SINERGI Vol. 29, No. 1, February 2025: 51-58
http://publikasi.mercubuana.ac.id/index.php/sinergi
http://doi.org/10.22441/sinergi.2025.1.006

Advanced shooting target with bullet collector, semi-automatic bulls-eye paper positioning and automatic shooting score

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Abstract
Shooting exercises in Indonesia typically use simple bulls-eye targets on wooden boards with sand backstops, requiring manual setup and score calculation. This setup is inefficient, especially for long-range shooting, as operators must walk far to retrieve targets, and bullets embedded in sand are hard to recycle. This project developed an advanced shooting target featuring a bullet collector, semi-automatic target setup, automatic scoring, and target monitoring. A system with such complete features is not available in the market. This target system has a roll of bulls-eye paper and the roller is powered by a servo motor controlled by a switch to command a fresh new page of bulls-eye its positioning is helped by an infrared sensor to detect markers in the paper for correct positioning. This system is equipped with a bullet collector system by directing the bullet to a container using 45^0 angled armor and a layer of sand in the container to stop the bullet. This system is also equipped with a camera pointing to the bulls-eye paper and its output is transmitted to a monitor close to the shooter to identify bullet tracks for evaluating his shooting performance and to improve his shooting strategy. The image from the same camera is used for image processing with the OpenCV library and Python scripts to calculate the shooting score automatically. Several physical tests have been conducted and the system proves to perform reasonably well in the tests with some errors of around 3% for single bullet holes and simple multiple bullet holes. Based on test results, the pistol bullets have quite different properties from the rifle bullets. Pistol bullets follow the impact deflection with a coefficient of restitution e = 0 while rifle bullets follow the impact deflection with e ≈ 0.5. The pistol bullets are completely disintegrated after impact while the rifle bullets are just distorted.

Keywords:
Automatic shooting score;
Bullet collector;
Bulls-eye;
Image processing;
Multiple bullet holes;
Shooting exercise;
Target monitoring;

Article History:
Received: February 4, 2024
Revised: May 31, 2024
Accepted: June 13, 2024
Published: January 2, 2025

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INTRODUCTION

Shooting exercise is regularly performed by military, law enforcement, and even civilians to improve their shooting skills. For military and law enforcement officers, shooting skills are essential to prepare for combat situations. For civilians, there are national and international shooting competitions that they can participate in which require shooting skill as part of their hobby or self-defense. To improve the shooting skill, bulls-eye target is usually used where the area of the target is split into 10 regions associated with different scores depending on the distance to the center of the target. The center of the target is set to have a score of 10 and the outermost region is 1 as standard for 25 m precision and 50 m pistol target [1].

In most shooting exercise setups in Indonesia, the target paper is placed on a wooden board using staples done manually, and the shooting score is calculated manually as well. The process of preparation can take a while, especially for long range shooting such as 50 meters or above. More automatic setup is needed to speed up the preparation and calculation process. This automation will also improve the safety of shooting exercises because there will be no person will come close to the shooting target [2, 3, 4].

Shooting exercise facilities usually have mountains of sand to catch the bullet behind the shooting target for safety reasons. After a while, a lot of bullets will accumulate inside the sand. It is not easy to separate the bullets from the sand for the purpose of trying to recycle the bullets and to reduce the risk of lead poisoning as described in the handbook [5]. Therefore, a kind of bullet collector is needed for the purpose of recycling the bullets [6][7].

For long-range shooting exercises and when a telescope is not used in the rifle, the shooter cannot see the impact of the bullet on the target paper after pulling the trigger. This situation will prevent the shooter from knowing how to improve the shooting strategy and pose. The score is known after the shooting session is over when the officer calculates the hits. To improve the learning process for the shooter, monitoring is needed to show the impact of the bullet right after the shooter pulls the trigger.

