TecnoLógicas

Image Processing for Laser Impact Detection in Shooting Simulators

Procesamiento de imágenes para la detección de un impacto láser en simuladores de tiro

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Abstract

Simulation systems play a crucial role in firearms training by offering advantages such as the progressive improvement of shooting skills, reduced logistical costs, ammunition savings, and decreased need for personnel deployment to shooting ranges. A common feature of current systems is the use of wired communication between components, which ensures stability but introduces latency in data transmission. Moreover, wired setups limit their use in outdoor environments due to the lack of access to a power source. This study developed an image-processing-based method to replace live ammunition with a laser-emitting device. The methodology was structured in four phases: (1) system requirements analysis, (2) hardware and software development, (3) system integration with a real firearm, and (4) functional testing in both controlled and open environments. The system incorporates an automatic calibration mechanism that adapts to ambient lighting to ensure accuracy. When the trigger is pulled, the laser activates and projects onto an LCD screen; a camera captures the impact, and an integrated system detects the (x, y) coordinates. As a result, the prototype achieved an accuracy of 95.4% with latency under 80 ms. In conclusion, a portable, wireless system was designed, adaptable to various lighting conditions, consisting of 10 lanes with components specifically designed to integrate with a real firearm—offering a versatile and efficient alternative for training purposes.

Keywords

Embedded systems, image processing, lasers, shooting range, simulation systems.

Resumen

Los sistemas de simulación desempeñan un papel crucial en el entrenamiento de tiro, al ofrecer ventajas como la mejora progresiva de las habilidades del tirador, reducción de costos logísticos, ahorro de munición y menor necesidad de despliegue de personal a los polígonos de tiro. Un rasgo común en los sistemas actuales es el uso de comunicación por cable entre componentes, lo cual proporciona estabilidad, pero introduce latencia en la transmisión de datos. Además, las configuraciones cableadas limitan su uso en entornos exteriores por la falta de acceso a una fuente de energía. Este estudio desarrolló un método basado en procesamiento de imágenes para reemplazar la munición real por un dispositivo emisor láser. La metodología se estructuró en cuatro fases: (1) análisis de requisitos del sistema, (2) desarrollo de hardware y software, (3) integración del sistema con un arma de fuego real y (4) pruebas funcionales en ambientes controlados y abiertos. El sistema incorpora un mecanismo de calibración automática que se adapta a la iluminación ambiental para garantizar precisión. Al accionar el gatillo, el láser se activa y proyecta sobre una pantalla LCD; una cámara captura el impacto y un sistema integrado detecta las coordenadas (x, y). Como resultado, el prototipo alcanzó una precisión del 95.4 %, con una latencia inferior a 80 ms. En conclusión, se diseñó un sistema portátil, inalámbrico y adaptable a distintas condiciones de luz, compuesto por 10 pistas con componentes diseñados para integrarse con un arma de fuego real, como alternativa versátil y eficiente para el entrenamiento.

Palabras clave

Sistemas embebidos, procesamiento de imágenes, láseres, polígono de tiro, sistemas de simulación.

1. INTRODUCTION

The National Army of Colombia, in collaboration with military training academies, is enhancing the military education of future service members, particularly in the field of marksmanship, using innovative simulation technologies and training support systems. These advances aim to improve skills, optimize time and resources, and address key concerns such as ammunition conservation during shooting practice, the additional costs associated with live-fire training, and the increased risk of accidents.

Therefore, the development of a portable system to facilitate rapid shooting practice is justified, integrating as a complementary tool within rigorous training with the Galil 5.56 mm rifle. This system is envisioned as a new resource to reinforce marksmanship training, serving as an additional asset within a comprehensive instructional program to ensure the progressive development of students' skills and practices.

Furthermore, the primary objective of this work is to present the development of the technology implemented in the LID-ESMIC, providing a foundation for future research aimed at assessing the impact of simulator-based training on shooters' performance and their physiological and psychological responses under controlled conditions.

This work proposes a laser impact detection method called “LID-ESMIC,” implemented in a portable shooting practice system known as the Portable Laser Polygon (PLP). In this system, real ammunition is replaced by a laser device that impacts a digital target with Liquid Crystal Display (LCD) technology. These impact signals are captured and stored using image processing techniques to precisely determine the silhouette of the impact point.

The National Army of Colombia operates Instruction, Training, and Retraining Battalions (BITER), with at least one of these battalions present in each of the Army’s divisions and its 26 brigades [1]-[3]. However, the availability of shooting ranges within these units is limited, preventing all soldiers, including officers and non-commissioned officers, from regularly participating in retraining exercises. This limitation underscores the need to develop alternative and complementary systems that improve both the frequency and quality of marksmanship training within the institution [4].

Figure 1A shows one of the ten (10) subsystems of the PLP developed by the research group in Engineering and Simulation from the Military School of Cadets General José María Cordova [5], [6]. Each subsystem is made up of a digital target and elements that are attached to the weapon (Galil ACE 23 rifle): i) a power supplier with a snap-in system for the rifle, ii) an electromechanical recoil system, and iii) a laser device adapted for assembly on the picatinny rail (Figure 1B). It is worth mentioning that the ten subsystems can be used simultaneously with administration software.

Figure 1. System parts. A) Views from the target of the Portable Laser Polygon, a red circle indicates the camera location used to capture images during a shooting practice. B) Elements arranged to the Galil ACE 23 rifle, (1) electromechanical recoil system, (2) trigger, (3) power supplier, (4) laser coupling, (5) headphones to provide auditory immersion during a shooting practice. Source: own elaboration.

In general terms, the trajectory of a projectile is represented by a laser light beam, allowing the system to detect impact coordinates on the LCD screen. A calibrated camera continuously scans the target, capturing a set of three (3) images associated with the shooting instant [7]. Once the images are captured, the system detects the laser impact coordinates (x, y) and transmits them via a wireless communication protocol (802.11 bg) for further analysis and evaluation.

At an international level, various laser shooting simulation systems with image processing have been developed. However, these systems present limitations that affect their accuracy and applicability in military training. Recent research has analyzed human performance in virtual reality shooting simulators and their potential application in military training [8]. However, in the study mentioned [9], these systems rely on video games with limited interaction with visual and auditory stimuli, making it difficult to faithfully replicate real combat and training conditions.

