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Design and Implementation of a Low-Cost Dual-Structure Laser Shooting System with Physical and Web-Based Targets for School Physical Education

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Abstract

Shooting activities offer educational and recreational value; however, their application in school physical education and recreational settings remains limited due to safety concerns, high costs, and restricted access to specialized facilities and equipment. To address these constraints, this study designed and implemented a low-cost laser shooting system suitable for school physical education and recreational use. The proposed system comprises a laser-gun module, a physical electronic target providing immediate on-site feedback using an illuminance sensor, a Fresnel lens, and RGB LEDs, and a web-based electronic target that enables real-time scoring, logging, and visualization via smartphone or tablet cameras and browser-based processing. By adopting a low-power, projectile-free laser structure with pulse-limited emission, the system enhances operational safety, while the use of general-purpose components and web standards reduces cost and lowers barriers to adoption. Technical verification conducted under controlled indoor conditions demonstrated stable single-shot operation, reliable hit detection, and accurate score calculation for both the physical and web-based targets. Expert validation involving specialists in physical education, educational technology, and sports technology yielded consistently high evaluations across safety, cost efficiency, functional completeness, and field applicability. These findings suggest that the proposed system represents a practical and scalable alternative for school physical education classes and recreational programs. Future research should examine user-level usability, learning outcomes, system robustness under diverse environmental conditions, and structured expert consensus processes.

Keywords: electronic target system; laser-based shooting system; low-cost system design; real-time feedback; laser safety; school physical education

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1. Introduction

Shooting is classified as a precision sport in which performance is strongly influenced by fine motor control, sustained attention, precise aiming, and self-regulation abilities [1]. Previous studies have also reported that psychological factors, such as emotional regulation and arousal control, are closely associated with shooting performance [2]. These characteristics suggest that, when shooting activities are reconfigured into safe and accessible formats, their application can extend beyond elite sport to school physical education and recreational settings.

Recent advances in digital and sensor-based technologies have substantially expanded both the execution methods and application domains of shooting activities. Traditional approaches centered on live-fire shooting are increasingly being complemented or replaced by laser-based systems, electronic targets, and hybrid formats such as Laser Run in modern pentathlon, which integrates running and laser shooting [3,4]. These developments enable enhanced safety, real-time feedback, automated performance recording, and the integration of additional physical activity components, including running or circuit-based fitness exercises. These technology-enhanced formats have begun to reshape how shooting is taught and experienced. Consequently, laser shooting systems have the potential to evolve beyond specialized precision sport equipment into versatile physical activity platforms suitable for school physical education and recreational settings.

Despite this potential, the practical implementation of shooting-related activities in school physical education and recreational settings remains limited. Safety concerns associated with firearms, the high cost of equipment, restricted access to specialized facilities, and the complexity of maintenance and operation have long been recognized as major barriers to adoption in community programs and school-based instruction. In addition, many instructional environments face substantial constraints in staffing, instructional time, and equipment budgets [5]. In inclusive physical activity contexts, particularly those involving participants with disabilities, the costs associated with specialized equipment and facility requirements further restrict participation opportunities [6].

Existing laser-based shooting solutions partially address safety concerns. However, many commercial systems remain ill-suited for flexible use in these contexts due to their high cost and closed, proprietary architectures. Such systems typically rely on exclusive hardware and software ecosystems, which limit modification, repair, scalability, and large-scale dissemination in response to contextual needs. To overcome these limitations, alternative approaches have been proposed, including (i) commercial training platforms using proprietary laser devices and dedicated target units, (ii) camera- or screen-based simulators that infer shot positions through image processing, and (iii) DIY-style, low-cost open-source webcam–laser pointer systems [3,4,7–9]. While these approaches demonstrate the feasibility of laser-based shooting practice, they remain constrained by high total cost, limited immediate physical feedback, insufficient implementation-level reporting of safety mechanisms, and architectures that are closed or difficult for teachers to reproduce and maintain.

These gaps indicate the need for a low-cost, open, and safety-embedded system architecture that can provide both immediate physical feedback and digital logging in a form suitable for non-expert instructional environments. Accordingly, this study aims to design and implement a low-cost laser shooting system for school physical education and recreational use and to verify its performance and field applicability through quantitative evaluation and expert validation. The proposed system consists of a laser-gun module, a physical target unit capable of detecting laser impacts, and a web-based electronic target module that provides real-time feedback and data visualization. Core implementation details, including circuit design, control logic, and software architecture, are presented at a level that supports reproducibility and potential adaptation across diverse settings.

The contributions of this study are threefold:

(1) Architecture: We propose a low-cost, open, dual-structure architecture that integrates a physical electronic target and a web-based electronic target using off-the-shelf components and browser-based software, addressing key cost and scalability limitations of existing commercial and prototype systems.

(2) Safety and deployment: We implement and experimentally validate a safety-embedded laser control mechanism and modular hardware structure tailored for deployment in school physical education and recreational settings, explicitly documenting safety-related design and control logic.
(3) Integrated evaluation and guidelines: We provide an integrated design and performance evaluation of both target modules, establishing practical implementation guidelines for combining immediate physical feedback with digital logging and visualization in instructional shooting environments.

2. Materials and Methods

2.1. System Concept and Design Requirements

Shooting-based activities are increasingly used in sport and recreational training; however, their wider adoption in grassroots and instructional settings remains constrained by safety concerns, high equipment costs, and limited access to dedicated facilities. Conventional live-fire or air-gun systems introduce projectile-related hazards, noise, and strict operational requirements, which restrict their suitability for frequent use in community and educational contexts. To address these constraints, this study proposes a low-cost, projectile-free laser shooting system that enables safe operation, reliable hit-event detection, and real-time scoring with minimal infrastructure.

The system was designed around four primary requirements. First, optical safety was treated as a non-negotiable constraint. The design criterion targeted low-power visible laser operation in accordance with IEC 60825-1:2014 (laser product classification and requirements) [10], and the firing mechanism was implemented with pulse-limited emission (10 ms per trigger activation) to prevent continuous exposure during use. This approach is aligned with established laser safety guidance indicating that short-duration visible laser exposure, well below typical aversion response times, reduces the risk of ocular hazard [11]. Second, the system was required to provide robust hit detection at low optical power. This requirement guided the target design, including sensor sensitivity tuning and optical structuring, to ensure stable hit-event identification under typical indoor practice conditions. Third, the system was required to support low-latency feedback and scoring, enabling users to receive immediate performance information during training. Fourth, to facilitate dissemination and long-term use, the system emphasized low cost, accessibility, and maintainability, relying on widely available off-the-shelf components and open-hardware-compatible development practices. The design also prioritized ease of fabrication and reproducibility, with simplified electrical and mechanical structures that can be assembled using basic prototyping tools and supported by documented wiring, I/O mapping, and control logic.