The automatic shooting score is based on the image processing of detected bullet holes on the target paper. The bullet holes will be identified in different regions with different scores and then summed up to get the total score. The image from the camera in the shooting target is transferred to the computer's main controller using a WIFI connection using the same technology as in the IoT [8][9]. For image processing, some works [10, 11, 12] were developed using AI-based neural networks while others [2, 4, 13, 14] used OpenCV library with Python scripts and MATLAB. Vilchez et. al. [15] compared several methods of image processing for bullet detection.

In [2, 16, 17], air guns were used in their tests while [18] used a lab test. Automatic shooting scores were also used for training using laser guns [3] and in some sports games [19]. Aryan et. al. [20] used the automatic shooting score in mobile shooting range.

So far, analysis of multiple bullet holes has only been discussed in [11][21]. In this paper, an advanced shooting target with a bullet collector, automatic bulls-eye paper setting, automatic shooting score, and target monitoring is developed. A system with complete features is not available in the market a lot of research focused on improving automatic shooting scores only as mentioned above. The automatic shooting score uses the OpenCV library with Python scripts similar to [1, 4, 13] but with modification and enhancement for multiple bullet holes. The novelty of this paper is that the improved image processing can detect multiple bullet holes, and each bullet center is identified using *HoughCircles* and *kmeans* procedures. This method proves to be reasonably fast and accurate for single bullet holes and for simple multiple bullet holes. Real bullets are used in the tests using a rifle 5.56 mm bullet and a pistol 9 mm bullet to validate the image processing method developed. This paper also analyses the bullet impacts in the bullet collector system showing different types of bullet resulting in different deflection angles after the impact. This is then compared with impact theory. From the experiments, pistol bullets were shattered completely after the impact with a coefficient of restitution to be 0 while the rifle bullets were slightly distorted after the impact with a coefficient of restitution to be around 0.5.

METHOD

The design of the advanced shooting target is shown in Figure 1 and Figure 2. The camera di installed at the upper hood in front of the bulls-eye paper so the view is quite slanted from the top. All front parts of the frames is covered by armor to protect from astray bullets. The upper hood with rear and side covers is designed to protect the structure from rain and sun. Electronic components are placed behind the plate armor. The size of the showing target paper (height x width) is 75 x 60 cm and the total dimension of the shooting target structure (height x width x depth) is 210 x 80 x 190 cm.

Bullet Collector System

A schematic diagram of the bullet collector system is shown in Figure 3. Behind the target paper, plate armor is installed with an angle of 45 degrees to the vertical plane. This plate will deflect the incoming bullet downward to the bullet collector bucket filled with around 25 cm thickness of sand.

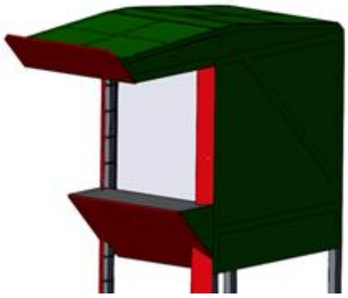

Figure 1. Shooting target outer design; front view

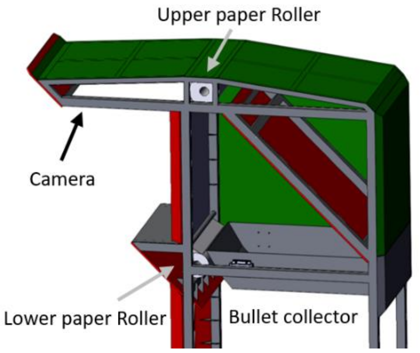

Figure 2. Interior design: side view

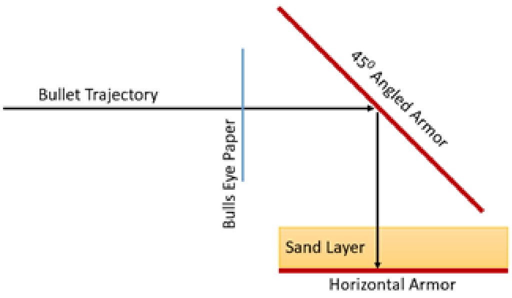

Figure 3. Schematic diagram of ideal bullet collector system

In the sketch, the bullet is deflected with ideal deflection such that when the incoming bullet angle is 45^0 then the leaving bullet after impact is 45^0 angle. The sand should reduce the speed of the bullet and the bottom of the container is protected with a horizontal plate armor to completely stop the bullet. The combination of a layer of sand with stopper armor should safely stop and retain the bullet.

