software and the aid of the checkerboard patterns. A series of adjustments were conducted on the setting to achieve more overlapping of all scans to get a single formation of the entire scene comprised of millions of point clouds. The process of registration worked by comparing every two clusters or scanned scenes. Consequently, it resulted in 25 pairs of matching clusters, (provided in the appendix).

The overall statistics of the Mean [mm] value for all tensions have resulted in 0.737. To justify the feasibility of the generated overlapped model, the FARO guidance defined the optimum registration result to be greater than 50% for all cluster pairs. Considering the overall overlap below 4.0 mm was 88.8%, this means a successful registration occurred.

Fig. 3. 3D scanning at the crime scene facility after being adapted to simulate a crime incident.

Cleaning the unnecessary point clouds of the scene has been undertaken with the aid of Autodesk Recap Pro – as shown in Fig. 4 (a). This involved eliminating all irrelevant point clouds generated by mistake as they would cause distortion to the 3D model when the conversion from point clouds to 3D polygonal model. At this stage, there was an attempt to export the initial 3D model despite it being a raw version and needing a long queue of amendments to be processed. The generated model had an enormous size with 31 million polygons - 31,576,406 faces – and this size is not feasible to be embedded or operated in an application of any immersive headset of handheld gadgets regardless of the high specification of the device. Moreover, when the panoramic images overlayed on top of the scene surfaces to preview the quality of the textures, it was found that colours were low contrasted with major flaws such as gaps in textures, white spots and other parts of the surfaces that did not capture the textures – as depicted in Fig. 5.

Photogrammetry – Most studies that rely on 3D scanning using laser scanners could not generate proper textures for the entire scene that can feature forensic features with high quality [43, 48]. Therefore, integrating photogrammetry to the 3D scanning process could potentially compensate for the missing data relevant to colours and textures to better feature forensic elements of the crime. The photogrammetry technique relies on the relation between the points that construct the object space and the corresponding points of image planes [49]. In another words, the process works by combining several images captured with considerable overlap among them, and then mathematical computations have to be conducted to generate a 3-dimensional surface or model that maps a particular space [50]. Some studies aimed to combine photogrammetry with 3D laser scanning for obtaining high quality textures [51, 52], other studies were in cultural heritage applications [50]. Despite the lack of applying this technique in crime scenes, this technique was adopted to explore the potential of extracting better indoor textures that are capable of displaying forensic features.

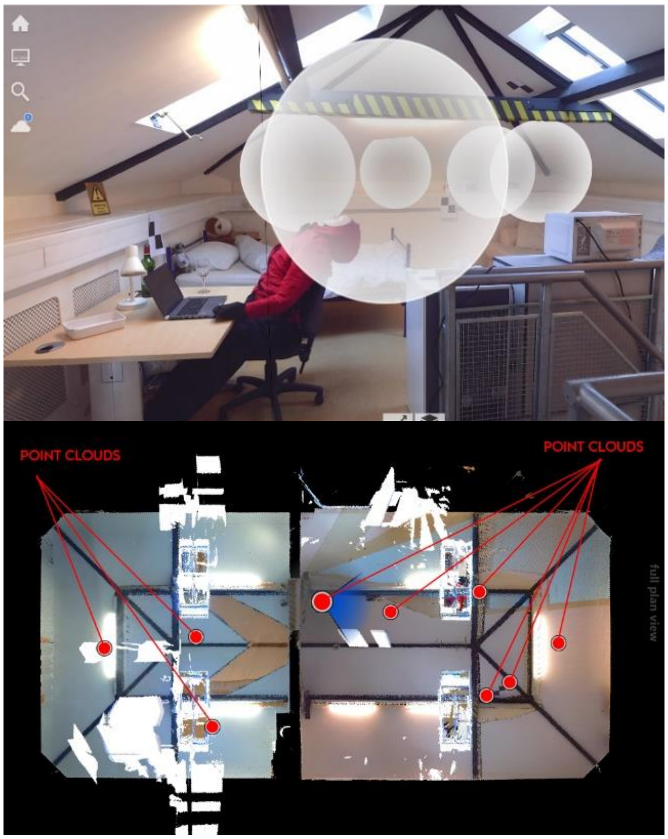

Fig. 4. (Top) (a) Quality checking in Autodesk Recap Pro (Bottom) (b) The Scene is cleaned in top-view

Fig. 5. Raw 3D model exported with poor textures generated from 3D laser scanning Process.

The photogrammetry process requires DSL cameras such as Canon EOS 5D Mark III with hardware specs e.g., 22.3 megapixels. A series of camera adjustments and settings have been experimented, and the final adjustments were as follows: ISO 100, F/8, shutter speed 1/400 and standard lens of 18-22. It was recommended to use manual focus on each capture but since this method requires an enormous number of images, auto-capture was chosen for faster performance. External flash unit – 580EX II - was in significant need to enlighten dark zones and to maintain the exposure balance for all captured images. Flash strength was adjusted to be 1/8 to 1/16 according to the existing lighting condition of the captured frame. This was in addition to four external lighting units fitted during the rapid capturing. For accurate results in the post-processing stage, 'Data color SpyderCheckr24' was used to aid the camera calibration and colour adjustments. 1457 images captured in 11 camera positions.

Post-Processing – This stage aimed to merge the results of laser scans – represented in a 3D Model – to the photos captured in the photogrammetry in order to generate a properly and optimised textured 3D model representing the scene. The process started by colour adjustments using Adobe Lightroom to control the colour grading, and tonality and perform all adjustments to define the most appropriate images for the photogrammetry process. 10% of the total amount of images were excluded and 1291 images proceeded to the next step.

Several pieces of software were investigated in terms of the quality of processing and models. RealityCapture has become well-known recently for effectively reconstructing textured 3D models. It works by combining clusters of images with significant overlaps automatically with further iterative alignments to construct a portion of the scene. Normally, the automated procedures resulted in the drawback of alignments; therefore, 40 manual clusters were involved to stitch the missing parts of the scene. Despite the adequacy of the highly overlapped images, the software failed to construct a coherent 3D model.

Therefore, another attempt was conducted with *Agi Soft Metashape*. After importing the 3D scanned room as 3D model accompanied by the captured images, the alignments were achieved efficiently. The initially generated scene was having 32 million faces as a raw version of the model and on top of the scene, the captured images were converted to texture the model. The depicted Fig. 6 showed highly realistic results compared to the camera captured images as no gaps in the room or changing colours. Also, the resolution of the textures is quite decent and close to the original images. Comparing these results with more recent publications that adopted similar techniques in crime scenes such as [43, 53].

Despite the acceptable results, model's size of the 31 million polygons is enormous. Indeed, it requires a long processing time and its weight exceed the average sizes of the model especially if it will be running on a portable device e.g. AR or VR headset.

