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Smart Fire Alarm and Visual Guidance System for Inclusive Campus Safety: A Technology Management Perspective

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Abstract

Conventional emergency evacuation infrastructures in academic institutions rely almost exclusively on acoustic warning systems paired with basic, binary blinking strobes, creating critical safety disparities for hearing-impaired/hard-of-hearing students. In high-density environments like the University of Cebu – Main Campus, relying solely on sound-based alerts compromises occupant safety and violates national and international statutory accessibility mandates. This study designed, constructed, and evaluated a localized, non-networked Smart Fire Alarm and Visual Guidance System to provide equitable, real-time emergency notifications and directional egress guidance for hearing-impaired/hard-of-hearing individuals. Utilizing a descriptive-developmental research design, an independent microcontroller-based system (Arduino Uno) was engineered with multi-sensor arrays (smoke/heat), xenon strobes (1.2 Hz), 105 dB buzzers, and addressable RGB LED matrix displays. Evaluation data were gathered from 70 purposively selected participants (40 hearing-impaired/hard-of-hearing students, 20 safety experts, and 10 facility administrators). Quantitative metrics were assessed via David Garvin's Dimensions of Quality and the Technology Acceptance Model (TAM) on 5-point Likert scales, complemented by One-Way ANOVA inferential testing ($\alpha = 0.05$) and qualitative focus group discussions. Baseline evaluations confirmed that existing campus systems lacked visual warning capabilities, resulting in an average 3.82-minute evacuation delay for hearing-impaired/hard-of-hearing students. Prototype field testing demonstrated near-instantaneous sensor-to-output activation latency (1.18 seconds). The overall system quality was rated as Outstanding (μ=4.815, SD=0.18), with high conformance ($\mu = 4.93$) to RA 9514, RA 7277, and ISO 21542. Overall system acceptability achieved a Very Highly Acceptable composite score ($\mu = 4.882$, SD= 0.15). One-Way ANOVA revealed no statistically significant differences ($p > 0.05$) across respondent groups for quality ($p = 0.561$) or acceptability ($p = 0.294$). The non-networked dual-sensory system successfully eliminates evacuation lag for hearing-impaired students. Localized hardware automation delivers cost-effective, fail-safe life safety protection, establishing a validated framework for inclusive smart campus infrastructure.

Keywords: Technology Management, Inclusive Safety, Fire Alarm, Visual Guidance, Hearing-Impaired Egress, Arduino Uno, TAM, Universal Design

1. Introduction

Ensuring the physical safety of academic environments is a foundational responsibility for educational institutions globally. As colleges and universities transition into "smart campuses", integrating modern technology into emergency response frameworks has become essential to meeting regulatory standards and protecting human life. While conventional fire detection and response systems adequately serve most of the academic population, they frequently fail a critical demographic: individuals who are hearing-impaired or hard-of-hearing. Relying exclusively on acoustic alerts creates a dangerous gap in emergency communications, putting vulnerable lives at risk. According to a global safety study by the World Health Organization (2019), individuals with disabilities face disproportionately higher risks during disasters due to inadequate or non-inclusive warning systems.

In a university setting that values diversity, emergency preparedness frameworks must be universally accessible, regardless of the physical capabilities of students and staff. The University of Cebu handles high-density, daily foot traffic across multi-story buildings actively with laboratory work, classroom activities, and project-based learning. Standard alarm infrastructures relying heavily on sirens, basic binary blinking strobes, and voice announcements fail to promptly alert hearing-impaired individuals, resulting in prolonged evacuation lag times during drills. Addressing this safety disparity is not merely a matter of regulatory compliance; it is an ethical imperative to ensure equitable protection for the entire university community.

To address this challenge, this study proposes the design and construction of an independent fire alarm and visual guiding system utilizing the Arduino Uno microcontroller. While modern safety trends lean heavily toward the Internet of Things (IoT) and Cloud-based remote monitoring, network dependencies introduce vulnerabilities. During catastrophic emergencies, power outages and network failures frequently compromise internet connectivity. By utilizing a non-networked microcontroller, the proposed system operates as a localized, fail-safe automation tool. This architectural choice minimizes maintenance complexities, reduces deployment costs, and guarantees operational reliability, making it an ideal framework for resource-constrained academic environments.

Operating as a standalone controller, the Arduino Uno processes real-time input from localized smoke and heat sensors to trigger immediate, multi-sensory outputs. Upon detecting particulate matter or thermal anomalies exceeding predefined thresholds, the system simultaneously activates acoustic buzzers, high-visibility strobe lights, and directional evacuation instructions on LED signboards. This dual-signal approach ensures that individuals unable to hear the acoustic alarm are immediately directed toward safe exits via distinct visual cues.

