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Forward Spatter Bloodstain Pattern Analysis: AO Estimation Using Image Processing and Numerical Modeling

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ABSTRACT

The aim of examining the forward spatter bloodstain patterns of gunshot wounds is to accurately describe the relationship between the victim, the culprit, and the crime scene. The purpose of this study is to determine the approximate location of the blood source, i.e. the victim, at the crime scene by using an image processing and numerical modeling approach. To achieve this, an experimental setup is designed with cardstocks and a cow blood-soaked sponge. In total, twenty forward spatter patterns are obtained onto cardstocks after successful shootings. In the post-processing phase, ellipses on the cardstocks are detected by processing the forward spatters in MATLAB. To achieve this, ellipse properties are identified for calculating the impact angles. The impact angles are then utilized as inputs to the tangent method within the program to estimate the Area of Origin (AO_x). For visualization, 2D and 3D images are generated. In conclusion, it is observed that the program works the best in determining the AO_x, for the scenarios where the real AO_x distances (blood source to target distances) are 35 cm, 50 cm, and 100 cm respectively. The program's weakness while determining AO_x for the source distance of 5 cm is also reported. It is necessary to improve the program for short blood source-to-target distances and long shooting distances. It can be concluded that image quality is also a key factor for post-processing as it might mislead the results with visible ellipses.

1. Introduction

Bloodstains are one of the most significant types of physical evidence and can greatly help to establish the connection between the culprit, the victim, and the crime scene. The formation of the stains depends on physical, environmental, and biological factors and can appear in various sizes and forms [1]. Patterns resulting from a force applied directly to the source of blood are referred to as impact spatter. Such spatters may be caused by firearms, blunt objects, stabbing, electrical devices, or explosions [1]. The size of bloodstains is typically less than 1 mm or larger, and the velocity of the applied force can start at 30 m/s. However, there is no direct correlation between stain size and the velocity of the applied force [2]. By analyzing the spatter bloodstains, the following questions can be answered regarding the crime scene:

- Possible location and position of the culprit, the victim, and other objects at the scene
- Chronological order of events
- Verification or refutation of statements made by the victim, witnesses, or culprit

There are a variety of software and algorithms developed in the literature for the location of the blood source, i.e. Area of Origin (*AO*) estimation in bloodstain pattern analysis [3]. The aim of these methods is to estimate *AO* based on the size, shape and directionality of bloodstains. The string method is a well-known traditional method that uses physical strings to determine the *AO*. This method is time-consuming, and its accuracy depends on the performer. Modern approaches use primarily image processing and numerical modeling. The currently available and most used programs include HemoSpat, Sherlock, BackTrack, HemoVision, FARO Scene [3]. In the study by Arthur et al. MATLAB was used to analyze bloodstain patterns. Digital images were processed and basic features such as eccentricity, major and minor axis lengths, orientation, area and center of mass were calculated using the regionprops function. The methodology involved preparing digital images, isolating the bloodstains by applying segmentation and

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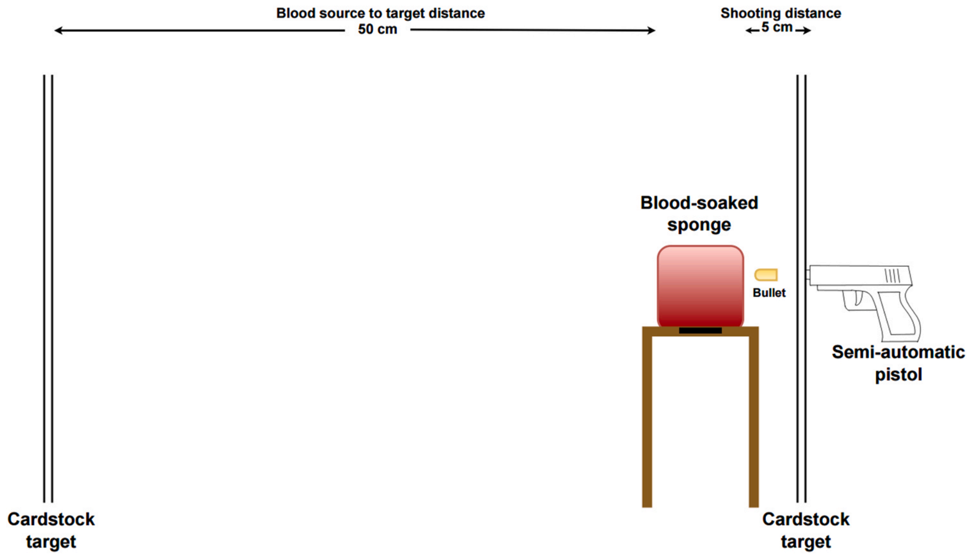