Therefore, the compression or decimation stage for the raw model stage started to generate a feasible version to enable the processing of the scene. The compression was performed gradually as the drastic downsizing caused major drawbacks in the final model. Hence, the gradual compression started from 31 million to 10 million, then to 5 million, then to 2 million, then to 1 million moving town gradually to 99,999 faces. This is the decent trade-off between the model quality, texture resolution and processing in portable devices including AR/MR devices.

Fig. 6. Top images are the scanned results, and the bottom images are the camera captured images.

Post Processing – Despite the highly realistic visualisation of the crime scene that was outputted, the model, normally some problems can be spotted such as uneven surfaces or holes in the surfaces. However, the only holes that were found are the area that is neglecting during the 3D scanning and the photogrammetry. It is very critical to make changes on the structure or the textures of the room for the reasons of leaving crime evidence intact. Therefore, minimal refinements were conducted to the model using Autodesk 3Ds Max to amend the wall straightness and close holes to the blind spots e.g. under beds or behind sofas. Refinements were done carefully to avoid altering the essential measurements of the scene.

For training purposes and directions from expert investigators, certain digital brush paintings were overlaid on the crime environments to create a chain of clues and to simulate real crime scenes. The added artificial clues are such as pigmenting a crime tool with blood, adding blood droplets and adding biometric evidence on glossy surfaces.

B. Part 2 - Mixed Reality Holographic System

Following the stages demonstrated in Fig 1, the process entails the structure design, development cycle, getting models into the virtual scene, user interfaces using MRTK 2.0, app deployment to the headset, testing and fixing bugs, and finally testing and fixing bugs.

Structure Design – Designing the system from the initial stages was built to be tailored to the specification of the Microsoft HoloLens 2.0 – the mixed reality headset that will be used for investigation training. The goal is to superimpose the crime scene virtual scene in a wider space to accommodate it on top of the physical environment. The structure of the system divided the training into four main essential stages; Look Around, Add Markers, Check Victims and Guess the Criminal – as depicted in Fig 7. Then, it will be followed by an optional station that simulates the crime with an animated virtual avatar. Designing the training was structured based on the standard framework demonstrated by Beebe and Clark [54]. This is in addition to the consistent consultation with a group of experts in serious investigations.

Development Cycle – Microsoft HoloLens team released an effective toolkit that can encapsulate all needed scripts that support building different functions named as MRTK 2.0. MRTK was adopted as it can be integrated into Unity Game Engine to support building the system using C# scripting language. Microsoft Visual Studio was used to deploy the application files into the headset.

Getting Models into Virtual Scene – Migrating the 3D model and its set of texture images to Unity was the initial step. 3D model was exported from 3Ds Max, and the textures were exported from Adobe Substance Painter. Specifying the ultimate shader to display the realistic texturing was a challenging task as testing 'Mixed Reality Toolkit' shader outputted a semi-transparent environment. While the 'Unlit/Texture' was the most appropriate shader in spite of the lack of shadow that casts on surfaces – the final result displayed in Fig. 5. was not a straightforward mission to place the virtual crime scene on the physical environment. Adjusting the scaling involved matching the actual size of the room towards the physical environment and mapping both grounds to be on the same level. It is preferable to overlay the visuals in an environment that does not have obstacles as it would risk the safety of the user.

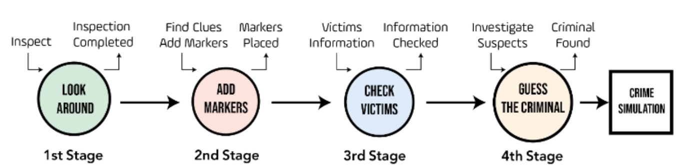

Fig. 7. Structure design and the trainee flow

User Interface using MRTK 2.0 – MRTK is a tool kit for mixed reality applications that introduce certain components and features to aid the application with needed functions. It also supports building floating user interfaces with related blocks for spatial interactions with hand air tapping. It also supports creating buttons for touching, interacting and pinching objects, particularly after the AI of HoloLens 2.0 was developed to understand natural hand gestures. Therefore, these tools enable us to build interactive visuals of the system UI.

Stage 1: Look Around – The aim of this stage is to familiarise the trainee with the crime scene and get the initial prediction of the crime. This is mapped to the 'incident response' according to the unique investigation framework demonstrated by Beebe and Clark [54]. Having a critical eye for exploring the clues and recognising changes and movable objects in the scene is the required skill set for investigators, and this stage is designed to make these practices take place. The main questions that the trainee should answer at this stage are; a) How did the criminal enter the scene? b) Did the criminal leave any murder weapon in the crime scene? Any blood traces recognised or seen. As depicted in Fig.7 (a), the investigation control is where the user will be allocated once the scene starts. Moreover, the system is designed based on the completion of each stage. Hence once the user completes or achieves what is required from the task, it unlocks the next stage.

Stage 2: Find Clues –The stage tackles the most vital investigation skill as this task maps with 'Data Collection' in the unique investigation framework demonstrated by Beebe and Clark [54]. The scenes are pre-set to have a number of clues distributed in both rooms and the main task. Therefore, a floating board appears in front of the user with yellow numbered tags that allow the user to take this virtual clue and place it on top of the potential evidence. These virtual tags auto-generate themselves whenever the user grabs one, a new tag with an incremental number generates itself in the same spot. In the current scene, 24 tags exist and there is a board with check boxes to list all potential clues that the trainee needs to find. Moreover, a virtual keyboard is also fitted in the corner for leaving notes for other investigators. Completing this stage is conditional to unlocking the next stage, as depicted in Fig. 8 (b).

Stage 3: Check Victims –This stage mapped to the 'Data Analysis' and 'Finding Representation' in the unique investigation framework by Beebe and Clark. Considering the biometric evidence sent to the lab and returned with results, this station is more like an informative task. Therefore, the communicative board guides the trainee to explore the spots of the collected evidence to see reports sent from the forensic team. At this stage, the investigator trainee can reveal the victims' identities. The informative board is designed to follow the investigator whenever he or she walks to ease making connections between clues to support building a scenario.

Stage 4: Identifying the Criminal – The 'incident Closure' stage, based on Beebe and Clark's framework, helps trainees identify the criminal when the evidence analysis falls short. It provides information on suspects with biometric traces and utilizes the 'Guess Who is the Criminal' tool, a gamified approach that allows users to read suspect profiles and investigate further using CCTVs. The holographic UI differentiates between investigation functions and suspect information through visual, interactive, and audio design of buttons.

Simulation –Part of the normal investigation practices is to simulate the crime by the criminal after the detainment as it potentially can help recall what really occurred and would connect all clues with the performed actions [55]. To practically collate all the puzzle pieces, it was significant to demonstrate an animated simulation of the crime once the task was resolved. Therefore, once the task is resolved, the user can click a button to see a 3D avatar character appears at the crime scene and perform the crime and interact with the virtual scene.

