Integrating AI and Computer Vision for Ballistic and Bloodstain Analysis in 3D Digital Forensics

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***Abstract*—Despite that modern tools provide 3D reconstruction of real crime scenes, the analysis of the events is often a result of manual measurements from experienced personnel. In this study, AI and Computer vision-based methods, integrated in a 3D VR crime scene, are introduced to automatically determine the trajectory of bullets and the origin of bloodstains. These methods enable the precise analysis of bullet holes and bloodstain patterns on surfaces, providing essential insights for forensic investigation. This innovative approach combines practical, hands-on experience with advanced analytical methods, offering a comprehensive tool for analyzing crime scenes and supporting law enforcement personnel in their duty.**

***Index Terms*—forensic analysis, virtual reality, bullet trajectory, bloodstain pattern analysis, computer vision**

I. Introduction

Crime scene recreation is a fundamental aspect of forensic investigations, aiming to decipher and unveil the sequence of certain events leading to a criminal act [1]. Real-life scene recreations often require manual measurements to estimate a crime scene's key aspects, such as a bullet's trajectory [2] which can offer insights about the direction from where a shot was fired, or a bloodstain's trajectory [3] [4] which can provide information about its origin point. Consequently, the estimation of the position of a shooter or a victim at a crime scene is crucial information investigators can utilize for recreating certain aspects of the shooting incident [5] [6].

Over recent years, advancements in technology, specifically in the domains of computer vision, artificial intelligence (AI), and virtual reality (VR) have opened innovative and revolutionizing ways for analyzing and reconstructing crime scenes [7]–[10]. Furthermore, recent advancements in 3D reconstruction through the use of photogrammetry have enabled the representation and recreation of real-life scenes with unprecedented realism and precision [11]–[13]. Typically, crime scene investigators and forensic analysts utilize rulers and metric devices to manually measure and document information about the impact angle at which a bullet or a bloodstain hit a surface, either in reality or in static 3D reconstructed environments [14]. Moreover, they often use rods and lasers to visualize their trajectory [15] which helps them estimate the shooter's or the victim's position. However, to recreate and simulate, in the most realistic degree, specific events that took place during the execution of the scene, such measurements should be taken as precisely and accurately as possible. Besides being time-consuming, this procedure should be conducted only by highly-expertise and well-trained personnel with years of experience in crime scene analysis, and of course, human error should always be taken into consideration.

In this work, we offer dynamic analysis tools to enhance 3D crime scene environments that can be exploited by officers to offer fast and robust investigation solutions. More specifically, we propose two methodologies for estimating the trajectory of bullets and the origin point of bloodstains, respectively, in a 3D environment based solely on images taken from the crime scene. Those images capture bullet holes and bloodstains in the crime scene as they have been imprinted on their respective impact surfaces. These methodologies based on computer vision and AI algorithms extract crucial information that can provide forensic investigators and examiners with valuable insights for the dynamic analysis of the scene, such as the bullet's impact origin with the victim in 3D space during the shooting as well as the estimated shooting position. To demonstrate and showcase the effectiveness of these methods we have integrated them into a VR crime shooting investigation game that places players in the role of a forensic examiner tasked with identifying the positions of the shooter and the victim at the time when the shooting occurred. Combining the immersive VR experience with automated computer vision-based analysis tools adds a layer of sophistication to the overall investigation and learning process [16] [17]. This enables law enforcement officers to leverage advanced analytical techniques to accurately recreate certain events of a crime. Through this game law enforcement officers, examiners, and investigators can familiarize themselves with cutting-edge forensic technologies which can, ultimately, lead to applying such methodologies effectively in real-world scenarios.

II. Methodology

In the following subsections, we will describe our methodologies for analyzing bullet hole and bloodstain images in the 2-dimensional space for estimating a bullet's impact angle and a bloodstain's point of origin, respectively.

A. 2D analysis

1) ***Bullet hole image analysis****:* Given an ideally captured bullet hole image (e.g., the image should center the bullet hole and it should be taken perpendicular to the impact surface and at the closest possible distance) we utilize the ellipse method [2] to calculate the bullet's impact angle. By applying a series of advanced computer vision and image processing techniques we calculate an ellipse that fits the bullet hole [18], the dimensions and rotation of which will, subsequently, facilitate the estimation of the azimuth (horizontal or top-view) and elevation (vertical or side-view) angles at which the bullet hit and penetrated the surface. Typically, shots fired perpendicular to a surface will result in an almost circular bullet imprint. However, when the azimuth impact angle decreases the imprint of the bullet will elongate and become elliptical.