Fig. 1. A visualization of the experimental setup, where the distance between the blood source and the target surface is 50 cm, with a shooting distance of 5 cm.

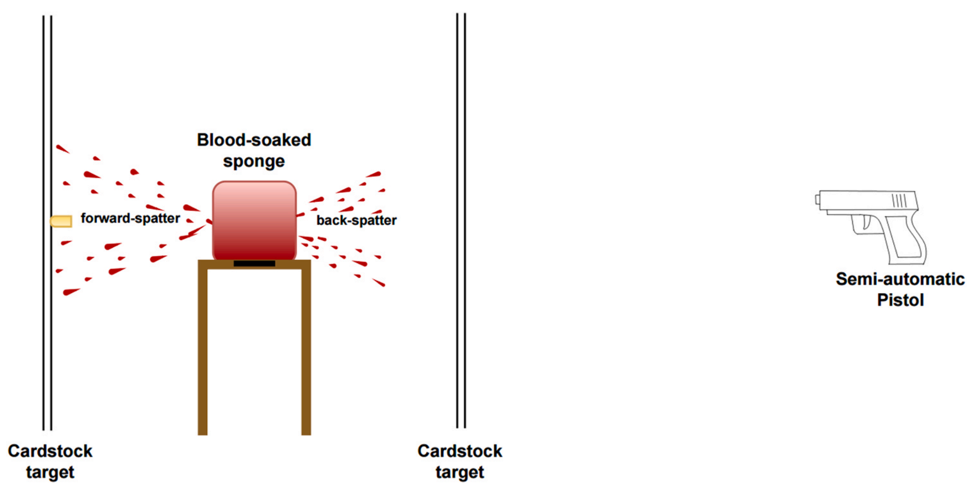


Fig. 2. A visualization of the experimental setup immediately after the bullet passed through the blood-soaked sponge.

morphological processing, and then using these features to calculate the impact angles and determine the Area of Convergence (*AC*) [4].

2. Material and methods

2.1. Experimental setup

In this study, bloodstain patterns formed by forward spatter on flat, plain, and light- colored surfaces due to gunshot wounds are investigated using image processing and numerical modeling methods. For the experimental setup (Figs. 1 and 2), the blood used for both back spatter and forward spatter is aimed to mimic human blood. Thus, cow blood is selected as the most suitable option based on the literature review [5]. Soft sofa sponges, measuring 13x10x7 cm, are soaked to absorb 50 ml of EDTA-anticoagulated cow blood each are then utilized during shootings. In various studies, white cardboard has been used as a target surface to observe the resulting forward spatter bloodstain patterns [6–11]. Subsequently, bloodstain images were taken with a Canon EOS 1200D camera using an 18–55 mm lens. The shooting settings were adjusted based on lighting conditions to ensure image clarity, with an aperture of f/4.5, a shutter speed of 1/100 s, and an ISO of 6400. The images were recorded at a resolution of 3368 × 4776 pixels with a bit depth of 24 and a DPI of 72.