Based on these requirements, the proposed platform adopts a modular three-component architecture consisting of: (1) a laser-gun module providing pulse-controlled emission in response to trigger input; (2) a physical electronic target that detects incident laser signals via optical sensing and microcontroller processing and delivers immediate feedback using addressable RGB LEDs; and (3) a web-based electronic target module that estimates hit locations and computes scores from smartphone or tablet camera input using browser-based processing.

The overall system architecture and interaction among these modules are illustrated in Figure 1. The modules can operate independently or in parallel, allowing flexible deployment depending on training objectives, equipment availability, and data recording needs.

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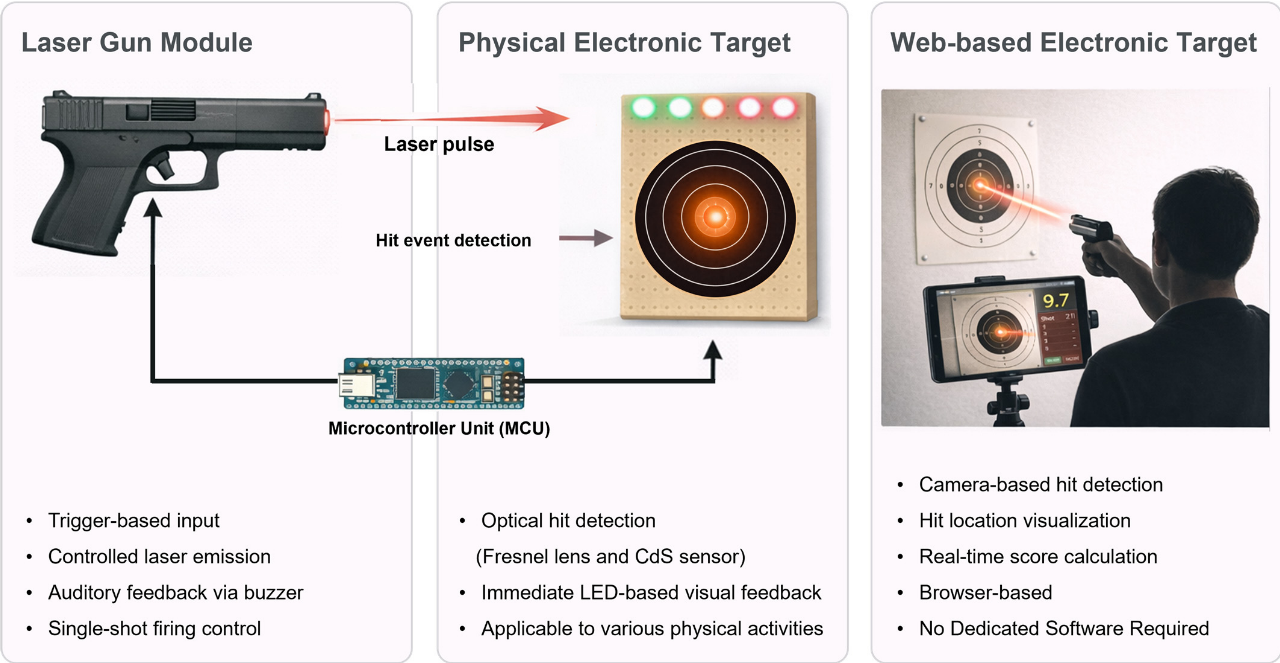

Figure 1. Overall system architecture of the proposed low-cost laser shooting system, illustrating the laser-gun module, physical electronic target, and web-based electronic target and their data flows.

2.2. System Implementation

2.2.1. Laser-Gun Module

The laser-gun module was implemented as a compact input device that converts a user's shooting action into a digitally controlled laser pulse. The module integrates a microcontroller, user input switches, a laser emission unit, an auditory feedback device, and a battery-powered supply and was designed to support portable operation and reproducible fabrication. The gun housing was fabricated using a 3D printing method and was designed to accommodate the Arduino Nano, trigger switch, and laser diode module.

An ATmega328P-based microcontroller board (Arduino Nano-compatible board; generic manufacturer, Shenzhen Makerfabs Technology Co., Ltd., Shenzhen, China) was selected to achieve a small form factor while maintaining low cost and wide component availability. Laser emission is provided by a visible red laser diode module (e.g., 650 nm, $\leq$1 mW), which is directly controlled by a digital output pin of the Arduino Nano. The laser module includes an integrated current-limiting circuit to ensure safe operation within the manufacturer's rated conditions.

User input is acquired through two mechanical switches: a limit switch for trigger input and a tilt switch for cocking detection. Both inputs are configured as active-low digital inputs using the internal pull-up resistors of the Arduino Nano (INPUT_PULLUP). In this configuration, the inputs remain at a logic HIGH level during idle conditions and transition to LOW when the switch contacts ground.

A piezoelectric buzzer is included to provide auditory feedback corresponding to system state transitions. Distinct sound signals are assigned to cocking and firing events to support intuitive user interaction.

Power is supplied by three AAA batteries connected in series. To simplify wiring and improve mechanical robustness, the battery output is routed through a USB Type-C connector used solely as a physical power interface, without data communication. The same VCC and GND rails supply the microcontroller and peripheral components, and a slide switch is installed in series with the supply line for power control. All components are housed within a portable enclosure, and plug-type connectors are used to facilitate inspection and replacement. The pin assignment and I/O configuration of the laser-gun module are summarized in Table 1.

Table 1. Pin Mapping of the Laser-Gun Module.

Pin	Connected Component	Signal Type /Configuration	Description
D6	Micro switch	Digital input, active-low	Detects trigger press (short to GND when pressed).
D2	Tilt switch	Digital input, active-low	Detects cocking action via orientation change.
D5	Laser module	Digital output	Drives the laser module with a time-limited pulse.
D4	Piezo buzzer	Digital output	Provides sound feedback for cocking and firing events.
VCC, GND	Power rail	DC supply	Powered by three AAA cells; VCC/GND supplied via a USB power connector.