Initially, the image's (Fig. 1a) background is removed and replaced with a total white background (Fig. 1b). In the next stages, the image is converted into grayscale with an added Gaussian blur (Fig. 1c) to which a thresholding is applied to capture the area corresponding to the whole impact surface of the bullet hole (Fig. 1d). Immediately after, we detect the contour of the impact surface, i.e., the curve joining all the continuous points (along the boundary) having the same color or intensity (Fig. 1e, red outline). Finally, we fit an ellipse to the contour found in the previous step (Fig. 1e, green outline) by defining its length (e.g., minor axis), its width (i.e., major axis), and its rotation (according to a cartesian coordination system set to the center of the ellipse). Having computed the above the azimuth, a, and elevation, e, angles, are defined as follows:

$$a = \sin^{-1}\left(\frac{l}{w}\right), \tag{1}$$

$$e = r, \tag{2}$$

where l, w correspond to the lengths (in pixels) of the minor and the major axis, respectively, of the given fitted ellipse and r corresponds to its rotation.

For the azimuth angle, a, equation 1 will compute an angle in degrees in the range $(0, 90)$. To ascertain the bullet's directionality, i.e., whether it came from the right to left or the left to right (Fig. 2a), we analyze the ellipse that best fits the darkest area of the bullet hole (Fig. 1f and 1g), presumed to be the point of deepest penetration. The relative position of this ellipse's center to the center of the ellipse fitting the entire bullet hole indicates the bullet's approach direction. As far as the elevation angle is concerned, an angle in degrees in the range (-90, 90) is computed the sign of which indicates the vertical directionality, i.e., from top to bottom and vice versa (Fig. 2b).

*2) **Bloodstain image analysis**:* Typically, a bloodstain generated from a person's wound when hit by a blunt object, i.e., a knife or shot at by a pistol, would consist of several sub-blood drops imprinted on a hitting surface in a specific pattern (Fig. 4a). Similar to the imprint of a bullet hole, when a blood drop hits a surface at exactly 90° it forms an almost perfect circular mark. When the impact angle decreases, however, the blood drop tends to form an elongated mark (Fig. 3). This elongated mark could be approximated by an ellipse and by identifying and extending its major axis in the 2D hit surface, we can determine the direction from which the blood drop came. In the presence of multiple, and close in proximity such blood drops, by identifying and extending the major axis of each "ellipsoid" blood drop (Fig. 4f, green lines) in the 2D hit surface, i.e., floor, an area of convergence can be determined (Fig. 4f, white circle), i.e., an area containing the intersection point (Fig. 4f, blue dots) between every pair of extended major axes.

To this end, when provided with an ideally captured image of a bloodstain, as imprinted on an impact surface, we can perform a series of steps to estimate the bloodstain's 2D origin point, i.e., x and y coordinates in the 2D image space. Similar to the bullet hole image analysis, the steps of removing the background of the bloodstain image, converting it to grayscale, applying Gaussian blur, thresholding, detecting the contours, and fitting the ellipses are applied (Fig. 4a-4e). By fitting an ellipse to every blood drop, $i = 1, 2, \ldots, n$, we have calculated its length, l_i, its width, w_i, its center in two (i.e., image) dimensions, (x_{c_i}, y_{c_i}), and its rotation, r_i. Having computed the 2-dimensional image coordinates of each ellipse's center[1]

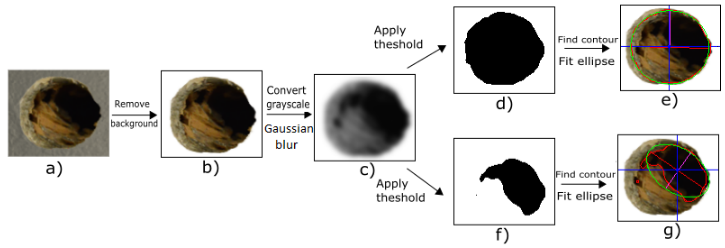

Fig. 1. Illustration of the advanced computer vision techniques applied to the captured bullet hole image. a) original bullet hole image taken from the crime scene, b) image with removed background, c) grayscale image with Gaussian blur, d) thresholded image to capture the whole bullet impact surface area, e) original image with painted contour and ellipse detected based on d), f) thresholded image to capture the inner bullet surface area, g) original image with painted contour and ellipse detected based on f). By comparing e) and g) we can deduce that the horizontal directionality of the bullet is 'left'.