2.2. Image processing algorithm & analysis

The MATLAB code for this study is based on the numerical calculation of the *AO* of a bloodstain pattern on a flat and light-colored surface at the crime scene by processing an image containing bloodstains. The code initially receives a bloodstain pattern image from the user. In the case of a colored image, the code converts it to black-and-white for better identification of the stains. Later, it converts the image to binary format so that the bloodstains appear as white on a black background. With the 'regionprops' function, the code analyzes each of the ellipses in the image and calculates their major and minor axis lengths, eccentricities, centroids, and areas. Using these features, it selects bloodstains that are small, elliptical, and within a certain size range (the minimum area for selected ellipses is 5-pixel, whereas the maximum area for selected ellipses is 500-pixel) so that only the appropriate stains are utilized in the analysis.

By utilizing the discussed methodology, a set of cardstocks that are the outcome of the experiment which are the combination of different real AO_x distances and different shooting distances are analyzed. The real AO_x distances are 5 cm, 35 cm, 50 cm, and 100 cm while the

Fig. 3. Forward spatter bloodstains resulting from a shooting distance of 0 cm with an AO_x distance of 35 cm.

shooting distances are 0 cm, 5 cm, 25 cm, 50 cm, 100 cm respectively. Thus, a total of 20 forward spatter patterns are obtained, then, these images are post-processed with MATLAB.

2.3. Impact and gamma angles

The angle of impact (θ), a crucial factor in bloodstain pattern analysis, refers to the angle at which blood drops strike a surface. The appearance of the bloodstain varies with changes in the impact angle. Perpendicular impacts produce circular shapes, while at more oblique angles the ellipse appears more elongated [12].

$$\theta = \sin^{-1}\left(\frac{width}{length}\right)\# \tag{1}$$

In Eq. (1), "width" refers to the minor axis of the ellipse, while "length" denotes the major axis. In bloodstain analysis, gamma angle, known as directional angle, is an important indicator to identify the direction of movement of the blood drop with relative to a reference axis (typically a horizontal or a vertical plane) [13]. It is calculated by considering the orientation and direction of movement of the stain. For example, if a stain is tilted at 45 degrees and the droplet moved to the right, the gamma angle is 45 degrees. If the same stain resulted from a droplet moving to the left, the gamma angle would be 225 degrees (180 degrees in the opposite direction). By looking at both the gamma angle and the impact angle, analysts can estimate where the blood drops came from before it hit the surface, helping to find the source of the bloodstain [12]. However, this estimation does not consider other forces like gravity and air resistance.

2.4. Method for area of origin calculation

There are various methods in the literature such as tangent method, stringing, automated tangent method, least squares angles for analyzing the ellipse models formed and determining the area of origin. The tangent method and string stretching are mostly manual methods [3, 14]. In order to understand the tangent method, it is necessary to

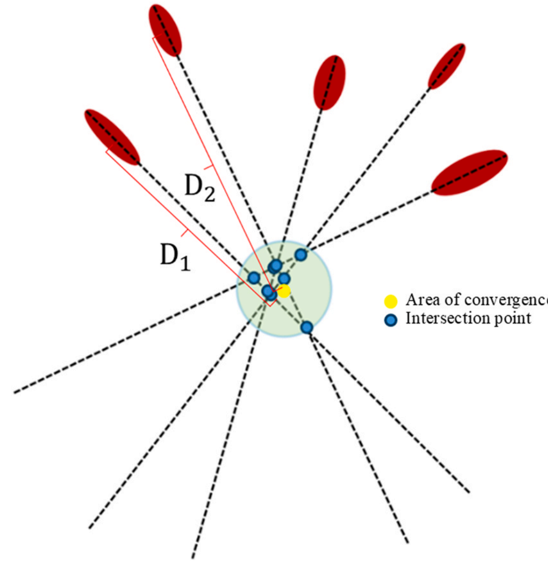


Fig. 4. Intersection points (blue) formed by extending the major axes and the 2D projection of the area of convergence (yellow).

understand how to determine the *AO*. As a result of examining each of the bloodstains formed because of the Impact Mechanism, the impact angle is obtained.