The firmware of the laser-gun module was implemented using a finite state machine (FSM) structure with four states: SAFE, COCKED, FIRE, and LOCKOUT. This structure was used to manage cocking detection, trigger input handling, laser pulse generation, and auditory feedback. Laser emission is generated only in the FIRE state and is limited to a predefined pulse duration of 10 ms. After firing, the system enters a LOCKOUT state for a predefined interval before returning to the SAFE state. The control parameters, including pulse duration and timing intervals, are configurable. The firmware was developed using the Arduino IDE (Arduino, Ivrea, Italy). Figure 2 presents the laser-gun module at key assembly stages and in its fully assembled configuration. The complete firmware source code is provided in the Supplementary Material (Code S1).

Figure 2. Laser-gun module: (**a**) internal view showing the circuit connections and major components; (**b**) partially assembled state after circuit integration into the enclosure; (**c**) fully assembled laser-gun module used in the experiments.

2.2.2. Physical Electronic Target Module

The physical electronic target module was implemented as an output device that detects laser pulses emitted from the laser-gun module, determines hit events, and provides immediate visual feedback. The module integrates an optical sensing unit, an optical enhancement structure, a microcontroller, an LED-based feedback unit, and a battery-powered supply. The design focuses on rapid hit-event indication and intuitive feedback rather than precise spatial scoring.

Laser detection is performed using a cadmium sulfide (CdS) photoresistor (generic manufacturer, Hongfa Electronics Co., Ltd., Guangzhou, China), which exhibits resistance changes in response to variations in incident light intensity. The sensor output is read through the analog input of a microcontroller to monitor illuminance levels. The CdS sensor was positioned at the center of the module and serves as the reference point for hit detection. To maintain fabrication flexibility, the sensor can be substituted with alternative optical sensors, such as photodiodes or phototransistors, while preserving the same detection principle.

To compensate for the limited sensing area of a single photoresistor, a Fresnel lens (generic manufacturer, Shenzhen Optoelectronic Co., Ltd., Shenzhen, China) was installed in front of the sensor. In the prototype implementation, a Fresnel lens with an effective diameter of approximately 7 cm and a focal length of 4 cm was used. The lens was aligned to direct incident laser light toward the sensing element. Depending on deployment conditions and component availability, Fresnel lenses with different diameters and focal lengths can be substituted while maintaining the same optical detection principle. The physical configuration of the target module and the corresponding optical detection concept are shown in Figure 3.

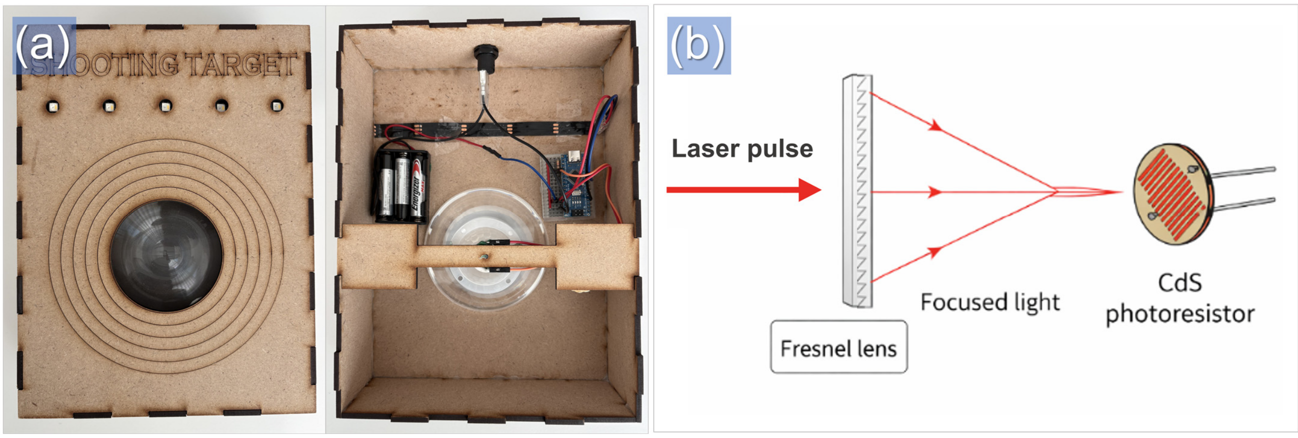

Figure 3. Physical electronic target module: (**a**) photographs of the assembled target, showing the front view with the Fresnel lens and the internal layout including the power supply, control board, and sensor placement; (**b**) conceptual optical diagram illustrating the Fresnel-lens-assisted laser detection principle using a single CdS photoresistor.

For visual feedback, five individually addressable RGB LEDs, such as those from the WS2812B series, were arranged on the front surface of the module. The LEDs are controlled via a single-wire digital interface and can be individually programmed in terms of color and illumination sequence. This configuration provides a simple indication of hit status and progression without requiring an external display.

The power supply was designed for battery-based operation. In the prototype implementation, three AAA batteries connected in series were used. Power is delivered through a USB Type-C connector employed solely as a physical power interface, without data communication. The same VCC and GND rails supply the microcontroller and LED unit, providing a common electrical reference. The circuit design minimizes the number of passive components and adopts simplified wiring to facilitate fabrication, inspection, and maintenance. The pin assignment and I/O configuration of the physical electronic target module are summarized in Table 2. The firmware was developed using the Arduino IDE (Arduino, Ivrea, Italy).

The firmware of the physical electronic target module was implemented to manage ambient light calibration, hit detection, hit counting, and LED feedback control. At startup, the sensor signal is sampled for a calibration period of approximately 3 s to establish a reference ambient illuminance level, denoted as L_{ref}. During operation, a hit candidate is identified when the instantaneous sensor reading satisfies

$$L(t) \geq (1 + \alpha) L_{\text{ref}} \tag{1}$$

where $L(t)$ denotes the instantaneous illuminance measured by the sensor and α is a sensitivity coefficient. In the prototype setting, α was set to 0.3. During operation, a hit candidate is identified when the instantaneous sensor reading satisfies Equation (1). A hit event is detected when the sensor signal exceeds the predefined threshold condition. This threshold-based event detection approach was adopted to ensure reliable real-time processing on a low-cost microcontroller. Once a hit event is confirmed, an internal counter N is incremented and the LED output is updated. In the initial state, all five LEDs are illuminated in red, and the LEDs are sequentially switched to green as N increases. When $N = 5$, the module outputs a completion illumination pattern and then returns to the initial state after a configurable reset delay T_{reset}. Key parameters, including α, T_{hold}, and T_{reset}, were implemented as configurable values. The complete firmware source code is provided in the Supplementary Material (Code S2).