Unlike these approaches, LID-ESMIC not only integrates an impact detection system but also incorporates an electromechanical recoil mechanism, providing a more realistic shooting experience using a real rifle. Furthermore, its portable design allows the system to adapt to any real-world scenario, ensuring its implementation in various operational environments without the need for a fixed infrastructure [8].

Other studies have explored how brightness and contrast levels in virtual reality simulations can induce motion sickness [10] and the implementation of physiological measurements in realistic shoot/no-shoot simulations [11]. The Laser Shot Simulator, widely used in military and law enforcement training, is based on sensors placed on the screen or a weapon for impact detection, which limits its adaptability to different training conditions [11]. Similarly, other systems such as the Laser Ammo Smokeless Range 2.0 and the IPN Laser Capture Shooting Simulator present constraints in haptic feedback and the fidelity of real shooting [12], [13]. Recent research has explored improvements in impact detection through advanced computer vision algorithms [14], multisensory feedback training systems [9], and predictive models to optimize shot detection [15], [16]. Additionally, studies have analyzed the relationship between virtual reality and military shooting training [17], the impact of brightness and contrast variation in shooting simulations [18], and the use of embedded cameras and image processing techniques to detect laser impacts in shooting simulators with high accuracy [19]. Augmented reality training systems and optoelectronic techniques have also been developed to improve laser impact detection in simulators [20], [21]. Furthermore, some studies have evaluated training systems based on low-cost motion sensors [12] and the development of training pistols with laser simulation [13], [22].

LID-ESMIC aims to overcome these limitations by integrating computer vision and an electromechanical recoil system, providing a more realistic shooting experience with the Galil ACE 23 rifle. Unlike other simulators that require controlled lighting conditions to ensure effective laser detection, studies have shown that natural light can affect accuracy in some systems [14]. LID-ESMIC has been designed to operate under various lighting conditions without compromising its performance, making it more adaptable for use in various operating environments. In contrast to more modern systems that require robust and stable infrastructure, LID-ESMIC has been specifically designed for implementation in training and retraining battalions, where practicality and rapid deployment are essential. Many of these units operate as mobile battalions deployed in rural areas for strategic missions. Due to the nature of these operations, they lack the infrastructure necessary to install large-scale simulation systems, as their primary mission is to maintain operational mobility [10].

While other simulation systems may require large screens, high-performance workstations, projectors, or advanced development engines to emulate realistic environments, LID-ESMIC stands out for its operational simplicity and ease of deployment. Its design enables instructors and shooters to conduct shooting practice without relying on fixed infrastructure, ensuring both safety and efficiency in training. Moreover, unlike other reviewed studies, which require dark rooms to ensure shooting effectiveness due to the interference of natural light with laser detection, LID-ESMIC has been developed to function under varying lighting conditions, allowing its use in open spaces without compromising detection accuracy. This represents a significant advantage compared to more complex solutions, which may be challenging to implement in mobile and constantly shifting military environments.

Image processing requires high-performance computing, which means having good memory and processing resources. The Raspberry Pi 3 B Model board was selected as the central process unit, in charge of detecting the laser impact. It has a Quad-Core 1.2 GHz Broadcom BCM2837 64-bit Central Process Unit, 1 GB RAM, BCM43438 wireless LAN, and the Operating System Raspbian GNU/Linux. It can be programmed using Python language [23]. Inside the hardware it is included a specific connector for the Raspberry camera [24], which is specially designed to operate with this device, the configuration, operation and algorithms were developed with the OpenCV artificial vision library, and the embedded system design was based on general principles for the construction of customized images, as described in the specialized literature [25], [26].

In the following section, a general methodology is described, and the most relevant technical characteristics of the hardware are shown. The result section will provide the algorithms implemented for laser impact detection. Then, a discussion is made considering the current technology implemented by the Colombian National Army. Finally, the main conclusion will be presented for future references to improve the proposed method.

2. METHODOLOGY

The portable laser range system is based on the development of an electronic prototype capable of emulating the shooting exercises performed by Colombian soldiers or security and defense professionals. Therefore, this project corresponds to applied research, as its objective is grounded in the implementation of technical concepts such as electronics, Wi-Fi communication, and image processing, with the aim of recreating safe scenarios that facilitate the training and instruction processes of shooting ranges. Consequently, research can be defined as having an experimental approach [27], as it is not based on theory or qualitative models, but rather employs existing systems for the development of new technology that contributes significantly to practical training [28].

Research focused on designing and building a device capable of adapting to any terrain and weather conditions, since end users are security professionals who frequently perform their duties in remote areas, often far from cities or regions with limited access to the Internet and electrical power from distribution networks. For this reason, the PLR (Portable Laser Range) became an essential tool, capable of ensuring the continuity and consistency of training sessions without relying on an external power source or communication systems. This enables the implementation of a simulation device that meets validation procedures and has been tested by experts in the field [29].

During project development, four phases were considered aligned with the main research objective (see Figure 2). These phases were defined as follows: (1) Study of device requirements, (2) Electronic and software development, (3) Adaptation of the components developed to the weapon, and (4) Functionality testing.

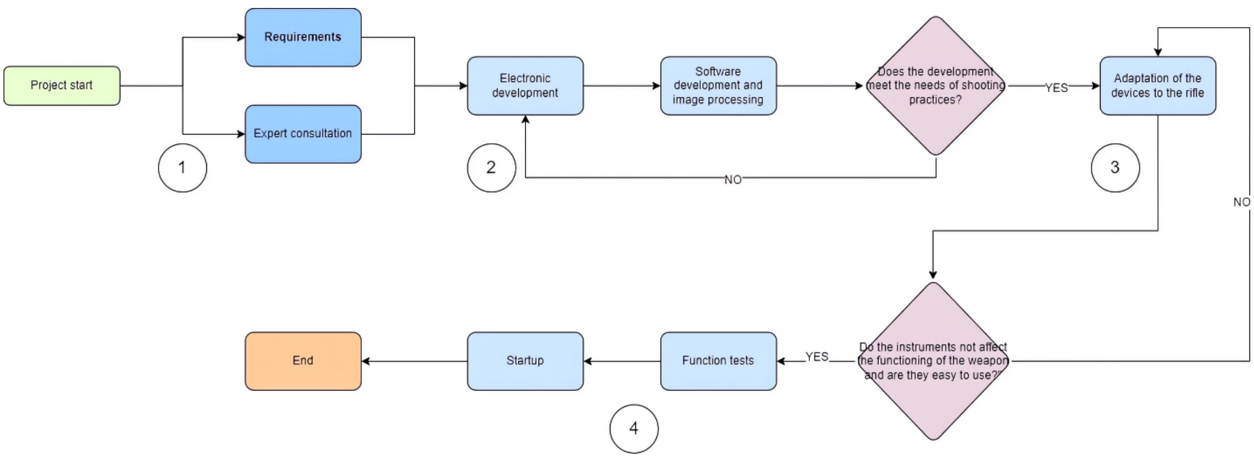

Figure 2. Methodology block diagram. Source: own elaboration.