In the first stage of the tangent method, the intersection points of the lines drawn and extended from the major axes of the ellipses are analyzed in a pairwise manner. Then, the intersection region is determined, and the Y and Z coordinates of the *AO* are determined. The second stage is to find the X coordinate by applying the tangent rule. In this stage, first, the distance D_i, which is the projection of each ellipse to the intersection region, is determined as shown in Fig. 4. Then, the length and width of the ellipse are used to determine the impact angle (θ_i) [14].

$$AO_y = \frac{1}{n}\sum\nolimits_{i=1}^{n}\left(D_i \cdot \tan(\theta_i)\right)\# \tag{2}$$

As shown in Eq. (2), multiplying the distance to the intersection D_i by the tangent of the calculated impact angles gives us the total distance perpendicular to the target surface. Since the calculated value contains information from all ellipses, we then divide the found value by the total number of ellipses (n) to come up with the X coordinate of the Area of Origin (AO_x) [14].

Note that, Area of Origin in this case refers to a point since the Area of Origin is defined as "*The space in three dimensions to which the trajectories of spatter can be utilized to determine the location of the spatter producing event*" [13]. For the scope of this study, coordinates AO_y and AO_z are not calculated intentionally due to the experimental setup. Since, the experiment is set up in a way that the source is placed globally (AO_x, 0, 0). That means, the source is placed perpendicular to the origin point of the cardstock. Thus, finding the remaining two coordinates other than AO_x is an unnecessary effort.

As a result of each analysis, the estimated source distance is calculated with supporting 2D graphics where detected ellipses and impact angles are shown (Figs. 5), and 3D graphics where the AO_x is shown (Fig. 6). For convenience, details of a single case study in which the source to target distance is 35 cm and shooting distance is 0 cm is presented.

In forensic practice, analysts determine whether the observed bloodstains are more circular (eccentricity close to 0) or more elongated (eccentricity close to 1) before inputting a suitable minimum and maximum eccentricity range. Once these values are provided, the algorithm further optimizes the selection by prioritizing the most frequently occurring eccentricity values within the image, ensuring that