Fig. 8. Top – (a) Investigation Control, Bottom – (b) Finding Clues and Adding Markers

VI. METHODOLOGY

A feasibility study was taken place as it aims to assess the crime scene holographic training system in terms of usability and user interaction and investigate the satisfaction level by the targeted group of users. The intervention of testing the crime scene system was conducted to the police academy students who are considered junior investigators as a training part that reflects their educational curriculum.

The research design established in this study by adopting three instruments to employ different approaches to evaluate usability, effectiveness, efficiency, satisfaction, and other factors – as demonstrated in Table 1. The System Usability Scale (SUS) and the Think-Aloud Protocol focus on subjective measures, with the SUS being quantitative and the Think-Aloud Protocol being qualitative. On the other hand, performance metrics use objective and quantitative measures to compare investigation skills between two groups. Each instrument provides unique insights into the evaluated aspects based on the nature of the data collected and the characteristics of the sample.

A. Participants and Procedures

The study was granted ethical approval by the ethical committee of Liverpool John Moores University. Participants will be from three different groups:

The first group of participants were recruited from the students of the Kuwait Police Academy who are aged between 18 – 50 years. The sample size is sufficient for SUS test, as it lies between [56, 57] and [58]. The Police Academy students are considered junior investigators who practice crime investigation in traditional methods. This stage starts by providing training to each student on using Microsoft HoloLens 2.0– the MR headset- in a wide space or an empty classroom and it has to be wider enough to accommodate the virtual room for safety and usability purposes. This would take approximately 10 minutes. They then been instructed to wear the headset and are expected to see a virtual scanned crime scene; then, they need to go around and inspect the crime scene. Their task is to collect virtual evidence, e.g., blood traces, crime tools, and any potential object with fingerprints. Then, they need to send this biometric evidence to the virtual lab. The next task is to solve the case and find the criminal among different suspects. The total time for this task to be completed is approximately 20 minutes. Then, they will need to fill out the system usability scale (SUS) questionnaire, which considers the critical assessment of the usability and their satisfaction with the user interactions of the HoloLens 2.0. The approximate time for filling out the questionnaire took another 10 minutes.

TABLE 1
RESEARCH METHODS

Instrument	Measure	Sample	Nature
System Usability Scale (SUS)	Usability Effectiveness Efficiency Satisfaction	(44) Young Investigators	Subjective Quantitative
THINK-ALOUD PROTOCOL	Usability Effectiveness Efficiency Suitability Satisfaction User Experience	(11) Expert Investigators	Subjective Qualitative
Performance Metrics	Comparative analysis for developing investigation skills.	Group 1 (20) Young Investigators Group 2 (20) Young Investigators	Objective Quantitative

The second group consisted of senior expert investigators and police chiefs from the Kuwait Police Academy. They were tasked with evaluating the mixed reality system. The sample size is sufficient for this procedure, which approximately matches this study's size [59]. These experts received a 10-minute training session on how to use the Microsoft HoloLens, the mixed reality headset. They were then given time to experiment with the system, similar to the first group. Afterwards, they were interviewed using open-ended questions to assess the suitability of the virtual crime scene and the usability of the system design. The interview questions also aimed to explore the proper sequence of investigation practices and the system's potential to enhance the crime scene investigation process. The interviews lasted approximately 10 minutes.

To invite participants, experts and students were emailed through the internal network of the Police Academy. A booking system was used to allocate 20 to 30 minutes for each participant. The system trial took place for four weeks, with participants attending day after day. Prior to using the device and the mixed reality investigation system, all participants signed a consent form. The questionnaire and interview questions were translated into Arabic, the local language in Kuwait. The answers were digitally recorded for transcription and translation purposes.

B. Instruments

1) System Usability Scale (SUS)

The System Usability Scale (SUS) is a widely used instrument for measuring the perceived usability of a system. Developed by John Brooke in 1986, the SUS is a 10-item questionnaire that assesses users' attitudes towards a system based on five dimensions: effectiveness, efficiency, satisfaction, learnability, and memorability.

The SUS has been applied in a wide range of contexts, including the evaluation of websites [60], software applications [61], mobile devices [62], and virtual reality applications [63]. In addition, the SUS has been used to compare the usability of different systems [64] and to assess the impact of design changes on usability [65]. One limitation of the SUS is that it only assesses users' perceptions of usability rather than objective measures of performance. Therefore, it is recommended that the SUS be used in conjunction with other metrics or questionnaire tools in order to provide a more comprehensive evaluation of a system's usability [64]. Hence, the questionnaire on user interaction satisfaction will be employed to assess the missing aspects.

2) Think Aloud Protocol

Qualitative analysis research often relies on verbal reports to capture the true cognitive thinking processes of participants. The use of think-aloud protocols, first introduced by Ericsson and Simon [66] for psychological studies, has been extended to the field of human-computer interaction. This study utilises the protocol to interview investigators with expertise, as these questions are formed to stimulate them to express ideas and cognition to comprehend their thinking while experimenting with the system. The interview questions were designed based on the design principles and guidelines from Mixed Reality design and guidelines [67]. These guidelines involve designing holograms, interaction design, tracking, audio, and hand interactions. Also, this includes the user experience elements and guidelines that are essential for application publishing [67]. The design of questions also formed from recent academic publications that investigated the UX principles [12, 68] and interaction principles [69].

3) Performance Metrics

Performance Metrics is a method designed to evaluate the proficiency of young investigators in crime scene investigation. This method aims to measure the investigators' ability to locate and identify evidence in two different environments: a traditional training environment and a technologically advanced mixed reality system. By assessing their performance in these scenarios, the effectiveness of the training methods can be evaluated and compared.

The method involves recruiting two groups, each consisting of 20 young investigators. The first group will conduct their investigation in a mimicked crime scene at the Kuwait Police Academy, representing a traditional training environment. The second group will explore HoloHolmes MR training system which is based on 3D scanned and reconstructed crime scene, which offers interactive holograms for training purposes.

Measurement Criteria:

- Correct Identification of Evidence:

The primary metric for assessing performance is the number of evidence items correctly identified out of the total 24 items present in both environments. Investigators will be evaluated based on their ability to locate and categorize each piece of evidence accurately. This criterion focuses on the investigators' attention to detail, observational skills, and understanding of forensic protocols. The traditional approach will be supervised by a senior investigator who prepared the crime scene facility at the Kuwait Police Academy after designing a mimicking crime scene and distributing 24 pieces of evidence throughout the facility. After each participant, the supervisor assesses the location of each evidence to validate the judgement of defining the correct evidence. While in the mixed reality system training, a senior investigator visits the virtual scene after completing the task by each participant and count the correct locations and count also the incorrect placements of marks.