In the first stage, a review of current technologies and a consultation with experts was conducted to identify key differentiators that would ensure the system's optimal performance and adaptability to the needs of locally employed exercises. This was essential due to the necessity of conducting exercises in open fields and under complex weather conditions. Additionally, technical variables were considered according to regulations and the knowledge of experienced professionals.

In phase 2, based on the captured data, the design and construction of electronic components and software were started. A system was used to enable communication between the laser and the target [30], with a maximum range of 800 meters. Power sources were devised to ensure the execution of the exercises, and simultaneously, software development and image processing were carried out to capture data via screens that serve as shooting silhouettes [31], [32].

In stage 3, the developed components shown in Figure 1 were adapted; the aim is for the user to become accustomed to the weight, control, and reaction of the weapon so that, when exposed to a real scenario, they have the experience of operating the actual components. The implementation of these mechanisms seeks to approximate the user and the instructor to situations as realistic as possible in a controlled environment. Finally, in phase 4, entire system tests were conducted in both closed and open environments to verify its proper functioning [33]. In addition, the device was ensured to meet the standards and regulations for firearm training practices [34]. Furthermore, the operation of the electronic components and software was verified to ensure that the device did not encounter any issues when performing a shooting range test.

In general terms, the LID-ESMIC algorithm is made up of the following stages:

1. Calibration of the camera lens: The camera includes a variable focal lens, which should be adjusted. To make the adjustment, a grid pattern was designed to precisely focus on the image.
2. Calibration of the digital target: The characteristics of the camera and its corresponding lens cause the captured image to support two types of distortion: tangential and radial. It is possible to find physical parameters that produce this type of distortion and transform the images to be as real as possible.
3. Image processing: Once the trigger is pulled, three images are captured. After that, processing techniques are applied to adapt and detect the center of the laser impact, where the acquisition of coordinates (x, y) of the laser impact in the calibrated area is acquired. If in any case the laser beam does not hit the target, the central processing unit (Raspberry PI 3 B Model) will send a "null" coordinate, which means that the screen was not affected.

To ensure accurate laser impact detection, calibrating the target was a crucial step. Initially, the camera captured two images at a resolution of 480x640 pixels: one of a fully black screen and another with a reference pattern. These images were processed to identify the working area by applying corrections for radial and tangential distortions. Subsequently, a Contrast-Limited Adaptive Histogram Equalization (CLAHE) [30], [35] was applied to enhance contrast and edge detection. The Harris corner detection algorithm was used to locate the inner corners of the reference pattern, ensuring a precise calibration of the target [36]. If the calibration failed, the system performed up to five iterations to obtain acceptable results. This calibration process proved robust against varying light conditions (200–400 lumens/m^2) [37].

Once the trigger is activated, three frames are captured at 25 ms intervals using a 640x480 resolution. The images are converted from the RGB color space to HSV, isolating red hues (H = 0-25, H = 330-359) to detect the laser impact. Morphological operations, such as erosion and dilation, refine the shape of the impact, and the centroid is determined for the coordinates (x, y) [15]. The Raspberry Pi 3 B Model processes these data and transmits them over Wi-Fi 802.11ac in a structured format that includes the identification of the shot, the target number, and the address [38], [39].

LID-ESMIC was developed using Python language, specifically to be used with a Raspberry Pi 3 B Model board with Raspbian OS (GNU/Linux), using a "Raspberry Pi-Camera". The Python language offers the advantage of being a multiplatform interpreted language [40], [41]. The hardware required to achieve laser impact detection on a target is shown in Figure 2.

2.1 Raspberry Pi Camera

The Raspberry Pi Camera is a module (Figure 3A) designed to be connected to the Raspberry Pi via a specific serial interface connector. The camera has an 8-megapixel Sony IMX 219 with fixed lens. It allows taking static pictures of 2592 x 1944 pixels and it is compatible with the following video format: 1080 p – 30 fps, 720 p – 60 fps, 640 x 480 p – 90 fps [42], [43].

The Raspberry Pi Camera v2 is integrated in a board size (25 mm x 20 mm x 9 mm), and weighs just over 3 g, making it perfect for mobiles and other applications where weight and size are important [44].

2.2 Raspberry Pi

The Raspberry Pi is an 85 x 56 mm minicomputer Figure 3A and 3B based on an ARM processor. The Raspberry Pi 3 model B has 1 GB ram and a quad core 1.2 GHz Broadcom BCM2837 64-bit CPU processor [4]. It has four USB ports, an Ethernet port, and a BCM43438 wireless LAN. The module is equipped with an HDMI output for the interface with a screen monitor, a microSD slot, up to 40 general purpose Input/Output pins, and a switched microUSB power input up to 2.5 A [45].

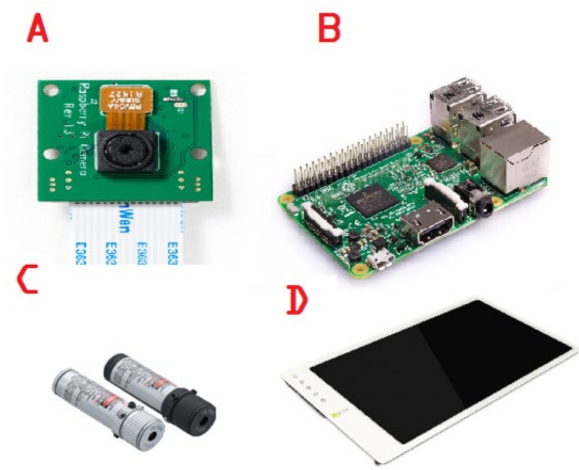

Figure 3. A) Raspberry**)** Pi-Camera. B) Raspberry Pi 3 Model B. C). Laser Beamshot 1000. D) Screen Gechic 1303H 13.3 "resolution 1920x1080 with HDMI. Source. [46].