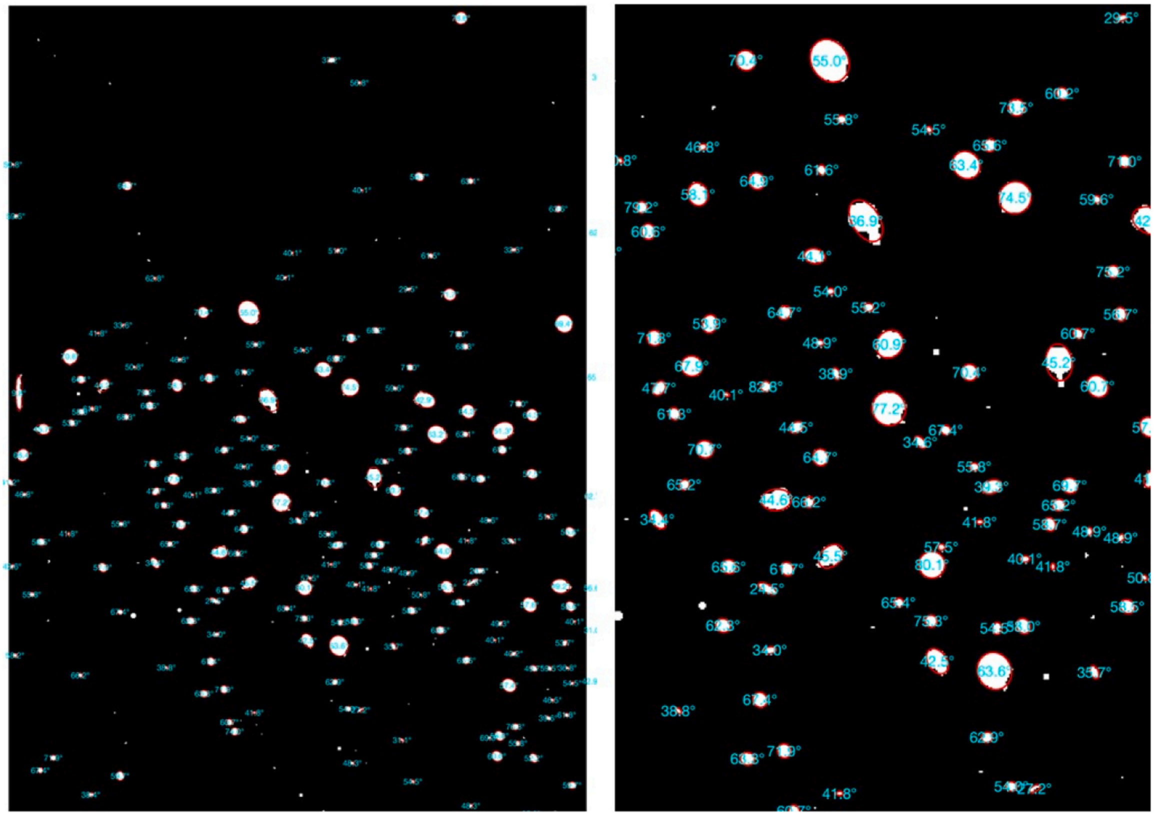


Fig. 5. Zoom in image of detected elliptically shaped ellipses (red outline) and impact angles (cyan).

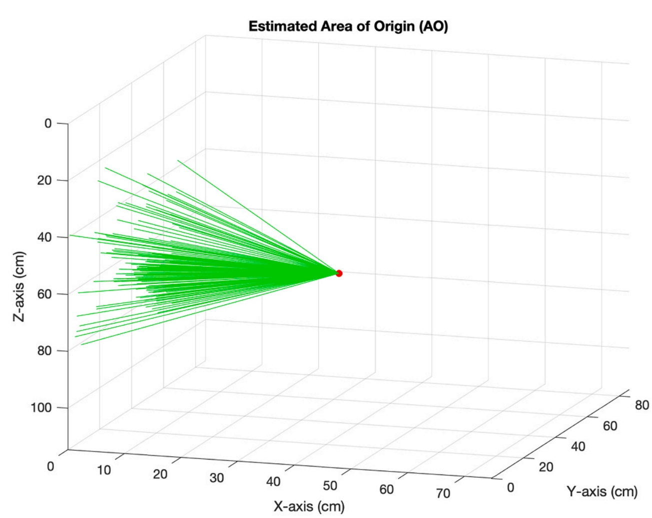


Fig. 6. 3D plot of the estimated *AO* with linear trajectories of bloodstains (green).

the selected stains best represent the dominant pattern and minimizing error (Table 1). The minimum and maximum eccentricity value where the calculated distance is closest to the actual distance is shown in Table 2 by applying the narrowing process. With the minimum 0.00 and maximum 0.57 eccentricity values, the X coordinate of the blood source (AO_x) is found to be 34.8607 cm, which has a −0.40 % error relative to the actual source-to-target distance of 35 cm. The same process is applied to the remaining data sets as well. A more detailed discussion of the analysis results for all cases is provided in Section 3.

Table 1
Optimum eccentricity input scan of bloodstains for cases where a pistol was fired at a distance of 0 cm, with an AO_x of 35 cm.

Min. Eccentricity	Max. Eccentricity	Calculated AO_x (cm)
0.1000	0.1000	NaN
0.1000	0.2000	85.0625
0.1000	0.3000	63.4777
0.1000	0.4000	49.1850
0.1000	0.5000	38.8244
0.1000	0.6000	32.7369
0.1000	0.7000	29.5459
0.1000	0.8000	26.9083
0.1000	0.9000	25.9758
0.1000	1.0000	24.8537

Table 2
Narrowed optimum eccentricity input scan of bloodstains for cases where a pistol was fired at a distance of 0 cm, with an AO_x of 35 cm.