Table 2. Pin Mapping of The Physical Electronic Target Module.

Pin	Connected Component	Signal Type/Configuration	Description
A0	CdS photoresistor	Analog input	Detects laser hits based on a rapid increase in illuminance.
D7	Addressable RGB LED strip	Digital output (single-wire data)	Drives addressable RGB LEDs for immediate visual feedback on hit events.
VCC, GND	Power rail	DC supply	Powered by three AAA cells; VCC/GND supplied via a USB power connector.

2.2.3. Web-Based Target System

The web-based electronic target module was implemented to complement the immediate visual feedback provided by the physical electronic target by enabling real-time recording, aggregation, and visualization of shooting results. The module was developed using standard web technologies (HTML, CSS, and JavaScript) and operates directly within a mobile web browser on a smartphone or tablet. No dedicated application installation is required, which supports accessibility and flexible deployment across different devices. The system is executed in a standard web browser (e.g., Google Chrome, Google LLC, Mountain View, CA, USA).

Laser-hit detection and scoring are performed in real time using client-side image processing applied to camera input. After user permission is granted, the browser receives a live video stream from the device camera. Each video frame is rendered onto an analysis canvas, from which pixel-level RGB values are extracted. Frame processing is executed using a request Animation Frame-based loop to support real-time operation within the browser environment.

The user interface consists of a camera view area and a score and settings panel. A virtual target overlay is rendered on top of the camera view using an HTML5 canvas, displaying circular scoring rings and reference guides. To accommodate alignment differences between the camera field of view and the physical target during on-site setup, the interface provides touch-based drag controls for manual repositioning of the overlay, along with zoom controls to adjust target size according to shooting distance and camera characteristics.

Laser detection is based on frame-level identification of pixels exhibiting dominant red intensity. For each sampled pixel, a laser candidate is identified when the following conditions are satisfied: (1) the red channel intensity exceeds a minimum threshold R_{min}, (2) the red channel exceeds the green and blue channels by at least a predefined difference R_{diff} and (3) the overall brightness, calculated as $R + G + B$, exceeds a specified threshold. To reduce computational load, pixels are sampled at fixed spatial intervals rather than exhaustively evaluated. Among the detected candidates within a frame, the pixel with the highest brightness value is selected as the representative laser-hit coordinate. The parameters R_{min} and R_{diff} are user-adjustable to allow rapid on-site calibration under varying lighting conditions and camera properties.

Detected laser coordinates are initially expressed in the camera coordinate system (x_{cam}, y_{cam}). These coordinates are transformed into the overlay coordinate system (x_{ov}, y_{ov}) by accounting for scaling and offset differences between the displayed video region and the overlay canvas. Score calculation is performed using a circular ring model. The distance d between the detected laser coordinate and the target center is computed, and the corresponding score zone is determined based on predefined ring widths. Coordinates falling outside the target radius are classified as MISS.

The score and settings panel displays key session variables, including the most recent score (LAST), cumulative score (TOTAL), and hit and miss counts (HITS and MISS). Round-based operation is supported by limiting input after a predefined number of shots per round ($n = 10$). Once the round is completed, further input is locked until a restart condition is triggered. In the prototype implementation, scores and system states can be reset by irradiating a designated RELOAD area on the display.

To prevent duplicate detections caused by frame-to-frame persistence, a cooldown-based input suppression mechanism was implemented. After a hit event is registered, subsequent detections are ignored for a configurable cooldown duration specified in milliseconds. This mechanism limits unintended repeated accumulation while maintaining real-time responsiveness. In addition to visual updates, the interface provides auditory cues at system initialization, upon hit detection, and at round completion to indicate system state transitions.

An example deployment of the web-based electronic target module is publicly available for demonstration and reproducibility purposes and can be accessed through a standard web browser. Figure 4 illustrates the user interface of the web-based electronic target module and an example in situ deployment with a smartphone or tablet camera aligned to the physical target.

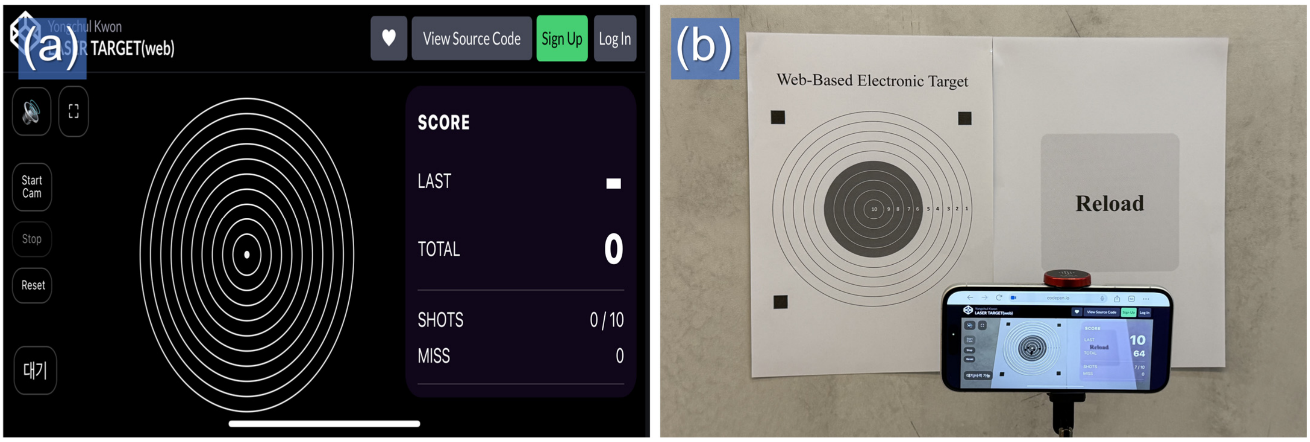

Figure 4. Web-based electronic target module: (**a**) interface screenshot (**b**) in situ setup during use with a smartphone/tablet camera aligned to the physical target. The system is designed to detect red laser signals only, while other colors are excluded during image processing.