2.3 Laser

A Beamshot 1000 laser was used as shown in Figure 3C. Dimensions are 69 mm x 19 mm, a wavelength of 650 nm (645 ~ 665 nm) / at 455 m, and a dot size of 12.7 mm at 9.11 m, and 102 mm at 91.11 m [47].

2.4 Screen

A GeChic 1303H (Figure 3D) was used to show the silhouette in which the shooting practice is performed. The screen has a size of 13.3" TFT IPS LCD (16:09), a resolution of 1920 x 108 / 16.7 million colors (antiglare) with HDMI, VGA input, mini-DP, a weight time response of 14 ms typical of the system, and a 1080p HDMI video format (60 Hz / 50 Hz), 1080i (60 Hz / 50 Hz), 720 p (60 Hz / 50 Hz), with a power supply of 5 V / 2 A with micro-USB input [48].

3. RESULTS AND DISCUSSION

This section presents results related to the calibration and image processing stages of the proposed method.

3.1 Lens calibration

In general terms, the economic advantages of the current cameras are in contravention of the relative distortion of the image, which can be compensated with a lens calibration procedure [49]. Radial and tangential factors are considered to correct the distortion. Radial distortion is shown in “barrel” or “fisheye” effects [50]. The radial factor correction uses (1) and (2), the position (x, y) of one point of the non-corrected image is transformed, and its position in the corrected image is determined by $X_{corrected}$ $Y_{corrected}$.

$$X_{corrected}\ x(1+K_1r^2+K_2r^4+K_3r^6) \tag{1}$$
$$Y_{corrected}\ \mathrm{y}(1+K_1r^2+K_2r^4+K_3r^6 \tag{2}$$

The taking of non-perfectly parallel images to the image plane produces tangential distortion, which can be corrected with (3) and (4).

$$X_{corrected}\ \mathrm{x} + [2p_1xy + p_2(r^2 + 2x^2)] \quad (3)$$

$$Y_{corrected}\ \mathrm{y} + [p_1\,(r^2 + 2y^2) + 2p_2xy] \quad (4)$$

Where: [k1, k2, k3, p1, p2]: are the distortion parameters. The conversion of units can be made with (5).

$$\begin{bmatrix} \mathrm{x} \\ \mathrm{y} \\ \mathrm{z} \end{bmatrix} = \begin{bmatrix} \mathrm{f_x} & 0 & \mathrm{c_x} \\ 0 & \mathrm{f_y} & \mathrm{c_y} \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \mathrm{X} \\ \mathrm{Y} \\ \mathrm{Z} \end{bmatrix} \quad (5)$$

Where f_x, f_y are the focal distances in the horizontal axis (x) and vertical (y), and c_x, c_y are the optical centers expressed in pixel coordinates for each axis.

If a common focal distance is used for both axes, then $f_y = f_x * a$. The matrix that contains these four parameters is called the camera matrix [51]. While the distortion coefficients are the same regardless of the camera resolution, these coefficients must be scaled according to the calibrated resolution [52].

The calibration aims to determine the distortion parameters and the unit conversion matrix [53]. The calculation of the entire set of parameters can be carried out using basic geometric equations implemented in the OpenCV library (3) and depends on the calibration pattern [54], [26]. The chess board pattern designed for camera calibration has 10 columns and 5 rows. Initially, snapshots of the selected reference pattern must be captured. Each pattern found results in a new equation, and a predetermined number of pattern snapshots are needed to form an adequate equation system [55], [56]. Although theoretically only two (02) images of the calibration pattern may suffice, practical scenarios often involve image noise and distortion, which affect accuracy. Therefore, it is advisable to acquire no fewer than ten (10) images of the chessboard from varied perspectives and positions to enhance the reliability and precision of the calibration process [56].

3.2 Target calibration

The laser impact detection on the screen requires a calibrated camera, to detect the laser impact coordinates in the most accurate possible area. Figure 4 shows the image with the white reference contour used as a pattern in the calibration procedure.

The algorithm implemented demonstrated its effectiveness in precisely detecting the inner white corners of the calibration pattern (Figure 4). The system captured and processed two high-resolution pixels (480 x 640), with a 4:9 aspect relation and a RGB plane color (Red, Green, Blue) [57]. Images, one of a completely black screen and another containing a reference pattern, were used to establish a calibration framework. A transition time of 500 ms between both captures ensured optimal contrast differentiation. The difference between the two images enabled the generation of a reference image, which was subsequently processed to correct radial and tangential distortions. This adjustment maintained geometric fidelity, preventing alterations to the captured data. Finally, a grayscale conversion was performed, optimizing computational efficiency in subsequent processing steps.

After grayscale conversion, Contrast-Limited Adaptive Histogram Equalization (CLAHE) [30], [35] was applied to improve local contrast and edge definition within the image. By segmenting the image into multiple sections and applying individual histograms, CLAHE dynamically redistributed brightness values, optimizing visibility in different regions of the reference pattern. Subsequently, bilinear interpolation was employed to remove artifacts at the edges of the calibration templates, further refining the overall accuracy of the impact detection algorithm.

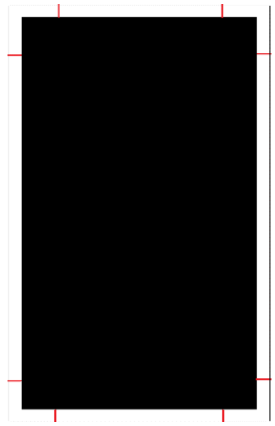

Figure 4. The reference pattern, the white contour, and the red corners are delimited to detect. Source: own work.

The preprocessing stage successfully enhanced the image contrast, enabling a more precise detection of the reference pattern's inner corners. The Harris corner detection algorithm [36]. effectively identified these key points within the calibration pattern, ensuring accurate alignment. However, initial tests revealed the presence of extraneous points that did not correspond to the expected inner corners, requiring the implementation of a thresholding mechanism to refine the detection. By dynamically adjusting this threshold, the system consistently distinguished valid calibration points, optimizing the overall accuracy of the setup.