Min. Eccentricity	Max. Eccentricity	Calculated AO_x(cm)
0.1000	0.5000	38.8244
0.1000	0.5100	38.4657
0.1000	0.5200	37.8221
0.1000	0.5300	37.5613
0.1000	0.5400	36.7058
0.1000	0.5500	36.2732
0.1000	0.5600	35.9497
0.1000	0.5700	34.8607
0.1000	0.5800	34.3223
0.1000	0.5900	33.1011

3. Results

In this paper, an algorithm for analyzing bloodstain patterns resulting from gunshot wounds has been developed using the tangent method

Table 3
Error analysis of AO_x, calculated with the maximum eccentricity values used for varying shooting distances and real AO_x distances.

AO_x real (cm)	Shooting Distance (cm)	Max. used Eccentricity	Average Max Eccentricity	Calculated AO_x(cm)	AO_x Percantage Error (%)
	0	1		15.8086	216.17 %
	5	1		10.0400	100.80 %
5	25	1	1.0	18.449	268.99 %
	50	1		16.7005	234.01 %
	100	NA		NA	NA
	0	0.57		34.8607	−0.40 %
	5	0.48		35.0918	0.26 %
35	25	1	0.66	35.8284	2.37 %
	50	0,63		34.9966	−0.01 %
	100	0,61		34.8685	−0.38 %
	0	0.46		50.0082	0.02 %
	5	0.50		50.4948	0.99 %
50	25	0.50	0.45	49.9367	−0.13 %
	50	0.55		50.9106	1.82 %
	100	0.26		50.5563	1.11 %
	0	0.30		99.735	−0.27 %
	5	0.34		98.8474	−1.15 %
100	25	0.34	0.33	102.7675	2.77 %
	50	NA		NA	NA
	100	NA		NA	NA

in the MATLAB program. Unlike blunt trauma, which is commonly analyzed in the literature, we focused on bloodstain patterns caused by high-velocity impact. This made detection and analysis challenging due to the image quality, complex patterns, and the presence of very small bloodstains.

In cases where the blood source and the target are separated by 5 cm, significant errors that are exceeding 100 % are seen. This is due to lack of quality of the image which causes complex patterns and small size ellipses that are hard to detect by the program. For these reasons, the ellipses are not detected with a blood source distance of 5 cm and a shooting distance of 100 cm. Thus, the estimated source distance is assigned as NA and not included in the calculation.

In cases where the blood source and the target are separated by 35 cm, the calculated distances showed minimum errors ranging from −0.40–2.37 %. This indicates that the code performs the best at this distance. The average optimized maximum eccentricity value of 0.66 received from the user is effective for accurate *AO* estimation at this distance.

In cases where the blood source and the target are separated by 50 cm and 100 cm, the errors are mostly below 2 %. At the longer distance of 100 cm source to target distance, when the shooting distances are 50 cm and 100 cm, the calculation could not be performed due to inadequate ellipses, which are assigned as NA and excluded from the calculation.