2.3. Experimental Setup and Validation

In this study, an experimental setup and validation procedures were established to examine the operational characteristics of the proposed laser shooting system. Test conditions, measurement protocols, and evaluation criteria were defined in advance to support systematic validation.

2.3.1. Experimental Environment and System Configuration

All experiments were conducted in an indoor environment to minimize the influence of uncontrolled external lighting and weather conditions. The laser-gun module, physical electronic target module, and web-based electronic target module were configured according to the system architecture described in Section 2.2.

The shooting distance between the laser-gun module and the target was fixed for each test condition, and the laser beam was aligned perpendicular to the target surface (0° incidence) to reduce the effects of angular deviation.

For experiments involving hit/miss detection and scoring with the physical and web-based electronic targets, ambient illuminance at the target plane was set to one of three indoor levels (300, 600, or 900 lx), which correspond to typical lighting conditions in school classrooms and indoor sports facilities. Illuminance was adjusted and verified using a digital lux meter before each experimental session and then maintained at a constant level during that session. Lighting conditions were not altered within individual test runs. The laser ON-time measurements were conducted under a single indoor lighting condition at a shooting distance of 5 m because ambient illuminance does not affect the microcontroller-level timing of the laser emission.

For experiments using the web-based electronic target module, a smartphone or tablet camera was mounted facing the physical target. The field of view was adjusted to capture the entire target area, and the on-screen target overlay was manually aligned with the physical target using the interface controls (Section 2.2.3). Once calibrated, the camera position and zoom level were kept fixed for the duration of each test session.

2.3.2. Shooting Protocol and Trial Structure

Shooting trials were conducted using a round-based structure. For each trial, a predefined number of shots were performed using the laser-gun module. The cocking and firing sequence followed the control logic described in Section 2.2.1, ensuring single-shot operation for each trigger activation.

To maintain consistency in operation, the laser-gun module was handled by a single user during each test session. The target position remained fixed throughout a given trial. Between trials, system states were reset using the predefined reset mechanisms implemented in the physical electronic target module and the web-based electronic target module.

2.3.3. Measurement Variables and Evaluation Metrics

Prior to testing, measurement variables and evaluation metrics were defined to characterize the system's detection reliability. Metrics were computed consistently across all test conditions using system logs and synchronized observations.

Detection outcomes were summarized using true positives (TP; hit trials correctly detected), false negatives (FN; hit trials missed), and false positives (FP; miss trials incorrectly detected as hits).

The primary evaluation metrics included:

- Hit detection rate, defined as $TP/(TP + FN) \times 100$ for the physical electronic target module.
- Agreement (exact match), defined as the proportion of trials in which both the numeric score and the hit/miss classification matched the manually labeled ground truth for the web-based electronic target module.
- False-positive occurrence, defined as the number of false detections recorded during miss trials (i.e., FP counts).

All metrics were derived from system logs and observed system responses. The same calculation procedures were applied consistently across all test conditions.

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2.3.4. Expert Validation Procedure

In addition to technical testing, an expert-based validation was conducted to examine the suitability of the system for recreational and instructional use. A total of five experts participated in the evaluation, including specialists with backgrounds in sports engineering, physical education, and educational technology. All participants were in-service physical education teachers or university faculty affiliated with local middle schools and universities in Busan, with approximately 10–20 years of relevant professional experience in school physical education, shooting-related activities, or technology-enhanced instruction. The experts were recruited using purposive sampling based on their prior involvement in digital device use, instructional design, or sports-related program development.

The experts were provided with a demonstration of the complete system, including the laser-gun module, physical electronic target module, and web-based electronic target module. Following the demonstration, participants completed a structured questionnaire consisting of multiple evaluation items. Each item was rated using a 5-point Likert-type scale (1 = strongly disagree to 5 = strongly agree). The evaluation focused on aspects such as system safety, functional completeness, ease of operation, and applicability in recreational and instructional contexts.

The expert validation procedure was designed to complement the technical measurements by collecting structured judgments about the perceived practicality and educational applicability of the system under controlled observation conditions.

2.3.5. Field Operation Safety Guidelines

Although the laser-gun module emits laser pulses for only 10 ms per shot, for deployment in school physical education and youth recreational settings, the system must be operated under basic safety guidelines. Users must maintain a minimum shooting distance from the target (3–5 m or more, depending on the installation environment). This distance was selected to accommodate the spatial constraints commonly found in indoor school physical education environments while maintaining safe system operation. However, the system itself can be configured for various shooting distances, including longer ranges such as 10 m, depending on the available space and instructional objectives. Users are strictly prohibited from aiming the laser device at the face or eyes of other participants or bystanders. A teacher or qualified supervisor should be present at all times to oversee operation, provide safety instructions, and intervene in the event of misuse. After each session, the power of the laser-gun module and target modules must be switched off, and the devices should be stored in a secure location to prevent unauthorized access or unsupervised use.

3. Results

3.1. Single-Shot Control and Abnormal Event Suppression

The single-shot control behavior of the laser-gun module was evaluated under three trigger input conditions: a sustained trigger press for 2 s, rapid repeated trigger activations (20 attempts), and conditions intended to induce switch bounce or mechanical jitter.

Each condition was repeated 20 times, yielding a total of $n = 60$ trials. Abnormal events were defined as one of the following conditions: (i) multiple laser emissions after a single arming action, (ii) laser emission without arming, (iii) firing or acceptance of inputs during the inter-shot lockout period, or (iv) failure to fire under a valid arming–trigger sequence, in accordance with the criteria described in Section 2.3. The results are summarized in Table 3.

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Table 3. Single-Shot Control with Inter-Shot Lockout.

Scenario	Trials	Abnormal Events	Error % (95% CI)	Notes
S1: Long press (2 s)	20	0	0.0 (0.0–16.8)	No unintended repeat firing
S2: Rapid presses (20×)	20	0	0.0 (0.0–16.8)	Lockout function verified
S3: bounce/jitter	20	0	0.0 (0.0–16.8)	Debounce and lockout verified
Total	60	0	0.0 (0.0–6.0)	—

Abnormal event was defined as (i) multiple laser emissions after a single arming action, (ii) laser emission without arming, (iii) firing or acceptance of inputs during the inter-shot lockout, or (iv) failure to fire under a valid arming–trigger sequence.