To further improve the efficiency of the detection process, the image was segmented into four equal sections (320x240 pixels). Each section generated individual templates of ten pixels per side with embedded five-pixel overlays, as illustrated in Figure 5. Then, a correlation analysis was performed within each section to locate the best matching pattern. In cases where multiple potential matches were found, the system selected the one with the highest correlation score, ensuring a robust and precise calibration process. This segmentation strategy significantly reduced processing time while maintaining detection reliability, reinforcing the adaptability of the system under varying operational conditions.

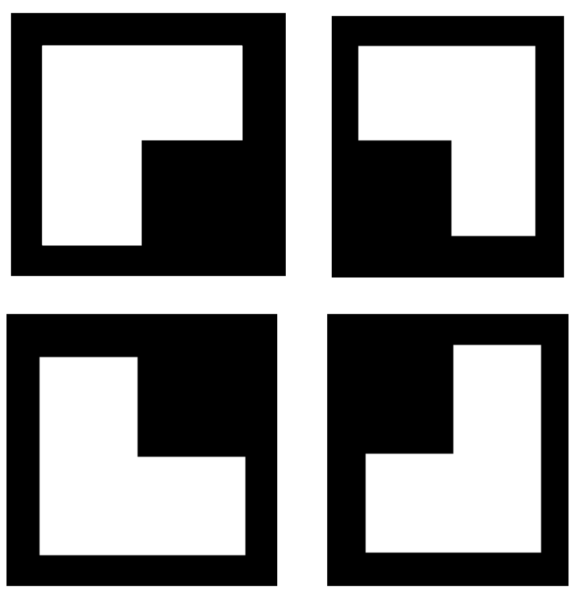

Figure 5. Templates generated to determine the pattern of the reference corners. Source: own work.

To improve the accuracy of laser impact detection, the Gaussian defocus algorithm was applied to minimize noise interference. This process used a linear filter to smooth the values of the pixels, ensuring that the output reflected a weighted sum of the input pixels [50]. By reducing noise artifacts, the system effectively improved image quality, leading to a clearer and more reliable identification of impact points. This optimization significantly improved the consistency of the results under different lighting conditions.

In cases where the initial calibration was unsuccessful, the software automatically performed up to five recalibration attempts until a high-quality acquisition was achieved. This iterative process ensured that detected edges were correctly aligned and stored as a reference for subsequent laser impact detection. The ability of the system to self-adjust minimized errors and ensure repeatability across different training environments.

Figure 6 illustrates the target calibration process under standard lighting conditions (200–400 lumens/m^2). The system initially captured two reference images: a fully black screen (Figure 6A) and an image containing the calibration pattern (Figure 6B). By computing the difference between these two images (Figure 6C), the algorithm extracted the key features necessary for accurate distortion correction. Figures 6D and 6E present the results of applying radial and tangential distortion corrections, followed by the CLAHE filter to enhance image contrast. The final binarized image (Figure 6F) delineated the working area, ensuring precise detection of laser impact. While there were minor noise artifacts, they did not significantly affect the overall accuracy of the calibration process [37].

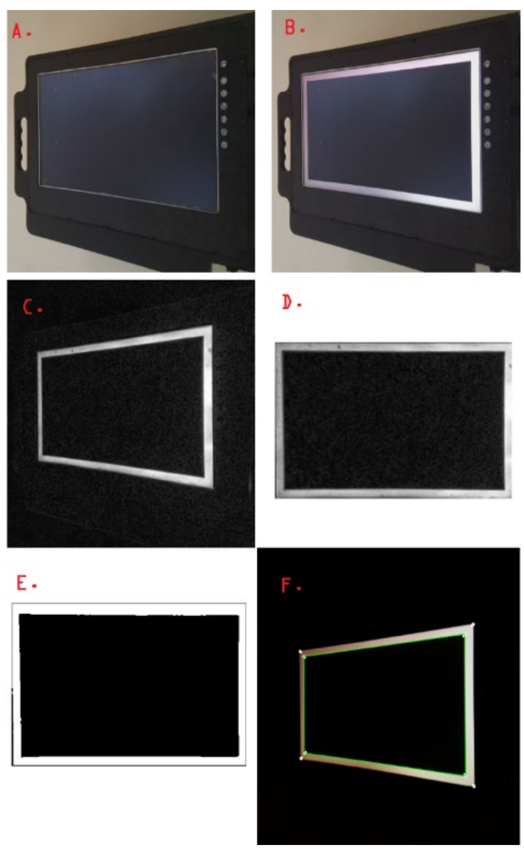

Figure 6. A) Photograph taken with the Raspberry Pi Cam without the reference shape of the dot. B) Photograph taken with the Raspberry Pi Cam with the reference shape of the dot. C) Difference between the images taken. D) Image with correction for radial and tangential distortion. E) Binarization and application of the CLAHE filter. F) The reference frame is highlighted in green, which indicates that the detection procedure of the work area considered has been successfully calibrated.
Source: own work.

3.3 Image processing

Initially, three photograms were captured at 25 ms intervals with 640 x 480 resolution. Once the trigger is activated, a command is sent to the target for camera activation from the power supplier (Figure 1b, 3) via the 802.11ac Wi-Fi protocol [38], [39] The beam light comes on 40 ms after the trigger is pulled and has an on duration of 5 ms.

The camera detects the beam light in two (02) possible scenarios depending on the laser impact location: first) in a unique photogram; or second) the impact covers two (02) photograms, as shown in Figure 7, in this case the detection algorithm considers only the first photogram in which the laser impacts the LCD screen, avoiding to analyze beam light trajectories.

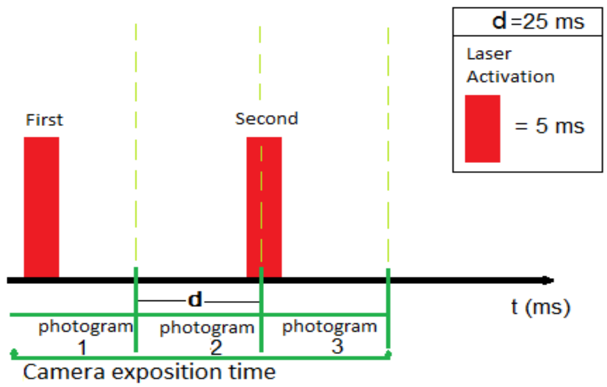

Figure 7. Camera events of laser detection. "d" corresponds to the duration of each photogram, the capture of each frame represented in time, a red bar represents the moment in which the laser impact is captured and has an activation time of 5 ms. Source: own work.