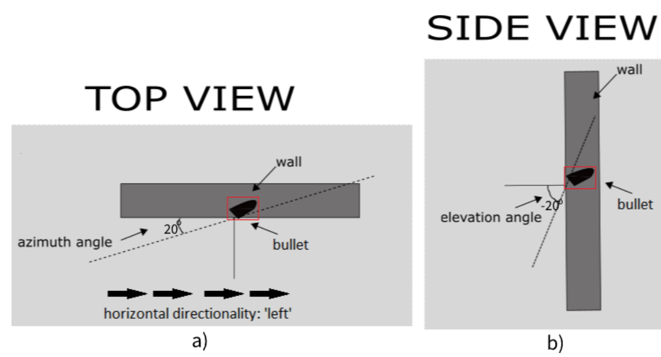

Fig. 2. a) Depiction of an azimuth or top-view angle. b) Depiction of an elevation or side-view impact angle.

[1]The sign of the y_{c_i} coordinate is reversed to obtain the coordinates with respect to the origin point of the coordinate system being on the bottom left corner of the image resembling, in this way, a Cartesian coordinate system. The x_{c_i} coordinate remains unchanged.

as well as its rotation[2], a mathematical linear equation can be formulated representing the 2-dimensional line that passes through the major axis of each ellipse, $i = 1, 2, \ldots, n$:

$$y = m_i * x + b_i, \tag{3}$$

where,

$$m_i = tan(r_i), \tag{4}$$
$$b_i = y - m_i * x, \tag{5}$$

are the parameters of the straight line. Having formulated a linear equation that passes through each ellipse's major axis, we continue by computing the intersection point between every pair of lines. Given a pair of non parallel lines $y = m_i * x + b_i$ and $y = m_j * x + b_j$, where $i \neq j$, and m_i, m_j, b_i, b_j are obtained by eq. 4-5 we can compute the intersection point (x_{ij}, y_{ij}) as follows:

$$y_{ij} = \frac{b_j - b_i}{m_i - m_j} \tag{6}$$
$$x_{ij} = m_i \frac{b_j - b_i}{m_i - m_j} + b_i. \tag{7}$$

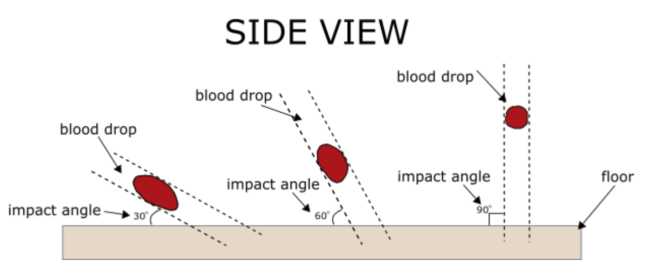

Fig. 3. : Illustration of different impact angles, e.g., $30°, 60°$ and $90°$ between a blood drop and a hitting surface, e.g., a floor.

By computing every intersection point, (x_{ij}, y_{ij}) for $i, j = 1, 2, \ldots, n$, an area of convergence is formulated. Our goal is to determine a single point, (x', y'), that best represents this convergence area. We compute this point in the following fashion:

$$x' = \text{median}(\{x_{ij} | i \neq j\}) \tag{8}$$
$$y' = \text{median}(\{y_{ij} | i \neq j\}) \tag{9}$$

We compute the median instead of the mean to avoid the influence of outliers.

B. Extension to 3D space

In this section, we will extend our methodology for a scene within a simple 3-dimensional space, as the one depicted in Fig. 5, where the x, z plane represents the floor, x and z axes are parallel to the walls, and the y axis is the upward vector.