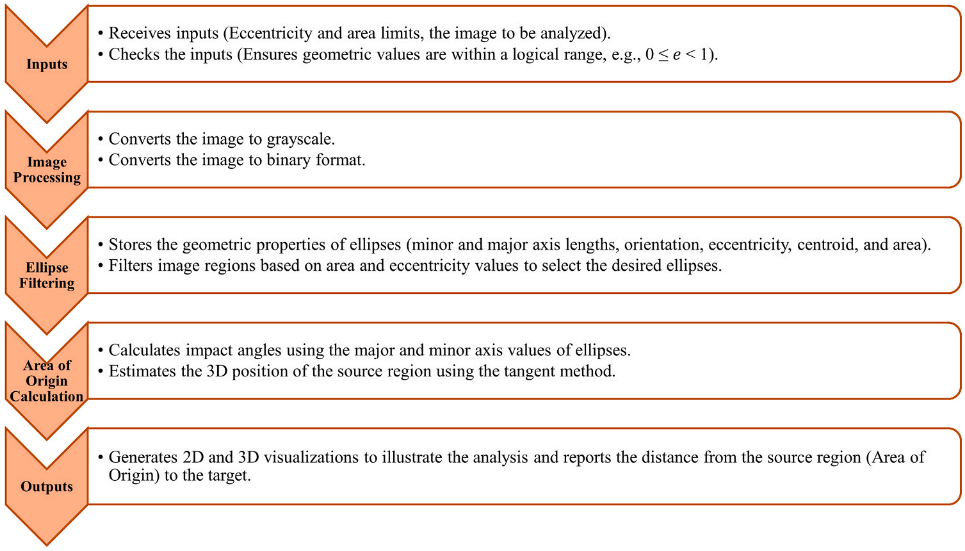
It is seen that as the source to target distance increases the maximum eccentricity value to be utilized decreases. This can be explained with the nature of bloodstain formation. At longer source distances, most ellipses are expected to have low eccentricity values considering that bloodstains will hit at an impact angle closer to 90̊, while at shorter distances, more elliptical bloodstains are produced when they hit at narrower angles and the eccentricity values of the ellipses are expected to be high. Therefore, to get the majority of the ellipses to be detected in photographs, these ellipses should be selected within a certain range of eccentricity values. A bloodstain pattern analyst is expected to determine whether the visible ellipses in the image are generally more circular or elongated and estimate an appropriate maximum eccentricity value accordingly. This input helps ensure that the selected range aligns with the dominant ellipse stains in the bloodstain distribution.

As a result, the code is observed to perform more effectively in analyzing the location of the blood source for bloodstains originating from distances of 35 cm and 50 cm. The code requires improvement for cases involving short source to target distances and long shooting distances. Factors such as image quality, and the appearance of mist-patterned stains should also be considered for more precise results. Thus, with future enhancements such as adding physical factors like drag and gravity correction, as well as automating eccentricity limitations, this program has the potential to become an effective tool for both academic research and crime scene investigations.

4. Discussion

In the literature, the majority of the studies have analyzed blood stain patterns resulting from blunt force trauma with low and medium velocity impact on the blood source [14] [3]. In contrast, in this study, spatter bloodstain patterns resulting from gunshot wounds or deaths, which are in the high-velocity impact group, are analyzed. This particular type of analysis has made the study more challenging since high-velocity impact patterns on the target surface usually result in the formation of a mist pattern that consists of unevenly distributed and extremely tiny ellipses. The numerical algorithm developed in MATLAB within the scope of the research utilizes the tangent method. The program requires several inputs from the user such as the minimum and maximum eccentricity limits, and minimum and maximum areas of the ellipses to be analyzed. These inputs are crucial in terms of excluding ellipses that will mislead the calculation. Once the user provides an initial eccentricity range, the algorithm systematically evaluates multiple ranges and optimizes the selection by prioritizing the most frequently occurring eccentricity values within the image. This data-driven approach helps minimize errors and improve accuracy. The current state of the program does not account for the effect of gravity and assumes that blood drop flight paths are linear, which impacts the precision of the calculated source distances. In reality, blood droplets are subject to gravitational pull, which introduces a downward curve to their trajectory. This means that the actual Area of Origin (AO) may lie slightly above the estimated point, especially at longer source-to-target distances. Air resistance can also influence the flight path by slowing down smaller droplets during motion, potentially affecting their final position on the surface. While improvements such as automating the selection of eccentricity limits are already being considered, future versions of the algorithm may also benefit from incorporating simple physical corrections. These could include modeling the parabolic path of a droplet under gravity or adjusting the analysis based on expected travel distance changes due to air drag. Integrating 3D surface mapping or applying correction factors based on surface characteristics may also improve accuracy in more complex scenes. These developments remain open for future research and are not limited to the scope of this study.