- Task Completion Time:

Another important metric is the time taken by each investigator to complete the assigned task. This measurement provides insights into their efficiency, organization, and ability to manage time effectively while maintaining accuracy. A shorter completion time may indicate higher proficiency and familiarity with the crime scene investigation process. In the traditional approach, the supervisor will observe and count the time spent by a stopwatch for each participant. While in the HoloHolmes, the system has a time counter that triggers from holding the first label till placing the last label on a rigid surface.

V. Results

A. Students Participant's Demographic

In this study, the participants were from the Kuwait Police Academy from different years of study. Therefore, the demographic did not include age information as all of them ranged from 18 to 22 years. The demographic structure is demonstrated in Table 2. The gender participation was quite balanced as the male and female percentages were 56.81% and 43.18, respectively. The majority of the students have XR knowledge, with a percentage of 70.4%. In addition, a higher number of students have experience using AR or VR applications practically for generic purposes, with a percentage of 59%. On the other hand, slightly less than half of the students have experience using AR or VR headsets, such as Microsoft HoloLens and Oculus Quest 2, with a percentage of 45.4%. Although the system has one aspect of the investigation training practices, the majority of the participants showed a willingness to use the full version of the system in their investigation training practices, with a percentage of 75%.

TABLE 2
PARTICIPANTS DEMOGRAPHIC DATA

Variables	*Question*	*N*	*%*
Gender	Male	25	56.81
	Female	19	43.18
Do you know what XR Technology (AR, VR & MR) is?	Yes	31	70.45
	No	13	29.54
Have you ever used AR or VR apps/solutions generally?	Yes	26	59.09
	No	18	40.90
Do you have experience using AR or VR headsets such as Oculus Quest, Microsoft HoloLens, or similar devices?	Yes	20	45.45
	No	24	54.54
If this system can perform complete training on investigation training, will it encourage you to use it for your practices?	Yes	33	75.00
	No	11	25.00

B. SUS Analysis

The scores of the system usability scale were computed for the 44 students in the Kuwait Police academy who completed 10 elements of the questionnaire after experimenting with the mixed reality application. Table 3 presented the SUS scores demonstrated against the usage metrics for the participants based on their gender, previous experience in AR/VR applications and their experience in using AR/VR headsets.

According to the results, it was reported that the HoloHolmes was preferred with an average rating of 4.2 out of 5. The complexity of the application received an average score of 2 out of 5. The ease of use was rated at 3.8 out of 5. On the other hand, the application's dependence on technical support received an average score of 1.9 out of 5. The integrated functions within the application were given an average rating of 4 out of 5. Inconsistency in the application was scored at 2 out of 5. The application's ability to be learned quickly received a rating of 4.1 out of 5. The application was considered somewhat cumbersome to use, with an average score of 2.4 out of 5. Users felt confident while using the application, giving it an average rating of 4.1 out of 5. Prior knowledge was considered somewhat necessary before using the application, scoring 2.2 out of 5. The overall usability score based on the subjective evaluation reached the value of 73.9% with a standard deviation of 7.30%. These values are good and express their satisfaction as these values were based on the study of Bangor, et al. [70], which defined the acceptable ranges for the SUS scores – as depicted in Fig 9.

For analysing the results of students from different genders;

surprisingly, female students score higher satisfaction with 75.7% compared to male students who scored slightly fewer metrics with 72.5%. In terms of groups who have previous experience with AR/VR applications, the satisfaction rate was higher than students with non-previous experiences as expected, with metrics respectively 76.5% and 70.1%. In regard to the group who has previous experience with AR/VR hardware, as expected, they scored 75.4% higher than the group have no prior experience with a score of 69.3%.

C. Experts Demographic

A group of 11 experts in criminology and crime scene investigation and evidence studies participated in the semi-structured interviews. The group of experts ranging from officers to senior officers to higher levels of management with long years of expertise were interviewed – a minimum of 15 years and a maximum of 37 years. Seven out of nine experts had experienced AR/VR applications beforehand.

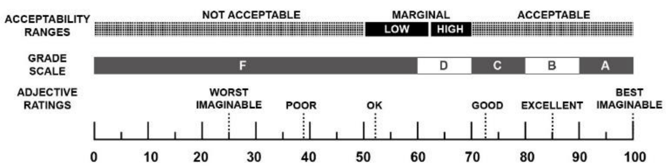

Fig. 9. The acceptable ranges for the SUS scores - from [93]

TABLE 3
SUS SCORES FOR DIFFERENT GROUP'S CRITERIA

Groups	*Question*	SUS Scores	
		Mean	*SD*
All Students		73.9	7.3
Gender	Male	72.5	8.3
	Female	75.7	5.9
Previous experience with AR/VR apps generally	Yes	76.5	7.1
	No	70.1	5.9
Previous experience in using AR or VR headsets.	Yes	75.4	6.2
	No	69.3	8.5

D. Think Aloud Protocol Analysis

The semi-structured interviews were analysed using NVivo, a powerful software for qualitative data analysis developed by QSR International. NVivo helps uncover patterns, identify themes, and draw evidence-based conclusions. To ensure rigorous analysis, the qualitative data was organized and prepared by transcribing interviews, ensuring consistency, and anonymizing responses. A data management plan was considered to establish structure within NVivo. The coding stage involved categorizing and labelling data systematically after researchers familiarized themselves with the responses. Emerging patterns and themes were identified by grouping related codes and searching for overarching themes. NVivo's tools facilitated exploring relationships, examining coding patterns, and generating reports summarizing the identified themes and sub-themes. Finally, four themes with sub-themes were constructed.

Theme 1: Crime scenes and their scanned environment

Several experts expressed their admiration for the quality of the scanned environment as an expert mentioned "The digitally scanned environment with the laser and the locations and spread of the evidence were present in a clear and easy way, and the closest thing is that it is realistic". Another expert elaborated on the accuracy of visualising the evidence by saying "The scanned environment was accurate and showed a very good representation of the crime scene. The system was good enough that it can be used in different environments to show accurate visualisation". However, an expert raised critiques regarding the graphics by saying "The graphics were good quality but can be improved. There can be more areas to explore like inside or under furniture and the outside environment, looking for entry and exits for the criminal and finding evidence outside".

Actual crime scene – A number of experts discussed the impact of mimicking the actual crime scene with the help of scanning technologies and mixed reality, which can potentially help reduce contamination and the security breach of the actual crime scene.

Low crime rates – A number of experts elaborated on using this interactive scan to train young investigators in different types of environments, with different weather conditions and in different locations, with the ability to increase accessibility. This would potentially impact on reducing the crime rates.