[2]The rotation of each ellipse is defined as the counter-clockwise rotation angle in degrees of its major axis with respect to the x-axis.

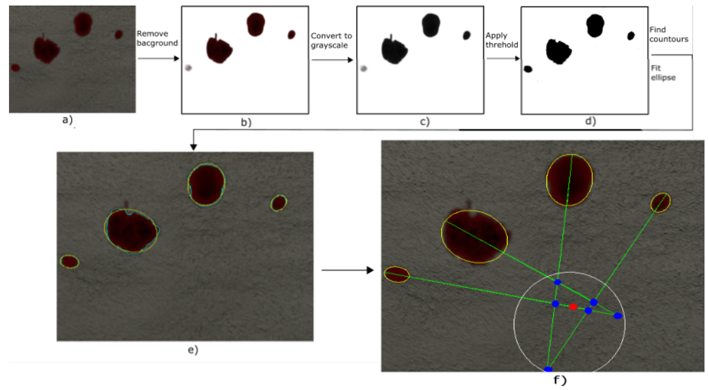

Fig. 4. Illustration of the advanced computer vision techniques applied to the captured image of a bloodstain. a) original bloodstain image taken from the crime scene, b) image with removed background, c) grayscale image, d) thresholded image to capture the area of each individual blood drop, e) original image with painted contours (cyan color) and ellipses (yellow color) detected based on d).

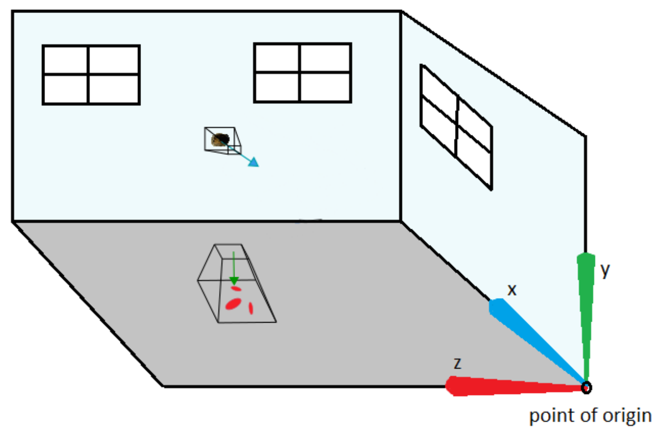

Fig. 5. Crime scene within a simple 3-dimensional space.

In this scene bullet holes and bloodstains, whose positions are always obtainable, are placed on their respective surfaces. Furthermore, a camera, whose position and orientation are obtainable at all times, is placed in the scene for capturing images.

*1) **Bullet trajectory estimation**:* In the presence of bullet holes imprinted on wall surfaces the vector that is perpendicular to each wall, i.e., the one defining the 3D orientation of the wall surface, defines the orientation of the bullet trajectory if the bullet hit the wall at 0^o azimuth and elevation angles. Specifically, the normal vectors perpendicular to the wall surfaces are the $(1, 0, 0), (-1, 0, 0)$ (Fig. 5, cyan arrow), $(0, 0, 1), (0, 0, -1)$, for each one of the four walls respectively. Afterward, the estimation of the bullet trajectory can be estimated through the following steps: a) capture an ideal image of the bullet hole, b) compute the azimuth and elevation angles, as well as the directionality, based on the methodology described in section II-A1, c) based on the position of the bullet hole, i.e., in which wall it appears, select the corresponding perpendicular vector, and finally, d) place the selected perpendicular in the center of the bullet hole and rotate it based on the angles previously computed. The straight line above the rotated vector's direction represents the bullet's trajectory[3].

2) ***Bloodstain origin point estimation:*** Regarding the bloodstain's origin point estimation, the following assumptions are taken for granted: a) the default camera orientation is when the camera axis coincides with the positive x semi-axis, b) bloodstain images are captured with the camera looking down, i.e., the camera axis coincides with the negative y semi-axis (Fig. 5, green arrow).