Semi-Automatic Bulls-Eye Paper Setting

Bulls-eye target paper is in the format of a 50-meter rolling paper consisting of around 55 bulls-eyes. Each of the bull eyes is shown in Figure 4 following the standards of the International Shooting Sport Federation and USA Shooting [1].

Figure 4. Bulls-eye target design

In the setup, this paper is supported by upper and lower rollers as shown in Figure 2 and both rollers are powered by servo motors to roll the paper for refreshing the bulls-eye target when a new shooting session starts. A fresh new roll will be set on the upper roller and then the paper is connected to the lower roller. The lower servo motor will act to pull the paper while the upper servo motor will provide rolling resistance to straighten the paper.

Each bulls-eye will be accompanied by four corner markers and one horizontal line marker as shown in Figure 4. These corner markers are ArUco markers [22][23] which are very robust binary square fiducial markers. The line marker is used to set the vertical position of the bulls-eye using infra-red sensor TCRT5000 to detect the line marker.

A camera is used to monitor the shooting target to let the shooter know the impact of the bullet on the target. This information is very useful for the shooter to correct the aim of the shooting to improve the score. Camera image is sent by using a long-range Wi-Fi connection to the PC controller and then the image is displayed by a monitor to the shooter. Wi-Fi connection was provided by high power wireless dual band router which can cover more than 100-meter range in open space.

Automatic Scoring

The automatic shooting score developed in this paper is based on the computer vision method using OpenCV [24] library and Python language programming [25] which are open sources. Input image is coming from the camera and then processed to calculate the score. The flow diagram of the step by step for image processing is shown in Figure 5. In image processing, the first step is to normalize the image in order to reduce the effect of ambient lighting during the tests. This step is necessary to standardize the level of darkness of the bullet hole image.

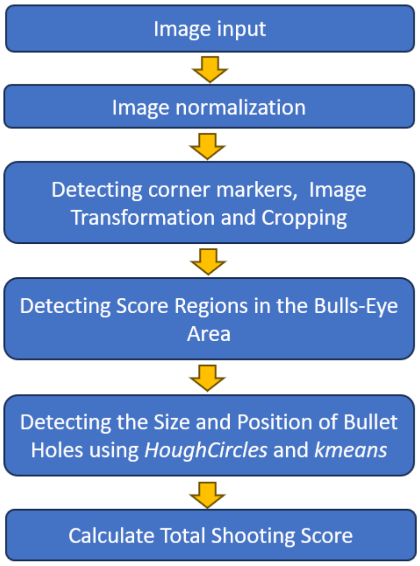

Figure 5. Flow diagram to calculate total shooting score

The next step is to detect 4 corner ArUco markers which will be used to transform the original image from the camera. This process is needed since the camera is located at the upper front of the bulls-eye therefore the view is from slanted upper. Then the image is transformed using the OpenCV library *warpPerspective* to make the image view square from the front. The image is cropped to keep only the bulls-eye area. The next step is to detect the center of the bulls-eye and all circular regions for different scores using circular feature line detection using OpenCV library *threshold*, *findContours,* and *boundingRect* of the contours.