Different crime scenes – A number of experts emphasised the variety of crime scenes that can be visualised in a realistic appearance by young investigators if the scanning proceeds to be scaled to many crime scenes with different natures and to be part of the investigation training programs.

Crime tool – An expert mentioned the perpetrator tends to hide the crime tool in some hidden places which are not visible to the investigator and the scanning is managed in some ways to capture it and present it in the mixed reality tool. However, he/she emphasised enhancing the scanning and capturing process in the blind spots based on the experience he/she gained from previous incidents.

Crime Scene mobility - A few experts expressed their satisfaction with the scanning results, which also mentioned the ability to define the mixed reality system and its device as a crime scene mobile tool. This means investigators can utilise this tool to gain more experience in real cases while carrying this device and superimpose different crime scenes anywhere without being restricted to a dedicated space such as the educational facilities.

Crime scene investigation process – Three experts discussed the similarity of the sequence of the investigation process that occurs in real practice compared to the training system. They elaborated to enhance the system by including more standard practices in the training system.

Theme 2: Immersive mixed realities

About five experts contributed to this theme to discuss their feelings towards the perception of mixed reality during the experience and this theme comprised of seven sub-themes.

Real crime scene – Experts expressed their satisfaction of their perception of seeing two realms simultaneously and the level of realism in the crime scene presented. As an expert mentioned, “I feel that I am in reality and all that exists is real and simulates reality”. In addition, the navigation between room in the crime scene was easy and manageable to walk between them without the confusion between the two realms.

Unique experiment – Experts considered the proposed system as a unique experience, and it needs to be adopted by governments in the near future. Moreover, other experts mentioned that it needs to be comprehensive to include all investigation practices with addressing the negative sides of it to provide better versions.

Clear Vision – A couple of experts elaborated on the level of immersion they can feel during the exploration of the crime scene as it provides a clear vision of the details such as droplets, crime tools, and the movable objects in the scene.

Being immersed – 7 experts mentioned several expressions that indicate being fully immersed in the crime scene. This is in addition to the 3D images and videos and, the ability to navigate and walk in all directions and being able to look in 360. One of the experts elaborated, “The feeling of being at the scene of the accident in 3D, where you can move between the monuments and the scene of the accident easily, and the easiest is to see all the results of the laboratories”.

Comfortable – Several experts mentioned being comfortable during the experience without the need to take off the device. No mention of headaches or being dizzy and that encourages experts to last for the last minute of the experience, considering people tend to leave the immersive experience if they feel these symptoms [71].

Theme 3: Tasks

Participants discussed the functionality of tasks and criticised it in this theme. This theme was divided into four sub-themes.

Advanced training – Positive feedback was stated from the experts regarding the facilitation of collecting evidence at the digital crime scene. Experts mentioned that this system could be used in more complex cases with more difficulties in collecting evidence. This would impact the detecting process.

User friendly – Experts expressed their satisfaction with the user interface and the ability to perform tasks, describing it as “user friendly”. One expert described their thoughts that “The application is friendly use and easy to find what you are looking for especially the tools that let you investigate the scene with comfort”. Other participants mentioned the usefulness of this system for new investigators as it has many hints and prompts to show where to look and what to do next. These elements make the experience move forward without the sense of confusion of being stuck between incomplete tasks.

Linking evidence – Experts suggest that linking evidence from multiple crime scenes can assist in developing a coherent scenario for trainees and young investigators. They also propose the use of a digital keyboard to add notes at the crime scene, allowing for prolonged discussions among the investigation team. This method aids in identifying evidence and maintaining admissibility in court. However, one expert criticizes the use of such systems during active investigations, suggesting they are more suitable for training purposes.

Direct instruction – Few experts criticised the fewer instructions to find clues and evidence independently, as this would make the trainee might stop the experience due to it difficulty level. On the other side, other experts appreciated the user experience by stating, “The tasks were all guided and there were a lot of instructions, so when I got stuck, I was able to continue using the instructions. The steps were easy to follow”.

Theme 4: Whole Experience

Participants in this theme discussed what they think of this experience in a broad manner as an open question. The fourth theme was divided into two sub-themes.

Training – Experts agreed that 3D scanning improved crime scene recreation accuracy. The technology captured small details, aiding young investigators. This positively influenced training practices. Other experts emphasized Mixed Reality for immersive crime scene visualization. It enhanced understanding and identified missed details. Combining 3D scanning and Mixed Reality provided a realistic experience for young investigators.

However, some experts raised concerns about the cost and feasibility of implementing the technology. It was complex, requiring extensive training and support for effective utilization. Additionally, the technology had limited applications and may not be useful for all crime scenes.

Essential for Police Academies - Experts are enthusiastic about a proposed training system that offers a hands-on experience for young investigators, closely resembling real-life scenarios. They believe this innovative approach will effectively prepare them for the challenges they may encounter in their work. The experts expect the system to enhance understanding of crime scene investigations, enabling investigators to make better decisions in the field. They highlight the benefits of 3D scanning technology, which would streamline the training process, ensuring accuracy in identifying critical evidence and connecting it to the perpetrator. Young investigators who struggle with visualizing crime scenes and comprehending complex evidence would particularly benefit from this technology-aided training. The experts also commend the system's interactivity, anticipating that it will engage and make the training process enjoyable. Moreover, they stress that the system's simulation of real-life scenarios will emphasize the significance of meticulous documentation and evidence preservation. The proposed system is considered an essential component of the police academy's training program, crucial for establishing a solid foundation in crime scene investigations. The experts are eager to witness its impact on the next generation of investigators, confident that it will shape the future of crime scene investigation.

E. Performance Metrics

The assigned investigation task yielded the following outcomes for the two groups, as shown in the appendix. Group (1), utilizing a conventional approach with a physical crime scene facility for training, gathered an average of 20.2 pieces of evidence, which accounted for 92.5% of the distributed clues within the crime scene facility. The average time spent on this task was 17 minutes and 15 seconds. In contrast, group (2) who experimented with HoloHolmes, the mixed reality (MR) training system, collected an average of 17.1 pieces of evidence, corresponding to 71.2% of the clues present in the virtual crime scene. The average time spent on this task was 23 minutes and 15 seconds.

VI. Discussion

This research study contributes to crime scene reconstruction by combining 3D scanning and photogrammetry methods to create a virtual scene. The goal is to provide practical training for young investigators through a mixed reality system. The study also evaluates the usability and satisfaction of the interactive environment. The use of mixed methods in visualizing crime scenes has gained attention, offering an innovative approach to collecting and analysing evidence. Incorporating 3D scanning and photogrammetry into a training system using mixed reality technology enhances the interactive and immersive experience for trainees, aiding their understanding and analysis of crime scenes.