Equations

The mathematical model for a one-way ANOVA splits the total sum of squares (SS_{total}) into variance between the distinct evaluation groups ($SS_{between}$) and variance within those groups (SS_{within}):

$$SS_{total} = SS_{between} + SS_{within} \quad (1)$$

By calculating the variance between group means relative to the variance within groups, the F-statistic is derived:

$$F = \frac{MS_{between}}{MS_{within}} \quad (2)$$

Results

Baseline Assessment of Existing Systems

Field evaluation of the current building safety infrastructure revealed an exclusive reliance on conventional, zone-based acoustic warning devices. Baseline evaluation metrics gathered from 70 participants are summarized below:

Table 1: Baseline Assessment of Existing Systems

Assessment Parameter	Frequency (f)	Percentage (%)	Summary of Field Findings & Baseline Gaps
Acoustic-Only Alarm Signals	70	100%	Alarm consists strictly of sirens and bells (105 dB)
Visual Alarm Infrastructure	0	0%	Total absence of illuminated directional signage
Evacuation Autonomy (Hearing-Impaired)	0	0%	Hearing-impaired students cannot evacuate without a third-party visual prompt.
Evacuation Latency Disparity	-	-	Hearing-impaired students experience a 3.82-minute lag compared to normative peers.

Technical Specifications and Quality Evaluation

The proposed hardware specs were benchmarked against David Garvin's Dimensions of Quality. The sensor-to-output activation latency averaged 1.18 seconds across testing.

Table 2: Technical Specifications and Component Justification

System Module	Selected Component	Operational Parameter	Literature & Engineering Justification
Microcontroller	Arduino Uno R3	ATmega328P, 16 MHz, 5V Logic	Low cost, high processing speed, zero OS lag.
Smoke Sensor	MQ-2 Photoelectric	Threshold: >400 ppm particulate	Detects combustion gases and dense smoke.
Thermal Sensor	DS18B20 / IR Flame	Threshold: >57°C or IR spectrum	Multi-sensor array prevents false alarms.
Acoustic Output	Piezoelectric Buzzer	105 dB output at 1 meter	Auditory alert for normative building occupants.

System Module	Selected Component	Operational Parameter	Literature & Engineering Justification
Microcontroller	Arduino Uno R3	ATmega328P, 16 MHz, 5V Logic	Low cost, high processing speed, zero OS lag.
Visual Strobe	Xenon Flasher Unit	1.2 Hz Flash Rate, 80 Candela	Optical intrusion meeting ISO 21542 accessibility standards.
Directional Matrix	RGB LED Matrix Panel	16×32 P6 Panel, 1200 cd/m^2	Dynamic vector lighting visible through smoke.
Power Autonomy	LiFePO4 Battery Bank	12V, 7.2Ah Backup System	Guarantees >12-hours operational uptime off-grid.

Inferential Analysis Across Stakeholders

To test significant variations in evaluation ratings among the three respondent groups (40 Students, 20 Experts, and 10 Administrators), a One-Way Analysis of Variance (ANOVA) was executed at $\alpha = 0.05$.

Table 3: One-Way ANOVA Summary Comparing Ratings Across Respondent Groups

Evaluation Variable	Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Square (MS)	Computed F-value	p-value	Decision on H_o
System Quality (Garvin)	Between Groups	0.038	2	0.019	0.584	0.561	Accept H_o
	Within Groups	2.181	67	0.033			
	Total	2.219	69				
System Acceptability (TAM)	Between Groups	0.062	2	0.031	1.248	0.294	Accept H_o
	Within Groups	1.662	67	0.025			
	Total	1.724	69				

Critical $F_{(2,67)}$ at $\alpha = 0.05$ is 3.134.

Conclusion

Relying exclusively on conventional acoustic fire alarms in multi-story academic facilities creates an unacceptable safety disparity for hearing-impaired occupants, resulting in significant evacuation delays. Field evaluations demonstrate that an independent, non-networked Smart Fire Alarm and Visual Guidance System—powered by an Arduino Uno microcontroller with multi-sensor arrays, xenon strobes, and dynamic RGB LED directional displays—successfully eliminates evacuation lag by providing rapid, localized, multi-sensory emergency alerts.

Operating independently of cloud networks and main power grids via a fail-safe battery backup, the standalone system achieves near-instantaneous hazard activation (1.18 seconds), Outstanding overall quality ($\mu = 4.815$), and full compliance with statutory accessibility and fire safety mandates (RA 9514, RA 7277, and ISO 21542). Uniformly endorsed as Very Highly Acceptable ($\mu = 4.882$) across students, technical experts, and facility administrators with no statistically significant differences ($p > 0.05$), this localized hardware automation offers a cost-effective, fail-safe life safety solution that establishes a validated benchmark for inclusive smart campus infrastructure.

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