When compared to existing bloodstain analysis software such as BackTrack™, HemoSpat, and Sherlock, the proposed algorithm offers both advantages and limitations. BackTrack™ and HemoSpat are widely used tools that provide visual modeling and include physical corrections such as gravity and air resistance. However, they often operate as closed systems and give the user little control over the internal parameters. HemoSpat also supports analysis on angled surfaces, but its accuracy can drop when analyzing stains from long distances. Sherlock is mainly used for educational purposes and has limited application in real-world forensic scenarios [3]. In contrast, the algorithm developed in this study allows for more user interaction and transparency, especially in controlling which stains are included in the analysis. This makes the method particularly adaptable for high-velocity cases such as gunshot wounds. On the other hand, it currently assumes straight-line trajectories and does not include surface orientation or air resistance, which may reduce accuracy in some conditions. It also struggles with very short source-to-target distances, where the mist-like stains are hard to detect due to their small size and inconsistent shape. One potential solution is to improve the current ellipse detection algorithm by integrating more advanced image processing techniques, which may help distinguish smaller stains from background noise. Additionally,



Scheme 1.

pre-processing filters like contrast enhancement could be applied to improve stain visibility in low-quality images. Incorporating machine learning-based stain recognition, trained on annotated spatter datasets, may also improve reliability at short distances. These enhancements will be considered in future studies to improve the algorithm's performance in challenging scenarios. Despite the challenges, the algorithm has demonstrated high accuracy at mid-range distances and offers a clear framework that can be extended and refined in future studies.

5. Conclusions

In this study, an algorithm for image processing and bloodstain pattern analysis is developed considering its importance in describing the relationship between the victim, the culprit, and the crime scene. The code is developed to be capable of determining the approximate area of origin of the blood, i.e. the victim, by utilizing an image of the crime scene including the bloodstains. This study differs from the literature in the sense that it includes high-velocity impact cases such as firearm related incidents rather than low and medium velocity impact cases such as blunt force trauma in which a lot of resources in the literature are available [3,14]. The method that is employed in this study, called the tangent method, requires the impact angle of the bloodstains to be calculated. This is achieved via extracting the properties of the ellipses that are fitted onto bloodstains in the images. With the impact angle calculated, estimated source to target distance can be calculated. Detailly discussed methodology is applied to a set of cardstocks that are obtained after the experiment. The experiment consists of different source to target distances and different shooting distances that are (5 cm, 35 cm, 50 cm 100 cm) and (0 cm, 5 cm, 25 cm, 50 cm, 100 cm) respectively. Obtained 20 forward spatter bloodstain patterns are analyzed. It should be noted that the code requires user input for minimum and maximum ellipse eccentricities and areas. This would narrow down the ellipses to be analyzed for better converged solutions. Results show that the algorithm performs the best in the source to target distances that are 35 cm and 50 cm with errors to actual distances are less than 1 % in general. For the source the target distance of 100 cm, the errors are still small as the maximum calculated error is 2.77 %. For source the target distance of 5 cm, the errors are huge, exceeding 100 %, due to lack of image quality and existence of extremely small ellipses. In addition, for each source to target distance, an optimum minimum and maximum eccentricity value is selected. It can be concluded that as the source to target distance increases, the optimum value for maximum eccentricity decreases. Since at longer distances, the majority of the ellipses have low eccentricity values due to high impact angles yielding 90°, utilizing a smaller maximum eccentricity value would enable the code the select the more circular bloodstains. With the same approach, as the distance becomes smaller, the impact angle becomes narrower which yields higher maximum eccentricity values, more elliptic bloodstains, are more appropriate. This study can be further improved via automizing the eccentricity and area selection process and training it with better prepared data sets such as wider range of source to target distances and shooting distances that are photographed better. This would help this algorithm and so does this study to be a go-to tool in bloodstain pattern analysis in academia and crime scene investigations.

CRediT authorship contribution statement

Ocak Fatma Nida: Writing – original draft, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation. **Yalçın Sarıbey Aylin:** Writing – review & editing, Visualization, Supervision, Project administration, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fsir.2025.100416.

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