The blended methods of scanning provided realistic results without holes or gaps in the surface structure compared to recent studies that implemented applications in the same domain such as [43]. Moreover, another unique contribution was the optimisation process that was performed to make the crime scene run on the mixed reality headset without lags or delays with 60 frames per second with a model size of 100K polygons.

The study also presented a full design system, including all stages of investigation by consulting experts during the ideation and creation process. The system demonstrated the needed stages for crime scene investigation and presented its implementation in the context of mixed reality applications and utilising spaces to perform interactive tasks. The system also showed the evidence collection method to be performed by the young investigators with visual tutorials and without the need for external help, which can be an independent tool for trainees.

The quantitative results provided valuable insights into the demographic characteristics and the participants' knowledge and experience with XR technologies. The gender distribution among the participants was quite balanced, with males representing 56.81% and females representing 43.18%. This gender balance is encouraging as it suggests that both male and female students at the Kuwait Police Academy are interested in and engaged with XR technologies. It also indicates that the findings of the study are likely to be representative of both genders within the given context. The majority of the participants (70.4%) demonstrated knowledge of XR technologies by questioning them on this phenomenon, they clarified they had some awareness events and seminars about AR/VR and they received some pilot training using VR headsets previously as part of their extracurricular activities. The high level of XR knowledge among the participants suggests that they are willing and ready to adopt XR technologies for training purposes within the law enforcement context. Another factor that assures this willingness act is that a majority of the participants (75%) expressed a willingness to use the full version of the XR system in their investigation training practices.

The SUS analysis of the MR application used by 44 students at the Kuwait Police academy provided valuable insights into its usability. The overall preference rating was 4.2 out of 5, indicating a positive reception. The application received an average complexity score of 2 out of 5, suggesting it was perceived as relatively simple. The ease of use was rated at 3.8 out of 5, indicating room for improvement in terms of intuitiveness. The application's dependence on technical support received a low score of 1.9 out of 5, implying self-sufficiency. Integrated functions were well-received with a rating of 4 out of 5. Inconsistency in the application was noted with a score of 2 out of 5, suggesting areas for improvement. The application's quick learning ability received a high rating of 4.1 out of 5. However, it was considered somewhat cumbersome with an average score of 2.4 out of 5. Users felt confident with a rating of 4.1 out of 5. The requirement for prior knowledge scored 2.2 out of 5, indicating it wasn't overly dependent on extensive background knowledge in AR/VR technologies.

One interesting finding from the study is that female students reported higher levels of satisfaction (75.7%) compared to male students (72.50%). This result is noteworthy as it challenges the stereotype that male students would be more inclined towards technology-related applications such as AR/VR. The higher satisfaction among female students could be attributed to various factors, such as their individual preferences, learning styles, or the specific context in which the applications were used. Further research is needed to explore the underlying reasons behind this gender difference in satisfaction.

The study also examined the impact of prior experience with AR/VR applications on satisfaction levels. As anticipated, students with previous experience scored higher in terms of satisfaction (76.5%) compared to those without prior experience (70.13%). This finding suggests that familiarity and exposure to AR/VR technology contribute positively to the overall satisfaction of students. Previous experience may enhance students' understanding of the capabilities and potential of AR/VR applications, enabling them to engage more effectively and derive greater satisfaction from their use.

Additionally, the study investigated the influence of prior experience with AR/VR hardware on satisfaction levels. Consistent with expectations, the group with previous hardware experience reported higher satisfaction scores (75.4%) compared to the group without prior hardware experience (69.3%). This finding highlights the importance of hardware familiarity and proficiency in enhancing the overall satisfaction with AR/VR applications. Students who are accustomed to using AR/VR hardware may feel more comfortable and competent, leading to higher satisfaction levels.

The overall results demonstrated highly satisfactory levels by the police academy trainees in terms of the usability of the system with a value of 73.9% in the system usability scale and this indicates very good satisfaction according to the study of Bangor, et al. [70]. This is score is much higher compared to similar studies such as; Acampora, et al. [72] which scored 57.5

and other training systems using mixed reality [73] with a score of 63.33. The findings of this study have implications for both educational practitioners and researchers in the field of AR/VR applications. Understanding the factors that contribute to student satisfaction can inform the design and implementation of AR/VR experiences in educational settings. It is important to consider the diverse needs and preferences of students, including potential gender differences. Furthermore, the results emphasize the importance of providing opportunities for students to gain prior experience with AR/VR applications and hardware, as this can positively impact their satisfaction levels.

The use of think aloud protocols in crime scene investigation training offers valuable insights into trainees' cognitive processes and decision-making strategies. Verbalizing their thoughts and actions while interacting with the training system helps researchers and instructors understand how the system is perceived and utilised and its impact on learning. Semi-structured interviews using NVivo analysis have yielded themes that can guide the implementation of think-aloud protocols in the training program.

One theme, "Crime scenes and their scanned environment," highlights the benefits of digitally reconstructed crime scenes. Experts praise the quality and accuracy of these representations, emphasizing their realistic nature and potential to reduce contamination and security breaches. They also suggest visualizing diverse crime scenes to enhance the training experience. Feedback on graphics indicates a need for improvement in exploring less visible areas, and guiding the development team to enhance the scanning process.

The theme "Immersive mixed realities" focuses on trainees' experiences with mixed reality technology. Experts expressed their satisfaction with the immersive experience, noting the realism and feeling of full immersion in the crime scene. The ability to navigate between rooms without discomfort or side effects is highlighted. While positive, experts suggest comprehensive coverage of investigation practices and addressing potential negative aspects for future system versions.

The theme "Tasks" examines trainees' perspectives on task functionality and usability. Think-aloud protocols provide insights into their engagement, interaction with tasks, and the effectiveness of the user interface. Feedback on advanced training capabilities, user-friendliness, evidence linking, and instruction adequacy informs task design and instructional support improvements.

The final theme, "Whole experience," captures trainees' broader perspectives on the training system. Think-aloud protocols gather feedback on the perceived benefits of 3D scanning and mixed reality technologies, cost and complexity concerns, and the system's suitability for different crime scenes. This feedback guides further system development and addresses trainees' concerns.

Integrating think-aloud protocols into the crime scene investigation training system enhanced the evaluation and refinement of the system. The protocols helped the researchers to identify strengths and weaknesses, uncover usability issues, and provide valuable insights into trainees' perceptions and experiences. Researchers and instructors can use the collected data from think-aloud sessions to make informed decisions regarding system improvements, instructional support, and training program development. Generally, most of the responses indicated that the system, as in the experimentation stage, has to proceed to be more in action and to be an essential part of the actual practices in the police academy curriculums. They also saw the benefits of this system as it can provide a highly accurate and detailed representation of the crime scene, allowing trainees to closely examine even the smallest details. This information can then be used to develop a better understanding of the crime and to identify important clues and evidence.