Following the above assumptions, the bloodstain's 2-dimensional origin point can be estimated through the following steps: a) capture an ideal image of the blood stain, b) add the rotation angle of each "ellipsoid" blood drop computed based on the methodology described in section II-A2, to the rotation angle of the camera with respect to the x axis, c) match the centers of the ellipses in the 3-dimensional world with the centers of the ellipses in the image, based on their distances from the axes origin point and the top left corner of the image, respectively, d) assign to each ellipse in the 3-dimensional world their corresponding rotations as obtained in step b), and, finally, e) compute the 2-dimensional origin point to the hit surface, i.e., the floor by applying the methodology described in section II-A2.

The last step in our analysis of the bloodstain is to calculate the perpendicular distance from the point in the hit surface from which the blood drops originated and, thus, define the actual 3-dimensional point of origin. To this end, we initially calculate the impact angle, az_i of each "ellipsoid" blood drop as depicted in Fig. 3 using eq. 1. Furthermore, we calculate the Euclidean distances, d_i, between each blood drop center and the 2-dimensional point of origin (Fig. 6, gray lines). As illustrated in Fig. 6 a right triangle is formed between the center of a blood drop, the origin point on the hit surface, and a desired 3-dimensional point of origin. The desired perpendicular distance, h_i (i.e., opposite of the formed right triangle), can be calculated as:

$$h_i = \tan(az_i) * d_i, \forall i. \quad (10)$$

However, calculating the perpendicular distance, h_i, for each blood drop can yield different results. In these cases, we calculate the mean perpendicular distance (Fig. 6, purple circle) as:

$$h' = \text{mean}(h_i), \forall i. \quad (11)$$

The calculated mean perpendicular distance, in combination with the 2-dimensional origin point on the hit surface defines the actual 3-dimensional point of origin of the blood drops.

[3]We assume that in close spaces where a shooting has taken place no extra environmental forces are exerted, thus, the trajectory of a bullet is simplified to a straight line.

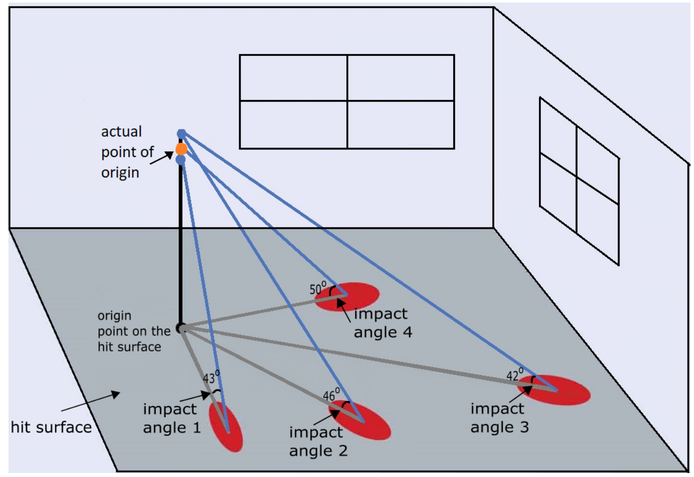

Fig. 6. Illustration of the calculated perpendicular distance for every blood drop present on the scene. In cases where different (but close in range) perpendicular distances are calculated the actual point of origin (orange point) is calculated by taking the average of the perpendicular distances.

III. Pipeline application in a simulated environment

In this section, we will describe how we can utilize the methodologies and results obtained from the 2-dimensional and 3-dimensional spaces and transfer them to a 3D crime scene environment created in Unity VR. The transfer to a 3D scene, and specifically a VR scene, can provide useful and interactive visualizations which in turn can help unravel certain aspects of the incident.

The developed environment in Unity simulates a crime investigation scene in which a shooting incident has occurred. The game scenario involves a perpetrator entering a house holding a pistol and starting shooting at the occupant of the house as well as at the wall surfaces. When shooting at the victim a bloodstain is generated to the floor of the scene originating from the point of the victim's body where the bullet penetrated. On the other hand, when shooting at random points on the wall surfaces bullet imprints are created at the points of impact. After the shooting has occurred, the police examiner arrives at the scene and is tasked with examining the scene and taking images of key pieces of evidence.

The game places players in the role of both the perpetrator and the forensic examiner. In the former case, referred to as the "forward" scenario, the player enters a room holding a pistol and can shoot at the wall surfaces or at the victim to generate the aforementioned key evidence creating in that way the crime incident scene. In the latter scenario, referred to as the "backward" scenario, the player enters the created crime scene as a forensic investigator and starts examining it trying to unravel events related to the possible movements of the victim or perpetrator.