In this stage, methods to detect the laser impact coordinates (x, y) are implemented, and the following class was developed. Image transformation methods from the RGB plane to the HSV (Hue Saturation Value) are implemented. The hue (H) ranges are selected to focus on the red color (H=0-25, H=330-359). Due to the hue red values in the two (02) sections, an OR operation must be done to create one unique mask. The image is binarized in such way that the red color is represented as white (laser impact), and the rest of the components are given as black. Morphological operations (erosion and dilation) are applied to highlight the structure of the laser impact. Finally, the contour of impact detection is drawn, and the coordinates are determined as the centroid [32].

The laser impact contour is shown in Figure 8A; once the contour is delimited, it is used to determine the centroid (Figures 8B and 8C). Finally, the target processing unit (Raspberry Pi model 3b) transmits the data frame via Wi-Fi 802.11ac with the information about detection in the following format: (center in X; center in Y; shot identification; target number; target address). Figure 9 shows the laser impact detection during a shooting practice.

The detection from a sample of fifty (50) laser shots at a simulated distance of 20 m, considering scale 1: is presented in Table 1. The detected coordinates by the proposed method (Xs and Ys) correspond in all cases to visual inspection.

According to the results, the military instructor can evaluate the shooters accurately since in the silhouette and table of coordinates the point where the laser beam hit simulating a projectile is fixed. As is well known, these silhouettes have different scores around the image, which is why the aim of the shooter is to hit the center of the figure or parts where the highest score is given.

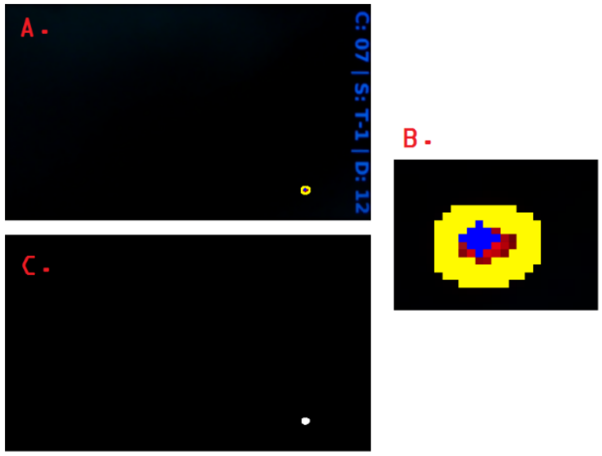

Figure 8. Laser impact detection. A) Laser impact contour detection. B) Magnification of the point of the detected laser impact (red color), a yellow contour, and its blue centroid. C) Segmented laser impact detection. It should be noted that when performing a shooting practice, these images are not shown on the LCD screen. They are only used in debug mode. Source: own elaboration.

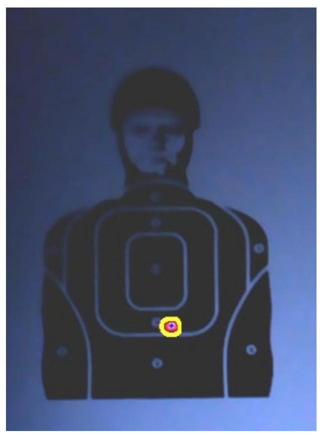

Figure 9. Capture of laser impact detection over a given shape. Source: own elaboration.

The PLP system, being a controlled environment, can instruct military personnel in different shooting techniques, because it does not expose the physical integrity of the personnel and does not generate over costs for the training of such practices, therefore, by identifying the points of impact by the method used (Xs,Ys) guarantees an objective and efficient evaluation, where the shooters develop their skills under the constant training and feedback reviewed by the instructors.

Finally, the laser impact detection algorithm demonstrated an average accuracy of 95.6 % under controlled lighting conditions (200–400 lumens/m^2). At a simulated shooting distance of 20 meters, the system maintained a deviation of ±3 pixels on the x-axis and ±4 pixels on the y-axis (Table 1).

A total of 50 laser shots were analyzed to validate the detection system, ensuring that the coordinates (x, y) corresponded precisely to the expected impact locations. The algorithm correctly identified impact points within a 1 cm margin of error in more than 98 % of the cases.

Additionally, the system was tested in both indoor and outdoor environments to evaluate its robustness. In outdoor conditions with natural light, the detection accuracy remained above 92 %, demonstrating its adaptability to real-world operational scenarios. Unlike other systems that require controlled environments with artificial lighting to function optimally, the PLP system exhibited resilience under various lighting conditions.

Table 1. Detection of laser impact coordinates. Source: own elaboration.

Distance = 5m					
Shot	Xs	Ys	Shot	Xs	Ys
1	386.133	259.466	26	219.733	208.799
2	354.133	525.866	27	381.866	342.933
3	386.133	497.066	28	430.933	259.199
4	288.533	138.133	29	426.666	187.199
5	174.933	442.399	30	356.266	244.533
6	198.400	436.533	31	458.667	456.533
7	477.866	249.333	32	403.200	461.600
8	328.533	599.999	33	189.867	615.200
9	369.066	367.999	34	514.133	287.733
10	394.666	246.133	35	445.867	202.667
11	409.600	576.800	36	437.333	208.533
12	337.067	506.400	37	313.600	346.667
13	364.800	556.800	38	254.933	176.000
14	373.333	151.200	39	277.333	544.800
15	401.067	293.867	40	371.200	595.733
16	354.133	522.667	41	420.266	238.933
17	266.667	240.267	42	335.733	396.799
18	354.133	563.733	43	320.000	622.933
19	366.933	219.200	44	199.733	272.533
20	337.067	178.667	45	301.600	402.933
21	381.866	178.666	46	471.466	556.266
22	396.800	537.599	47	217.600	243.466
23	232.533	244.533	48	230.400	274.933
24	209.866	495.466	49	251.733	356.266
25	390.933	238.666	50	234.666	183.466

During the validation phase, the electromechanical recoil simulation was assessed in terms of usability and realism. Test participants reported that the simulated recoil accurately replicated that of the Galil 5.56 mm rifle, contributing to a more immersive and realistic training experience. The feedback from the military instructors indicated that the system successfully replicated real-world shooting scenarios, allowing shooters to practice without live ammunition while maintaining an authentic training environment.