Next is to detect the sizes and positions of all the bullet holes in the target paper using the same OpenCV library for detecting the center of the bulls-eye but the value of the *threshold* is different to catch holes only which are darker. This image processing works well for all single bullet holes with no overlapping bullet holes. Ruolin et al. [26] developed bullet detection anywhere in the image using AI in a vector machine. In this paper, bullet holes are found only in the bulls-eye target area and less searching process is required. A hole with multiple bullets is quite challenging for image processing to detect and analysis for multiple bullet holes will be discussed later.

The last step is to calculate the total shooting score based on the detection of the bullet center and the distance of the bullet center to the center of the bulls-eye similar method to [2][16]. The bullet track will be identified in different regions for different scores and then summed up to get the total score.

Testing Method

The shooting test was performed in an official shooting range facility with well protection behind the target by a mountain of sand and concrete walls as shown in Figure 6. Although the shooting target system has bullet protectors, sand protection is still needed to protect from the shots outside the target. In this test, a rifle with 5.56 mm ammunition and a pistol with 9 mm ammunition were used. Rifle shooting was performed for the 50-meter range to the target while pistol shooting was for the 15-meter range.

RESULTS AND ANALYSIS

Bullet Collector Test Results and Analysis

The test results of the bullet collector system are quite well. All the bullets that pass through the target paper hit the 45-degree armor and are deflected to the container filled with sand. All the bullets were caught and collected in the container and there was no bullet bouncing out of the container. However, the test results showed that the bullets were not deflected following ideal deflection. The rifle bullets were deflected with a larger angle to the normal line than the ideal deflection as schematically shown in Figure 7. This was shown in the test by tracking the bullet marks in the angled armor and the sandmark locations as shown in Figure 8.

Pistol bullet deflection is quite different. The bullets seemed to be disintegrated after the impact with angled armor then the bullet debris slid along the armor surface and entered the container. This result of bullet ricochets aligns with other studies of bullet ricochets from different wood objects [27].

The impact of a bullet on the angled armor can be analyzed using oblique impact theory as explained in [28]. The incoming bullet velocity is decomposed into x and y-axis components as shown in Figure 7 and the *x-axis* acts as the line of impact. $V_x = V \cos 45^0$ and $V_y = V \sin 45^0$.

Figure 6. Shooting target system in shooting range area

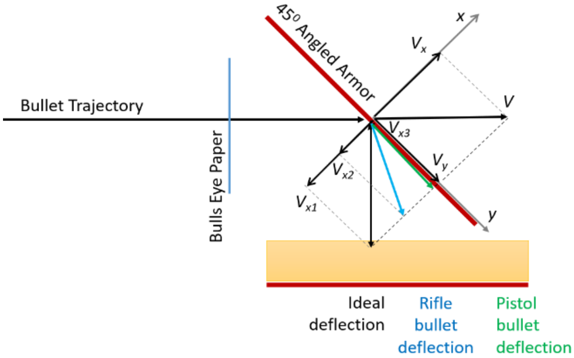

Figure 7. Schematic of ideal deflection vs. rifle and pistol bullet actual deflections

(a) (b)

Figure 8. Bullet tracks, (a) Sand marks from rifle bullets. (b) Bullet marks on angled armor

Momentum in the *y-axis* remains conserved while the impact happens in the *x-axis* direction. Before and after the impact, the velocity of each object on the *x-axis* will follow the coefficient of restitution formula as stated in (1) [28]:

$$e = \frac{(v_{Bx})_2 - (v_{Ax})_2}{(v_{Ax})_1 - (v_{Bx})_1} \qquad (1)$$

where the upper components are the velocity difference after the impact while the lower components are the velocity difference before the impact. If B is the angled armor, then $(V_{Bx})_2 = (V_{Bx})_1 = 0$ because it is stationary. Then (1) becomes $(V_{Ax})_2 = -e\,(V_{Ax})_1$. The negative sign indicates that the velocity direction after the impact is in the opposite direction before the impact. The value *e*, the coefficient of restitution, is controlling the magnitude of deflection velocity. For different values of *e*, oblique impact for different bullets can be described in Table 1.