Across all 60 trials, no abnormal events were observed, corresponding to an error rate of 0.0% for each condition and for the total trial set (Table 3). No unintended repeat firing occurred during sustained trigger presses, and the inter-shot lockout and debounce mechanisms operated as specified under rapid activation and bounce or jitter conditions.

In addition to the laser-gun module, cooldown-based suppression of duplicate score accumulation was evaluated for the web-based electronic target module under single-shot firing conditions. A total of $n = 20$ trials were conducted, and a double-count event was defined as two or more score registrations generated by a single laser shot. As shown in Table 4, no double-count events were recorded across all trials (0/20).

Table 4. Cooldown-Based Suppression of Double Counting in the Web-Based Electronic Target Module.

Item	Trials (*n*)	Double-Count Events (*n*)	Double-Count Rate % (95% CI)
Single-shot firing	20	0	0.0 (0.0–16.8)

A double-count event was defined as two or more score registrations generated by a single laser shot. The double-count rate was calculated as (double-count events/trials) × 100. Two-sided 95% confidence intervals were computed using the exact binomial (Clopper–Pearson) method.

3.2. Laser Emission Timing Characteristics

Laser emission timing was examined using the laser ON-time derived from microcontroller timing logs under indoor conditions at a shooting distance of 5 m and with normal incidence (0°). A total of $n = 30$ nominal firing events were recorded under identical operating conditions. The descriptive statistics of the measured ON-time are presented in Table 5. The mean laser ON-time was 10.021 ms with a sample standard deviation of 0.0021 ms. The minimum and maximum observed values were 10.016 ms and 10.024 ms, respectively, resulting in a total range of 0.008 ms across all trials. All timing values were obtained directly from microcontroller-level logs recorded for each firing event.

Table 5. Measured Laser On-Time Under Indoor Conditions.

Total Trials (*n*)	Mean	SD	Min	Max	Range
30	10.021	0.0021	10.016	10.024	0.008

Laser ON-time was derived from microcontroller timing logs for each firing event. SD denotes the sample standard deviation. All times are in milliseconds (ms).

3.3. Hit and Miss Detection Performance of the Physical Electronic Target

The detection performance of the physical electronic target module was evaluated at a shooting distance of 5 m under three incidence angles (0°, 15°, and 30°) and three indoor illuminance levels (300, 600, and 900 lx). For each angle–illuminance combination, 20 hit trials (targeting the Fresnel-lens area) and 20 miss trials (targeting locations at least 2 cm outside the lens boundary) were performed ($n = 40$ per condition). Detection outcomes were summarized using true positives (TP), false negatives (FN), and false positives (FP), and hit detection rates with two-sided 95% confidence intervals (Clopper–Pearson) were computed and are reported in Table 6.

Table 6. Hit/Miss Detection Performance of The Physical Electronic Target at Different Incidence Angles.

Illuminance (lx)	Incidence Angle (°)	TP	FN	Hit Detection Rate % (95% CI)	FP
300	0	20	0	100.0 (83.2–100)	0
	15	20	0	100.0 (83.2–100)	0
	30	19	1	95.0 (75.1–99.9)	0
600	0	20	0	100.0 (83.2–100)	0
	15	20	0	100.0 (83.2–100)	0
	30	18	2	90.0 (68.3–98.8)	0
900	0	20	0	100.0 (83.2–100)	0
	15	20	0	100.0 (83.2–100)	0
	30	17	3	85.0 (62.1–96.8)	0

For each condition, 20 hit trials and 20 miss trials were conducted (n = 40 per condition). TP, FN, and FP denote true positives, false negatives, and false positives, respectively. Two-sided 95% confidence intervals were computed using the exact binomial (Clopper–Pearson) method.

At 0° and 15°, all hit trials were detected across all illuminance levels (20/20; 100.0%, 95% CI: 83.2–100). At 30°, hit detection decreased with higher illuminance, from 19/20 (95.0%, 95% CI: 75.1–99.9) at 300 lx to 18/20 (90.0%, 95% CI: 68.3–98.8) at 600 lx and 17/20 (85.0%, 95% CI: 62.1–96.8) at 900 lx. No false positives were observed in miss trials across any condition (FP = 0/20 for all conditions).

3.4. Score Agreement and Hit/Miss Classification Performance of the Web-Based Electronic Target

The score agreement and hit/miss classification performance of the web-based electronic target module were evaluated by comparing system outputs with manually labeled ground truth data. Ground truth labels were assigned by manual inspection of recorded frames. The evaluation was conducted at a shooting distance of 5 m and with normal incidence (0°) under three indoor illuminance conditions (300, 600, and 900 lx) described in Section 2.3.1. At each illuminance level, n = 20 trials were performed (10 hit trials within the scoring ring region and 10 miss trials outside the scoring region; n = 60 overall). Because performance was identical across all illuminance levels, aggregated results are summarized in Table 7.

Table 7. Score Agreement and Hit/Miss Classification Performance of The Web-Based Electronic Target Module.

Condition	Trials (n)	Exact Match (n)	Agreement (%) (95% CI)	FN	FP
Hit (scoring ring region)	30	30	100.0 (88.4–100)	0	0
Miss (outside scoring region)	30	30	100.0 (88.4–100)	0	0
Total	60	60	100.0 (94.0–100)	0	0

Ground truth was obtained by manual labeling of recorded frames. "Exact match (n)" indicates trials in which both the numeric score and the hit/miss classification matched the ground truth. Two-sided 95% confidence intervals were computed using the exact binomial (Clopper–Pearson) method. Values are pooled across 300, 600, and 900 lx.

For hit trials ($n = 30$), the system matched both the numeric score and hit/miss classification in all cases (FN $= 0$). For miss trials ($n = 30$), all trials were correctly classified as misses (FP = 0). Across all trials, the overall agreement between system outputs and ground truth labels was 60/60 (100.0%, 95% CI: 94.0–100; Clopper–Pearson).

3.5. Expert Validation Results

Expert-based validation was conducted to examine the perceived suitability of the proposed laser shooting system across multiple evaluation dimensions. The quantitative results of the expert evaluation are summarized in Table 8.

Table 8. Expert Validation Results by Evaluation Dimension.