A. Forward scenario

In the role of the perpetrator, the player can utilize a pistol to shoot at the victim, represented by a rag-doll avatar, and

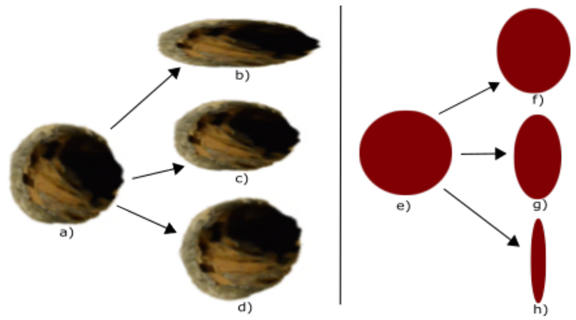

Fig. 7. a) Original bullet image prefab with 90^o and 0^o azimuth and elevation angles, respectively. b) Bullet hole with 20^o and 0^o azimuth and elevation angles, respectively. c) Bullet hole with 40^o and 0^o azimuth and elevation angles, respectively. d) Bullet hole with 65^o and -45^o azimuth and elevation angles, respectively. e) Blood drop image prefab with 90^o impact angle. f) Blood drop image prefab with 70^o impact angle. g) Blood drop image prefab with 50^o impact angle. h) Blood drop image prefab with 30^o impact angle.

at the surfaces of the walls. The simulation of the shooting is implemented by utilizing the Physics.Raycast method in Unity which at the moment of pointing and clicking at the aforementioned targets a ray is cast from the point of the muzzle of the gun. When the ray collides with a wall surface, the point of impact can be obtained, as well as the azimuth and elevation impact angles. We utilize a bullet hole image prefab (Fig 7a), resembling a perfect circle, and based on the returned values we alter its scale and rotation, concerning the x and z axes, respectively (Fig. 7b-7d), to create a realistic imprint of a bullet hole in the hit surface.

On the other hand, when the player shoots toward the rag-doll avatar, based on the point of impact a number of random (within a range) blood drops are generated to the scene's floor. Specifically, by utilizing the impact point's vertical height (Fig. 8c, cyan line), we generate an initial blood drop at a random distance (Fig. 8, green lines) on top of the imaginary shooting direction line (Fig. 8, yellow lines). For the depiction of the blood drop we use a blood drop image prefab, resembling a perfect circle (Fig 7e). By knowing the height and distance of the impact angle, az, (as calculated using eq. 1) and by keeping the height of the image, l, fixed we alter the width of the image, w (Fig. 7f-7h), and thus, the blood drop prefab, as follows:

$$w = \frac{l}{\sin(az)}. \tag{12}$$

After the creation of this initial blood drop the rest ones are generated in the same manner, at a close distance from the original one, rotated appropriately around the imaginary shooting direction line.

To this end, when an ideal image of a bullet hole or a bloodstain is taken and analyzed, based on the methodology described in section II, values close or identical to the ground-truth ones should be calculated. At this point, it should be noted that the purpose of the forward scenario is not to validate the effectiveness of the proposed pipeline. Its purpose is simply to provide a way within the game for interactively creating bullet holes and bloodstains instead of just having them placed in the scene in advance.

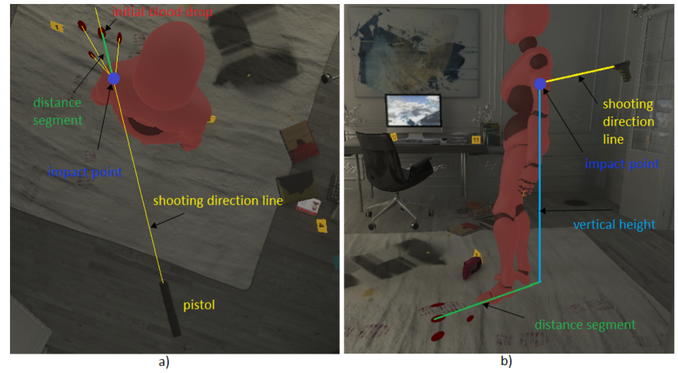

Fig. 8. a) Top view. b) Side view.