Table 1. Bullet deflected velocity for different values of coefficient of restitution

Velocity of Bullet After Impact	
Perfect deflection (e=1)	$(v_{Ax})_2 = -(v_{Ax})_1$
Rifle bullets (e ≈ 0.5)	$(v_{Ax})_2 = -0.5\,(v_{Ax})_1$
Pistol bullets (e=0)	$(v_{Ax})_2 = 0$

From the test results, pistol bullets follow the coefficient of restitution *e = 0* while the rifle bullets follow the coefficient of restitution around *e ≈ 0.5*. Perfect deflection follows *e = 1*.

Bulls-Eye Positioning Test Result

Target paper in the format of paper roll consisting of around 55 bulls-eye is controlled by upper and lower rollers powered by servo motors. After a switch button is pressed by the operator to request a new and fresh bulls-eye, these servo motors start to roll the target paper. The servo motors will stop when the infra-red sensor detects the black line marker in the paper as an indication of the correct position of the target paper as shown in Figure 9. The test results indicated that the infrared sensor needed to have a consistent distance to the paper in order to work properly. A custom-designed bracket was used for this purpose.

Automatic Scoring Test Result

Image processing from the camera with a slanted upper view is transformed into a perfect front view using the OpenCV library *warpPerspective* and then rotated and cropped to just keep the bulls-eye area as shown in Figure 10. Due to the camera position closer to the upper part, the quality of the image is better in the upper region than in the lower. However, since high high-definition camera is used, the quality of the image in the lower part is still good.

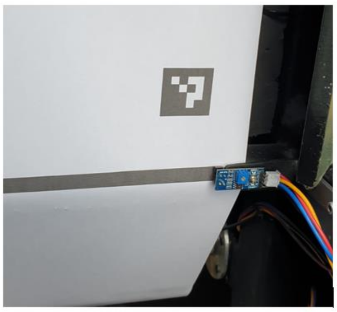

Figure 9. Infra-red sensor to detect the correct position of the bulls-eye target paper

Figure 10. Bulls-eye image after transformation and cropping

Next step is to detect the center of the bulls-eye from the circular lines. Smaller circle is better to define the center of the bulls-eye, but care need to be taken that bullet holes might ruin the small circular edge. The circular lines were detected using binary image processing from OpenCV library *threshold* and *findContours*. With conditioning, the center of bulls-eye is defined based on the circular contours using *boundingRect*. Note that when a bullet hole is touching a circular line, the score of the bullet is associated with higher score region. This adjustment is implemented in the score calculation by measuring the distance of the hole to the bulls-eye center and subtracted by the line thickness.

Bullet hole detection was then performed using OpenCV libraries by converting the cropped image into gray scale image. Next step is using *threshold* to highlight the bullet holes and cleaning the image using *morphologyEx*. The outcome after performing these libraries is shown in Figure 11 and it shows all the bullet holes in the target paper. Library *findContours* is then performed to find the contour of each bullet holes.

Each hole is identified using its contour to find its center using *boundingRect*. This process works well for holes from single bullet. Challenging identifications happen for hole from multiple bullets which means a hole from overlapping or connecting two or more bullets.

Multiple bullet hole needs to be defined mainly based on its area which is 40% larger than average hole area which means 60% overlapping area. Hou et al. [11] analyzed multiple bullet holes however in this paper, simpler but accurate method is performed. The area of hole is calculated using OpenCV library *contourArea*. Individual multiple bullet hole is investigated more details by masking other holes and then apply OpenCV library *HoughCircles* to identify two or more bullet centers. Based on contour of the hole the *HoughCircles* can find centers outside the hole therefore only centers inside the hole are kept by using OpenCV library *pointPolygonTest*.