Evaluation Dimension	Mean (M)	SD	S-CVI/Ave
Safety	5.00	0.00	1.00
Functionality	4.78	0.43	1.00
Cost Efficiency	5.00	0.00	1.00
Ease of Fabrication and Maintenance	4.61	0.50	1.00
Applicability	4.89	0.32	1.00

Expert panel: n = 5. Means and standard deviations were calculated using a 5-point Likert scale (1 = strongly disagree, 5 = strongly agree). For CVI, ratings of 4 or 5 were considered relevant; S-CVI/Ave represents the average of item-level CVI values.

The expert panel rated the system using a five-point Likert scale across five evaluation dimensions: safety, functionality, cost efficiency, ease of fabrication and maintenance, and applicability. As shown in Table 8, mean ratings ranged from 4.61 to 5.00, indicating consistently high evaluations across all dimensions.

The Safety dimension received the highest mean score ($M = 5.00$, $SD = 0.00$), indicating unanimous agreement regarding the appropriateness of the laser-based design and the embedded safety mechanisms. Cost Efficiency was also rated at the maximum level ($M = 5.00$, $SD = 0.00$), reflecting strong expert agreement on the suitability of the low-cost hardware configuration for educational and recreational use.

Applicability received a high mean score ($M = 4.89$, $SD = 0.32$), suggesting that the system was perceived as feasible for implementation in practical contexts such as physical education classes, after-school programs, and recreational activities. The Functionality dimension showed a mean score of ($M = 4.78$, $SD = 0.43$), indicating generally positive evaluations of operational stability and system behavior.

The Ease of Fabrication and Maintenance dimension received a slightly lower, yet still high, mean score ($M = 4.61$, $SD = 0.50$), suggesting minor variability in expert perceptions regarding fabrication and maintenance requirements.

Content validity index analysis indicated that the scale-level content validity index using the average method (S-CVI/Ave) was 1.00 for all evaluation dimensions, indicating complete agreement among experts regarding the relevance of the evaluation items within each domain.

4. Discussion

4.1. Interpretation of System Design Outcomes and Expert Validation

The expert validation results showed mean scores ranging from 4.61 to 5.00 across assessment domains, with particularly high ratings for Safety and Cost Efficiency. Overall, these findings indicate that the proposed laser shooting system addresses core requirements for practical deployment, including safety, cost efficiency, ease of fabrication and maintenance, and operational feasibility. The consistency of the ratings also suggests alignment between the intended design requirements and the implemented system, consistent with prior integrative reviews emphasizing that the effectiveness of technology-based physical-activity tools is shaped by implementation conditions [12]. However, because the expert panel was relatively small and recruited using purposive sampling, the validation results should be interpreted as preliminary judgments about practicality rather than generalizable estimates.

The high Safety rating reflects both the projectile-free laser-based structure and embedded control logic that structurally restricts continuous firing. The state-transition-based single-shot mechanism was intended to suppress unintended consecutive emissions under repeated input or operational errors, and this structural safety concept was supported by performance verification and expert evaluation. This emphasis is consistent with developments in modern pentathlon and laser run, where laser pistols are adopted as standard equipment and safety protocols are emphasized [4].

Cost Efficiency was likewise an expected outcome of the design strategy. By using a general-purpose microcontroller, commercially available sensors, and a web-standards-based interface, the system avoids proprietary ecosystems and associated costs. While component prices vary by country, supplier, purchasing volume, shipping fees, and exchange rates, a minimal configuration (e.g., laser module, trigger switch, and power supply) can generally be sourced at low cost (on the order of USD 10 per unit via common online retail platforms). In addition, operating the web-based electronic target entirely in a browser removes software licensing costs. These characteristics align with prior studies highlighting cost reduction as a key advantage of low-cost shooting simulators [13,14]. Beyond cost, the present study contributes a dual-structure design that combines immediate physical feedback from a physical electronic target with logging, aggregation, and visualization via a web-based target system, supporting both physical immediacy and data-driven operation [15].

The positive evaluation of Ease of Fabrication and Maintenance supports the suitability of a modular approach based on readily available components and simplified wiring. This is consistent with implementation perspectives emphasizing that systems should be deployable and modifiable by non-engineers [16] and with reports that teachers adopt digital tools to reduce instructional management burden [17]. At the same time, comparatively conservative ratings in this domain suggest the need for further standardization of supporting materials, including detailed assembly manuals, maintenance guidelines, and consistent operating procedures, reflecting broader discussions that teacher training, accessibility, and infrastructure can determine success in technology integration [18].

In summary, the expert validation supports the practicality of the proposed system's safety-embedded control logic and low-cost, web-based operational structure, while indicating that stronger standardization of fabrication and maintenance documentation and operational protocols may further support dissemination and repeated use.

4.2. Technical Contributions Through Comparison with Prior Studies

The primary technical contribution of this study is the proposed dual-structure architecture, which integrates immediate physical feedback from a physical electronic target with digital recording, aggregation, and visualization via a web-based target while maintaining a low-cost design. Prior low-cost shooting or target systems have largely focused on cost reduction through camera-based laser spot detection and automated score calculation [14]. Extending this line of work, the present system combines LED-based instant feedback for on-site use with browser-based logging and visualization for data management, thereby integrating immediate confirmation and record keeping within a single operational structure.

In addition, the proposed system can be differentiated from two common solution types used in the literature and practice. First, commercial training platforms typically provide integrated hardware and stable operation but are frequently delivered as closed hardware–software ecosystems, which can limit modification, repair, and cost-effective scaling for school-based use. Second, camera- or screen-based simulators emphasized in prior low-cost studies primarily provide digital scoring through image processing and often emphasize screen-based scoring interfaces, which may reduce the salience of physical, on-site confirmation in station-based instruction. By integrating a physical electronic target for on-site confirmation with a browser-based module for logging and visualization, the present dual-structure design aims to combine physical immediacy with data-driven management while remaining reproducible with off-the-shelf components.

From a performance and reliability perspective, the verification results and expert ratings for functionality indicate consistent operation under the tested conditions. The reference-value calibration, threshold- or ratio-based decision rules, and hold-time validation can be interpreted as practical measures intended to reduce false detections under environmental variability, including changes in ambient illumination, surface reflections, and camera-specific characteristics. In laser spot detection research, region-of-interest search, filtering, and robust feature extraction based on spot characteristics have been proposed to mitigate background-light interference [19]. In this context, the present approach can be characterized as an event-detection structure designed for field variability rather than an idealized laboratory-only mechanism.