The controlled experiment that relies on the performance metrics, conducted a comparison of two groups in an investigation task. Group 1 utilised a conventional approach with a physical crime scene facility for training, while Group 2 experimented with HoloHolmes, a mixed reality (MR) training system based on 3D scanned and reconstructed crime scenes using Microsoft HoloLens 2.

In terms of evidence collection, Group 1 gathered an average of 20.2 pieces of evidence, which accounted for 92.5% of the distributed clues within the physical crime scene facility. This suggests that the conventional approach was effective in identifying a high percentage of the available evidence.

On the other hand, Group 2, using the HoloHolmes MR training system, collected an average of 17.1 pieces of evidence, corresponding to 71.2% of the clues present in the virtual crime scene. This indicates a slightly lower performance in terms of evidence collection compared to Group 1. However, it is worth noting that there are many factors that most likely influenced the results. These factors could be the exposure to a new method of interaction with visual holograms and a new MR device with unique usability and user experience for the first time. It is expected the time spent would be less with more user experience with the device and the training system,

The results for the 2nd group in regard to the evidence collected and the time spent are promising since it is the first time to experiment with it in investigation training. This is due to the use of mixed-reality technology, which allows for the creation of multiple virtual crime scenes, each representing a different scenario. This provides investigators with a wider range of training experiences and enables them to practice their skills in various contexts. Mixed reality training systems, like HoloHolmes, require only a device per user (e.g., Microsoft HoloLens 2), making it a more cost-effective solution compared to building and maintaining physical facilities. It also allows for scalability, as multiple investigators can simultaneously access virtual crime scenes, expanding the training capacity. Virtual crime scenes can be accessed from any location, eliminating the need for physical travel to a specific training facility. This enhances accessibility and flexibility for investigators, allowing them to undergo training at their convenience.

On the contrary, physical environments are typically designed to represent specific crime scenes. As a result, training in a physical facility may only expose investigators to a limited range of scenarios and challenges. This may restrict their ability to handle diverse crime scene situations effectively. Moreover, building and maintaining a physical crime scene facility can be expensive. It requires dedicated space, specialized equipment, and ongoing maintenance and updates. Additionally, training sessions in physical environments may involve logistical complexities, such as scheduling and travel arrangements.

The United Kingdom and Kuwait may experience various types of crimes, including but not limited to theft, assault, robbery, fraud, drug-related offences, cybercrime, and domestic violence. These crimes are not unique to any particular country but occur worldwide. Higher crime rates are often associated with urban areas due to population density and increased opportunities for criminal activities. Major cities in both the UK and Kuwait may experience higher crime rates compared to rural areas. Since there is no significant difference between crime nature between the two countries, the crime scene reconstruction was conducted at a crime scene facility at the University of Winchester, UK. This is in addition to the members of the research group were based in the UK, particularly during the development phase.

This study prefers to use 3D scanning to reconstruct physical crime scenes over creating a crime scene using computer graphics due to several reasons. 3D scanning captures the actual physical environment, including the details, textures, and spatial relationships of objects within the crime scene. This level of realism provides trainees with an accurate representation of the crime scene, enabling them to observe and analyse the scene as it truly exists. On the contrary, computer graphic synthetic crime scenes lack of realism and accuracy of representing the chain of events and connection of evidence caused by the real criminals. Additionally, the ability to create multiple crime scenes based on real-world scenarios enhances the versatility of the training program, exposing trainees to a wide range of crime scene types and complexities.

Computer graphics have a valuable role in crime scene investigation training, particularly for simulating challenging scenarios that are difficult to physically reconstruct, such as complex or dangerous situations.

Incorporating victim details into virtual crime scene investigations using mixed reality systems like Microsoft HoloLens is crucial for training investigators. By paying meticulous attention to details like the victim's position, clothing, injuries, and surrounding objects, investigators can better identify and interpret vital evidence during real-life investigations. Accurate reconstruction of the crime scene with victim details allows investigators to practice documenting, collecting, and preserving evidence effectively.

The HoloHolmes MR system offers additional benefits by integrating crime scene scenarios that are typically formed after evidence collection. This facilitates the practical application of theoretical knowledge, enabling investigators to develop hands-on skills in identifying crucial evidence, making accurate observations, and devising investigative strategies. The creation of a virtual crime scene scenario within a mixed reality system provides a highly realistic training environment, fostering a deeper understanding of crime scene analysis, evidence collection, and preservation techniques.

The mixed reality approach surpasses virtual reality in crime scene investigation training due to its seamless blending of virtual objects with the real-world environment. Trainees can interact with both physical objects and digital content simultaneously, enhancing the authenticity of the training experience. Unlike VR, which provides a fully simulated environment lacking a connection to real-world objects, mixed reality offers a sense of presence and spatial understanding by overlaying virtual objects onto the real world. Trainees can analyse the crime scene from different angles, comprehend the spatial relationships between objects, and develop essential investigative skills. In contrast, VR replaces the trainee's physical environment entirely, potentially hindering the development of real-world spatial cognition.

Choosing Microsoft HoloLens for this system as MR device was due to it is a self-contained wearable computer that does not require tethering to a computer or external sensors. This is in addition to having advanced sensors, cameras, and spatial mapping capabilities, allowing it to create accurate and immersive mixed reality experiences. This portability and convenience make it well-suited for crime scene investigations, as it allows trainees to freely move and interact within the scene without cumbersome equipment. Additionally, HoloLens can be used in a variety of environments, from controlled training facilities to actual crime scenes, providing flexibility and adaptability to different training scenarios.

Additionally, mixed reality technology can also help to increase trainee engagement and motivation. By using immersive and interactive experiences, trainees can better understand and retain information, leading to improved performance and results. This can be particularly beneficial in the field of crime scene investigation, where proper training and attention to detail can be critical. The trainees will be able to examine the crime scene from different angles, zoom in and out on objects of interest, and access information about the objects and their relative positions. The system will also provide the trainees with various tools, such as virtual markers and measurement tools, to assist in their analysis of the scene.

Compared to traditional methods of crime scene training methods, the proposed method is more cost-effective and time-efficient, as it eliminates the need for multiple trips to the crime scene and reduces the amount of time required for analysis and reconstruction.

Enhancing the system with different crime scenes in various environments and weather conditions would increase adaptability and improve the effectiveness as investigators. It would enable them to navigate urban, suburban, rural, wilderness, and extreme weather settings. This adaptability would help young investigators develop situational awareness, assess surroundings, recognize threats, and identify evidence. This heightened awareness would lead to quicker responses, gathering crucial information, and making informed decisions, ultimately improving the chances of capturing perpetrators.

A limitation of the current system is the inability to detect participants stepping on evidence. This skill will be incorporated in the next version of the system.