The usability of the system Graphical User Interface (GUI) (Figure 10) was also evaluated. The control interface allowed instructors to monitor shooting sessions in real time, track shooter performance, and generate detailed reports on shot accuracy and dispersion patterns. As shown in Figure 10, the GUI displayed individual shooter statistics, impact positions on targets, and a summary of training sessions, ensuring an effective feedback mechanism for military personnel.

These findings confirm that the PLP system provides a practical and effective alternative to traditional marksmanship training, reducing costs and safety risks while maintaining high-fidelity simulation capabilities. The portability of the system further enhances its applicability in remote training locations where the infrastructure is limited.

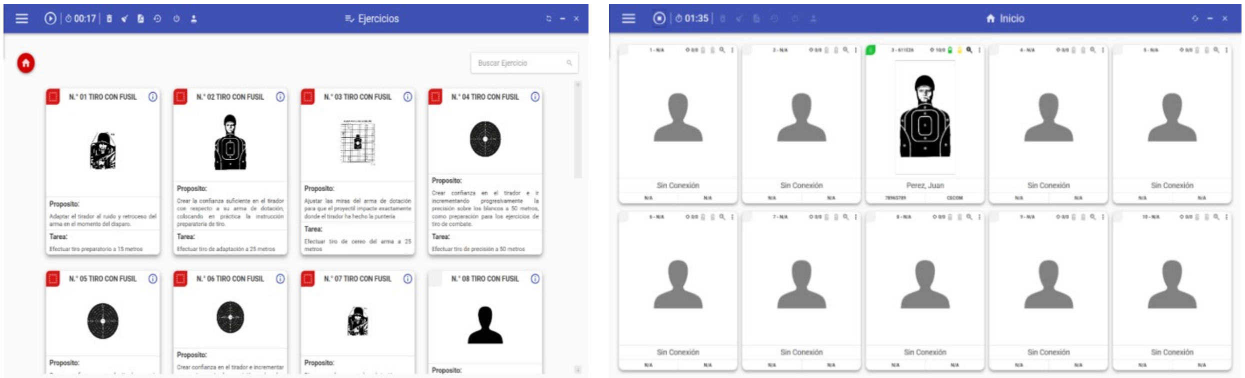

Figure 10. Graphic User Interface to administrate the PLP system of a line shot composed of ten (10) targets. Source: own elaboration.

3.4 Discussion

Currently, the Military School of Cadets General José María Córdova has implemented the training system "BeamHit 460 Laser Marksmanship" [58], which is used in shooting practices for military personnel belonging to the unit, as well as personnel from other national army units. The LTMS provides a capacity for a shooting line consisting of one to ten targets, operated by a computer and an instructor, the practice record includes the generation of data such as time, score, and dispersion for each target.

The Beamhit Company offers several shooting simulation systems, among them:

- 460: System for precision shooting at simulated distances between 25-100 m (6.25 m to 25 m real) with the use of several silhouettes pre-established in the software, can be used with long and short weapons. This system is made up of a line of fire with 10 targets, managed by software to visualize the results.
- Mini Rets: System for reaction shot, using folding targets, made up of lines of 7 to 10 targets, it is possible to configure a maximum of 10 lines each with 7 to 10 targets, all managed by the same computer and software.
- Alt-C: Long weapon system for selected shooters, made up of a target with simulated silhouettes at distances of 50 meters, 100 meters, 150 meters, 200 meters, 250 meters and 300 meters, and administration software for the programming of exercises.
- Sniper: Aimed at high-precision shooters, consisting of a suitcase, several silhouettes, and administration software with ballistic calculations and configuration of external variables such as humidity, wind, direction, among others, allows you to exercise with simulated distances of up to 1500 m.
- Machinegun: System for shooting with machine guns made up of a suitcase with several silhouettes and administration software for the execution of the exercises.

A comparative analysis based on the current simulators described, and the developed system (PLP), is presented in Table 2.

Verifying the information presented in the table, improvements can be observed regardless of simulators with similar characteristics found on the market. As for the administration software, it is possible to select the long weapon exercises established by the Colombian Army. On the other hand, it allows visualization of information about each target, battery levels, real-time results, and the generation of customized reports according to target, shooter, and exercise. Figure 9 shows the graphic user interface of the administration software.

Table 2. Strength and weakness analysis of practice shooting simulators. Source: own elaboration.

Current Technology (Beamhit simulators)	Portable Laser Polygon (PLP)
Continuous connection is required to the power grid supply	Use of rechargeable batteries, allowing a portable system
Electrostatic sensitivity filters are required in data cables.	No data cables are used for communication, all communication is done through a wireless network
Weapon and target are independent, and any target can get shots from any weapon, regardless of the one assigned.	Weapon and target are part of a synchronized system, which does not interfere with other users in the line shot.
Silhouettes according to country of manufacture	Silhouettes according to the Colombian doctrine
Manual configuration of the number of shots according to the shooting practice exercise is required	The number of shots is set automatically according to the shooting practice exercise defined in the doctrine.
Recoil by compressed air or CO_2, which implies monthly expenses, or the simulators do not have this feature	Weapon recoil is achieved with electric DC motors (no external expenses)
Maintenance and spare parts are imported	Maintenance is carried out by Colombian Army personnel, and most spare parts are obtained in the national market

The PLP system represents a significant advancement in military shooting training compared to other established simulators. Unlike the BeamHit 460 Laser Marksmanship [58] and the VirTra V-100 [18], [59], which require structured environments and fixed infrastructure, the PLP system introduces full portability, operating on rechargeable batteries and a locally functioning wireless Wi-Fi network, making it viable for open-field training without dependence on external power sources or internet connectivity [5].