The control logic that suppresses duplicate inputs and enforces a one-shot-to-one-record relationship further supports consistency of event-level data in educational and recreational environments, where operational control is typically lower. In addition, LED feedback and web-based visualization function as augmented feedback by enabling immediate confirmation of outcomes and longitudinal tracking through accumulated records. Motor learning research has reported that augmented feedback can support performance regulation and that delivery conditions, including knowledge of results and knowledge of performance, can influence outcomes [20]. While the present system provides immediate knowledge of results with minimal hardware and supports practice through cumulative recording and visualization, learning effects and motivational variables were not measured and should be examined in future work.

Finally, the web-based logging and visualization design aligns with the view that the value of technology lies not only in device ownership but also in reorganizing operational structures for recording, management, and feedback [12,21]. Critical discussions in physical education similarly emphasize that effectiveness depends on how technology is integrated with instructional, learning, and operational conditions [12]. Reports that teachers adopt digital tools to simplify management tasks such as record keeping, feedback provision, and monitoring further suggest that the present emphasis on reducing operational burden is consistent with field-based motivations for adoption [17]. In summary, the technical contributions of this study are threefold: (1) a low-cost, open, dual-structure architecture that combines a physical electronic target with a web-based electronic target; (2) robustness-oriented detection and control logic designed for field variability in school physical education and recreational environments; and (3) a web-based logging and visualization structure that integrates operational control, event-level recording, and feedback functions within a single implementation model.

While the proposed detection and control logic demonstrated reliable operation under the tested conditions, certain technical limitations remain that may be addressed in future improvements. In particular, the present system adopts a simple threshold-based detection algorithm to ensure reliable real-time processing on a low-cost microcontroller. More advanced algorithms exploiting the pulsed characteristics of the laser signal may further improve robustness under varying ambient light conditions and could enable more reliable operation in outdoor environments.

Because the laser pulse duration used in this system is approximately 10 ms, reliable detection generally requires a camera frame rate that allows at least one frame to capture the laser event. In practice, commonly available smartphone or tablet cameras operating at approximately 30–60 fps were sufficient to capture the laser spot under the tested conditions.

4.3. Practical Implications for Educational and Recreational Deployment

The primary practical implication of the proposed system is not maximal shooting precision but the ability to redesign participation and operational structures in a deployment-friendly manner. In station-based or small-group rotation formats, roles can be distributed beyond the shooter (e.g., recorder, safety monitor, equipment manager, feedback provider). Such role differentiation aligns with cooperative learning role assignments (e.g., recorder, equipment manager, and coach) [22,23] and may broaden participation pathways for individuals who might otherwise be marginalized in performance-centered activities. This orientation is consistent with inclusive physical education perspectives that emphasize expanded participation opportunities and experiential access [24].

The system's low-cost, modular design also enables teachers and program operators to adapt and refine the technology to local constraints rather than treating it as a fixed product. Because stable technology integration is shaped by interactions among teachers' knowledge, self-efficacy, beliefs, and school culture, rather than equipment access alone, the open design may function as a low-barrier tool supporting practitioner agency [25]. Simplified hardware assembly and inspection, together with a browser-based interface, further facilitates gradual adoption and iterative adjustment during instruction or program operation.

For deployment in school and youth recreational environments, explicit safety operation guidelines remain essential. Safety regulations in laser sports repeatedly emphasize range setup, equipment handling, and operational procedures [4], and these requirements are heightened in educational contexts where safety responsibility rests primarily with the operator. Accordingly, deployment would benefit from protocols specifying laser class selection (preferably low-risk classifications such as Class 1 when feasible), emission duration limits and adherence to single-shot firing principles, fixation of firing lines and target orientation, rules for maintaining safe states during and after shooting, and advance briefings for participants and guardians. Checklist-based guidance can strengthen accountability and translate safety responsibilities into standardized procedures [4].

Overall, the proposed system can be viewed as an implementation model integrating participation structure, operational design, and safety management rather than as a standalone technological artifact. This view aligns with discussions emphasizing that effectiveness depends not only on functionality but also on integration with implementation conditions [18]. Future work should accumulate application cases across school levels and recreational contexts and refine standardized deployment models incorporating role differentiation, safety protocols, and operational scenarios.

Although the present study demonstrates the feasibility and practical applicability of the proposed laser shooting system, several limitations of the system evaluation should be acknowledged. First, the experimental evaluation was conducted under controlled indoor conditions with predefined shooting distances and lighting environments, which may not fully represent all possible deployment contexts. Second, the web-based target module relies on camera-based detection using consumer mobile devices, and therefore detection performance may vary depending on device-specific characteristics such as camera frame rate, sensor sensitivity, and resolution. Third, the expert validation involved a relatively small panel of specialists recruited through purposive sampling; accordingly, the results should be interpreted as preliminary assessments of system practicality rather than broadly generalizable evaluations. Future studies should examine system performance under a wider range of environmental conditions and conduct larger-scale field trials in real educational settings.

5. Conclusions

This study designed and implemented a low-cost laser shooting system for educational and recreational contexts to address safety, cost, and facility-access constraints that have limited the use of shooting activities in school physical education and leisure environments. The system comprises a laser-gun module with single-shot firing control, a physical electronic target integrating an illuminance sensor, a Fresnel lens, and RGB LED feedback, and a web-based electronic target that performs camera-based hit detection and scoring using web technologies. By employing a low-power, projectile-free laser structure with pulse-limited emission and by using general-purpose components and web standards, the proposed design supports safer operation while reducing cost and barriers to adoption.

Technical verification under the predefined test conditions confirmed stable operation across the three modules, including single-shot control, hit detection on the physical target, and score calculation on the web-based target. Expert validation also indicated consistently high evaluations in safety, cost efficiency, functional completeness, and field applicability. Taken together, these findings suggest that the proposed system can serve as a practical alternative for school physical education classes, after-school activities, and recreational programs where conventional shooting equipment is difficult to deploy.

Several issues remain for further study. Future research should (i) examine usability and user-level outcomes using established frameworks such as ISO 9241-11 [26], (ii) evaluate robustness across a wider range of environmental conditions (e.g., lighting, reflections, distance, and device-specific camera characteristics), and (iii) adopt multi-round expert review designs (e.g., Delphi) to more systematically examine consensus formation and refine standardized deployment protocols.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app16073347/s1, Table S1: Expert validation questionnaire items; Code S1: Firmware source code for the laser-gun module; Code S2: Firmware source code for the physical electronic target module.

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