While there are challenges like the cost and complexity of equipment, as well as the need for specialized training and expertise, the benefits of using mixed reality in crime scene investigation outweigh these challenges. This process with associated cost can be justified in the complex cases that have debatable interpretations between the investigators as preserving the crime scene virtually will allow longer time and feasible access to more investigators to solve the crime.

There is a significant limitation of incorporating smell and tactile sensations in mixed reality applications for crime scene investigation training. The sense of smell is important in crime scene investigation as it enables investigators to identify potential chemical substances, detect odours associated with decomposition, and gather important olfactory clues [74]. Detecting temperature variations and identifying objects with different thermal characteristics are essential aspects of crime scene investigation [75]. However, MR applications currently lack the ability to simulate temperature sensations effectively.

One potential research limitation in the use of scanning activities for investigation purposes is the risk of crime scene contamination. As during the scanning process, investigators and technicians need to physically move around the crime scene to capture different angles and areas. This can compromise the integrity of the evidence and create challenges in establishing a clear chain of custody.

VII. Conclusion

Generally, this paper provided several contributions. One of the unique contributions of this research project is the use of a combined approach to the reconstruction process, which utilises 3D laser scanning and photogrammetry to produce high-quality textures that are essential for accurately displaying forensic features. Furthermore, the researchers have developed an optimisation process that enables the crime scene and victim(s) to be rendered in high-poly format and displayed in real-time on HoloLens without experiencing significant lagging.

A remarkable aspect of this approach is the optimisation process implemented, enabling seamless real-time execution of high-polygon crime scene models and representations of the victim(s) on the HoloLens platform. This optimisation eliminates the hindrance of significant lagging, thereby enhancing the user experience and providing forensic investigators with a smooth and immersive environment for analysis and examination.

Furthermore, this research makes another valuable contribution through the integration of various investigation processes and tasks, systematically aligning them with a well-recognised crime investigation framework widely employed within the sector. By mapping these procedures to an established framework, this research fosters a standardised and efficient workflow, streamlining the investigative process and aiding in the acquisition and organisation of pertinent information. This integration not only enhances the reliability and validity of the findings but also empowers investigators with a comprehensive framework to guide their analysis and decision-making, ultimately contributing to more effective crime investigation outcomes.

The use of mixed methods, such as 3D scanning and photogrammetry, in visualising crime scenes and incorporating this into a mixed reality training system is a promising development. This approach can provide a highly accurate and immersive way to train young investigators, helping them to better understand and analyse crime scenes and improve their performance and results. This proposed training system has the potential to revolutionise the way young investigators are trained. By using mixed reality technology, the system provides a highly realistic and immersive experience that allows the trainee to get a better understanding of the crime scene. Moreover, the use of 3D scanning technology ensures that the crime scene is captured in great detail, which provides an accurate representation of the scene for training purposes. The system has been designed to be user-friendly and accessible to all, regardless of prior experience or technical knowledge. It also provides a flexible and scalable platform that can be easily adapted to meet the needs of different training programs and institutions. In light of these features, it can be stated that the proposed training system has the potential to become a valuable tool for training young investigators and could play a significant role in improving the quality and effectiveness of crime scene investigation training. Despite its effectiveness, it faces some challenges, such as the current high cost of the MR device which will decrease through the current development of the related hardware by several mega companies. This is in addition to the inability to detect participants stepping on evidence, the lack of sensory simulation capabilities, and the potential risk of contaminating the crime scene during the scanning process. Despite these limitations, the advantages offered by employing such technologies—especially in cases with complex or contentious interpretations—cannot be understated.

For future work, it would be prudent to address the aforementioned limitations. Investigative efforts could benefit from further research on incorporating tactile and olfactory simulations into mixed reality applications for a more holistic training experience. Research could also be aimed at devising solutions for reducing equipment costs and simplifying operational complexity, thereby making these advanced tools more accessible for law enforcement agencies. Finally, a cross-disciplinary approach involving experts in computer science, artificial intelligence, and criminology could offer a comprehensive strategy to overcome the challenges currently impeding the widespread adoption of these technologies in crime scene investigation.

Generally, the proposed mixed reality training system holds great potential as a valuable tool for training young investigators and has the potential to significantly improve the quality and effectiveness of crime scene investigation training. The results of this research and the successful commercialisation of this system could pave the way for further innovation in the field.

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Appendix

System Usability Scale: One of the key advantages of the SUS is its brevity. As demonstrated in the appendix, the 10-item format allows researchers to assess the usability of a system quickly and easily without requiring a significant time commitment from participants. There are five possible responses, going from "Strongly Disagree" to "Strongly Agree." Lewis and Sauro [76] divided the questionnaire into two subscales: *learnability*, which assesses an individual's ability to quickly and independently learn how to use a system, and *usability* "is defined as *"the subjective perception of interaction with a system"* [77]. The SUS questionnaires are designed to have a positively stated question followed by a negatively stated question then followed by another positively stated question. This means questions with odd numbers (1,3,5,7, and 9) are stated positively and questions with even numbers (2,4,6,8 and 10) are stated negatively. This is to ensure the consistency of the participants' responses and to avoid arbitrary answers. Therefore, the scores of the odd items are calculated by subtracting 1 from the scale value selected by the user, while the scores of even items are computed by subtracting the user's scale value from 5 (since higher values for these items indicate worse opinions expressed by the user). The final score for each user is obtained by summing the item scores and multiplying this sum by 2.5, yielding a percentage scale.

Think Aloud Protocol: Researchers record the verbal reports and subsequently analyse the data collected [78]. The basic idea behind think-aloud protocols is to ask participants to verbalise their thoughts as they complete a task or engage with a product, providing researchers with valuable insights into the user experience [59]. Think-aloud protocols have the advantage of eliminating processing-reporting interval effects, as participants are able to report their thoughts while concurrently engaging in the targeted task [79]. This method has been used in evaluating the system design and usability, such as the study that adopted VR for e-commerce applications [12]. Another study utilised this method for evaluating a virtual twin VR system [80]. Table 2 demonstrates the think-aloud protocol questions that investigate all considerations mentioned earlier.

TABLE A. THINK-ALOUD PROTOCOL QUESTIONS FOR THE CRIME SCENE TRAINING SYSTEM

N	Question	Purpose
1	Please describe the scanned environment of the crime scene	Understand where the user can see the virtual crime scene properly, like the actual crime scene
2	Please describe how you feel in these immersive mixed realities	Understand whether the user feels comfortable in this mixed reality environment
3	Please describe your experience while performing the tasks	Understand whether the user able to understand how the system operates
4	Please describe what you think of the whole experience	Understand whether the user can understand the wholistic user experience
5	Please discuss what you think of using this application to train students on crime scene investigation practices	Understand whether the system design and its functions can help users to use it for the purpose is made for

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