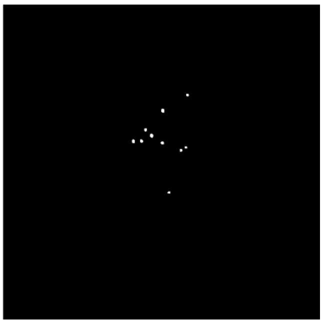

Figure 11. Bulls-eye image after thresholding and cleaning

The *HoughCircles* can give multiple centers which then are grouped into the correct number of bullets using OpenCV library *kmeans*. This process is shown in Figure 12 (a-e). The same procedure is applied for the 3-bullet hole. In regular shooting with 10 bullet sessions in 1 bulls-eye, a 3-bullet hole rarely happens. The identification of a 3-bullet is based on the area of the hole and the characteristic length of the hole. An example of a 3-bullet hole identification process is shown in Figure 13.

From the tests, possible errors in the identification of multiple bullet holes are mainly due to extra tearing of target paper which will enlarge the area of the hole and can lead to incorrect bullet number identification. Care needs to be taken to define the area for multiple bullet identification. Another source of error is the background color. A hole in the area with a black background color seems to be identified as larger than a hole in a white background color area. More study is required to make the size of the hole consistent regardless of the background color. Lastly, ambient lighting might also be a source of error as expected. Normalization of the image should be performed carefully to minimize the effect of different ambient lighting. This image processing procedure has been applied to more than 500 bullets with error around 3%.

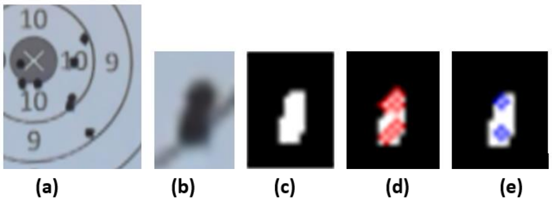

Figure 12. Identification of the centers of the bullet in a 2-bullet hole. (a) original image. (b) zoomed image on the 2-bullet hole. (c) after binarization for contour detection. (d) 6 centers from *HoughCircles* identification. (e) 2 centers after grouping using *kmeans*

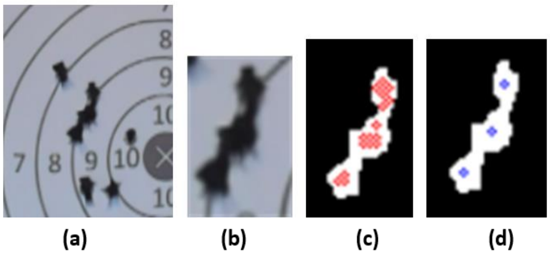

Figure 13. Identification the centers of bullet in a 3-bullet hole. (a) original image. (b) zoomed image on 3-bullet hole. (c) 17 centers from *HoughCircles* identification. (d) 3 centers after grouping from *kmeans*

CONCLUSIONS

It comes to our knowledge that based on the test results, the pistol bullets have quite different properties than the rifle bullets. Deflections of both bullet types do not follow the perfect deflection angle. Pistol bullets follow the impact deflection with a coefficient of restitution $e = 0$ while rifle bullets follow the impact deflection with $e \approx 0.5$. The pistol bullets are completely disintegrated after impact while the rifle bullets are just distorted. This different bullet property is related to its manufacturing process and more investigation shall be done to study this.

Automatic shooting score using Python script and OpenCV with *HoughCircles* and *kmeans* works reasonably well for single bullet holes and simple multiple bullet holes with an error of around 3%. Only a few researchers considered multiple bullet holes. The effectiveness of image processing is reduced when sunlight is directly shined on the target paper which makes it too bright. The solution for this is to protect the target paper with a fabric cover. Further research shall be done to investigate multiple bullet holes with tighter bullet overlapping.

ACKNOWLEDGMENT

The authors would like to acknowledge the financial support of the Ministry of Education, Culture, Research, and Technology of the Republic of Indonesia through the Matching Fund Kedaireka 2023 Program. We also would like to thank PT. Pindad to provide funds for conducting tests and support during the research.

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