B. Backward scenario

When the player plays the role of a forensic investigator he/she can enter and examine the crime scene. His/her prime utility tool for examining the scene is a digital camera which he/she can use to take pictures of the scene from various angles, distances, and fields of view. When the examiner takes an image depicting a bullet hole or a bloodstain a set of dynamic analyses and visualizations are triggered depending on the type of evidence captured.

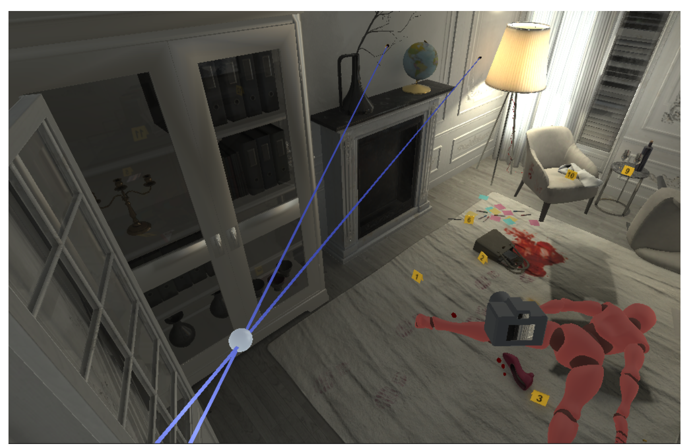

Fig. 9. Visualization of the trajectories of two bullets and the intersection point between them.

*1) **Bullet trajectory visualization and shooter position estimation**:* When a single bullet hole object is captured in the frame of the image the methodologies described in sections II-A1 and II-B1 are applied to compute a properly rotated unique vector initiating from the center of the bullet hole object. The next step is to visualize a straight line in the direction of the calculated vector, demonstrating in this way the bullet's trajectory (Fig. 9, blue lines). Finally, if at least two such trajectories are estimated a routine is triggered for computing the minimum distance between every pair of straight-line trajectories, i.e., the line segment of the shortest length perpendicular to both straight-line trajectories. If this minimum computed distance is lower than a specified threshold, e.g., 5 centimeters, then the possible intersection point is calculated by initially calculating one point in each straight-line trajectory in the edges of the minimum line segment and then averaging them. These possible intersection points indicate the positions from which the pistol fired and, thus, the positions of the shooter (Fig. 9, gray sphere).

Fig. 10. Visualization of a bloodstain's origin point.

*2) **Bloodstain origin point visualization**:* Accordingly, when a photo of a bloodstain consisting of at least two blood drops is taken the methodologies described in sections II-A2 and II-B2 are applied. After calculating the bloodstain's origin point a line between this point and the center of each blood drop is drawn to demonstrate the trajectory of each such blood drop (Fig. 10, red lines).

IV. Conclusions

In this paper, we explored two critical forensic analysis techniques for the computation of the impact angle of a bullet hitting a surface and the determination of the origin point of a bloodstain, respectively, by leveraging advanced computer vision techniques and geometric principles. By applying such techniques to images depicting bullet holes and bloodstains, we extended the traditional 2-dimensional analysis into a 3-dimensional framework. This extension allowed for the visualization of bullet trajectories and bloodstain origin points in a more comprehensive spatial context. To demonstrate the practical application of our methods we developed a virtual reality game in Unity, within which, users can apply the proposed framework and interactively visualize and understand the trajectories of bullets and the points of origin of bloodstains, thereby gaining insights into the dynamics of the shooting incident.

Exceeding the boundaries of a simulated crime scene, the functionalities developed in this study have significant real-world applications. In actual shooting crime scenes, our methods utilized within a reconstruction tool can be applied to recreate specific events with high accuracy. In conclusion, the integration of advanced image analysis techniques with 3-dimensional visualization tools presents a powerful approach to forensic investigation. Our work demonstrates the potential for these methods to enhance crime scene reconstruction, offering a new level of detail and accuracy in forensic analysis. This approach could not only improve the understanding of crime scene dynamics but also contribute to the overall effectiveness of forensic science in solving crimes.

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