Existing research highlights the importance of physiological monitoring to improve shooting accuracy and stress response during training. Studies on heart rate variability in shoot/don't-shoot scenarios indicate that physiological feedback in real time can improve decision making under stress [11], [60]. However, widely used simulators, such as the VirTra series, do not integrate biometric tracking. The PLP system, due to its adaptable architecture, allows the possible integration of biometric sensors, paving the way for real-time stress assessment during field training [11], [61].

A contentious topic in marksmanship training is the efficacy of video game-based simulators. Although VR-based systems improve cognitive response and reaction times, they lack realistic recoil, weapon weight, and environmental factors crucial for military training [8]. Unlike these VR-focused approaches, the PLP system incorporates electromechanical recoil simulation, providing an experience closer to live-fire training. Research on augmented reality-based shooting simulators suggests that while AR improves reaction speed, it still does not offer the tactile feedback and realism necessary for combat readiness [17], [16].

Another challenge with current simulators is maintenance and operational costs. Systems such as BeamHit and VirTra require imported and specialized components, increasing long-term costs [62]. The PLP system addresses this by utilizing locally sourced spare parts and allowing maintenance by Colombian Army personnel, reducing costs and logistical complexities.

Environmental adaptability is another crucial factor in effective training. Studies on optical tracking in VR simulators indicate that lighting conditions significantly impact accuracy in laser-based training [20]. While many systems require controlled lighting, the PLP demonstrated consistent performance in diverse lighting conditions, maintaining over 92 % accuracy even in outdoor environments. Research on laser spot detection in shooting simulators further support the importance of enhanced optical tracking for training accuracy [12].

The debate over the effectiveness of different shooting simulators continues as emerging research introduces low-cost and optoelectronic-based solutions. For example, studies on optoelectronic tracking in shooting simulators show that precision in laser detection can be improved by improving image processing algorithms [20]. Although these solutions improve tracking capabilities, they often lack real-world applicability due to infrastructure limitations. The PLP system mitigates these issues by incorporating optimized image processing and real-time wireless data transmission over a local Wi-Fi network [6]. Additionally, recent developments in single-board computer-based shooting simulators suggest that cost-effective implementations can still achieve high accuracy levels, in accordance with the PLP approach [63], [64].

Furthermore, previous research on augmented reality (AR) and virtual reality (VR) simulators emphasizes their ability to improve reaction time and decision making skills [17]. However, a key limitation is the lack of tactile feedback and realistic weapon handling, which can hinder complete combat readiness. By integrating physical weapon components, simulated recoil, and real-world field conditions, the PLP ensures that training bridges the gap between virtual and live-fire exercises.

These findings establish the PLP system as a cost-effective, mobile, and highly adaptable alternative to traditional simulators. It enhances realism, field applicability, and affordability, making it a valuable tool for military training. Future research should focus on long-term performance evaluations and the integration of AI-driven biometric analysis to further refine the skill assessment of shooters.

By bridging the gap between virtual training and real-world firearm handling, the PLP system emerges as a pioneering approach to military marksmanship training, offering a comprehensive, field-deployable solution that meets modern training needs.

The PLP is a portable device that allows simulating polygon exercises in real time, with a minimum distance of 5 meters, optimizing the consumption of ammunition to perform this practice, this system is integrated by a hardware capable of capturing and transmitting real-time data of the exercise performance, it also has a software capable of running on in different operating systems being responsible for processing said data captured in the shooting practice, such information travels through a bidirectional wireless link with the ability to be encrypted, e.g. Bluetooth, radio frequency (RF), etc. It also has a calibration system and alerts to adjust lighting, where it is reported if conditions are adequate to perform exercises.

The PLP system is powered by rechargeable batteries, which allows polygon activities in open fields without the need to rely on a constant supply source. Batteries can be adapted to the rifle in the ammunition loading area so as not to lose the feeling of real handling and shooting.

These exercises can be performed individually or in parallel, generating a report of the score and points hit on the silhouette, thanks to the control system that includes a graphical interface where the instructor can monitor the tests. In this way, reports are generated individually or on all shooting ranges. One of the advantages is that it is possible to perform a simultaneous training in a shooting line made up of one or more ranges, which guarantees its simultaneous application in different scenarios.

For the implementation of the device, it is possible to make use of the Galil 5.56 mm, with four components that integrate the PLP shooting system. As described, the projectile supplier is replaced by the casing in the form of this piece to supply energy to the electronic devices. Then, the laser device is installed which will project the light beam on the silhouette, considering that this laser is linked to the trigger. Finally, the butt of the weapon is replaced by the electromechanical system to simulate the recoil at the time of shooting.

Once the elements for the practice are configured and ready, the control software is started for the administration of the exercises. Shooters are assigned to each target or jointly according to the training objectives. This system has indicators of shooting effectiveness; through a green light, where they indicate that they are available to perform the shot, this system has early alerts that indicate the battery level and time elapsed in the test.

4. CONCLUSIONS

A laser impact detector ESMIC (LID-ESMIC) was developed, which is integrated on the prototype Portable Laser Polygon of the military school of the Military School of Cadets "General José María Córdova". The presented method proposes a lens calibration stage that is primarily responsible for performing correction of the radial and tangential distortion, thus ensuring an appropriate representation of the coordinates in the image being analyzed. The target calibration is an important component on the mobility factor of the PLP, calibration allows operation in different environments conditions. These processes are carried out automatically every time the target is turned on or a shooting practice is restarted.

In this shot simulator system model, an embedded camera is used to detect the laser impact on a certain silhouette, either by a shooting practice directive (Directive 300-7 National Army) or another specific standard. The camera is attached to the target, and the laser to the weapon. It uses a simple and effective image processing technique on a Raspberry Pi using Python OpenCV to detect and locate the red dot of the laser on the target with high precision and accuracy. We managed to detect the coordinates of the laser point on the white screen.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest with respect to the publication of this work.

AUTHOR CONTRIBUTIONS

José Antonio García Torres and Jhonnatan Eduardo Zamudio: Development of the technology, Design and development of the system software, Image processing and Assembly of the prototype.

Cristian Camilo García Rodriguez: Development of the prototype, Electronic configuration, and Development of the academic text.

Jhon Fredy Rincón Morantes and Daniel Guzmán Pérez: Methodology, Polygon tests, Adapting and arrange the scenarios to carry out the system tests.

Daniel Felipe Molina Martínez: Development and electronic assembly of the device, Methodology, such as manuals, User guides and maintenance of the device.