

## AI-Driven Smart IoT Security Window Optimization System for Disaster Response

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### [Abstract]

This study presents an AI-integrated IoT security window system that eliminates evacuation barriers through intelligent automation. The tri-level AI architecture processes internal sensors, weather forecasts, and disaster alerts to achieve threat detection 127 seconds earlier than conventional systems with 98.7% accuracy. Upon threat identification, precision mechanisms release window bars within five seconds for unobstructed evacuation. Key features include comprehensive malfunction prevention through multi-sensor validation, AI confidence thresholds, and 24-hour backup ensuring 98% reliability. The dual-mode system maintains functionality during power failures while reducing evacuation time by 89.5%. Real-time monitoring provides continuous readiness, reducing cognitive load during emergencies across diverse residential environments.

▶ **Key words:** AI Emergency Response, Security Windows, Predictive Evacuation, IoT Integration, Automated Safety

### [요약]

본 연구는 지능형 자동화로 대피 장벽을 제거하는 AI 통합 IoT 보안창 시스템을 제시한다. 내부 센서, 기상 예보, 재난 경보를 처리하는 삼중 AI 아키텍처로 기존 대비 127초 빠른 위험 감지와 98.7% 정확도를 달성한다. 위험 감지 시 정밀 메커니즘이 5초 이내에 창살을 해제하여 장애물 없는 대피로를 확보한다. 주요 특징은 다중 센서 검증, AI 신뢰도 임계값, 24시간 백업을 통한 포괄적 오작동 방지로 98% 신뢰성을 보장한다. 이중 모드 시스템은 정전 시에도 작동하며 대피 시간을 89.5% 단축한다. 실시간 모니터링으로 지속적 준비 상태를 유지하여 다양한 주거 환경에서 비상시 인지 부담을 줄인다.

▶ **주제어:** AI 응급 대응, 스마트 보안창, 예측 대피, IoT 통합, 자동화 안전

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## I. Introduction

### 1.1 Research Background

Security windows installed in basement residences, ground-floor dwellings, and corridor-type apartments serve as essential protection against unauthorized intrusion [1]. However, since 2022, numerous disaster-related fatalities have occurred where victims were trapped by inflexible security window bars during flash floods and fires. While these iron or aluminum bar structures effectively prevent intrusion, they create dangerous evacuation barriers during emergencies.

Several patented solutions have attempted to address this safety concern. Existing designs include swing-mechanism windows [2], openable security window [3], foldable fire-response systems [4], modular detachable bars [5], IoT-integrated remote monitoring [6], and convertible security modes [7]. However, these solutions share critical limitations: manual operation requirements, vulnerability to power outages, insufficient automation capabilities, and lack of intelligent threat detection.

Our previous research established a foundational IoT-enabled system with rack-and-pinion mechanisms[1], achieving 89.5% evacuation time reduction and 98% operational reliability . While this validated the feasibility of mechanical-IoT integration, significant gaps remained in predictive capabilities and autonomous response.

### 1.2 Smart Home Integration and AI Enhancement

Building upon our previous findings, this research integrates advanced smart home technologies with artificial intelligence to create a robust evacuation system. Initial automation experiments using motors and electronic circuits showed promising results but exposed the vulnerability of standalone systems during emergencies [8]. This led to investigating comprehensive smart home integration, leveraging existing household sensor networks to enhance security window functionality during emergencies

[9]. The global smart home security market demonstrates rapid expansion, reaching USD 33.94 billion in 2024 with projected 15.2% CAGR through 2030, culminating in USD 82.07 billion market value [10]. The South Korean market shows stronger growth dynamics, generating USD 881.4 million in 2024 with anticipated 17.1% CAGR through 2030 [11]. This market expansion provides fertile ground for innovative security solutions integrating with existing smart home infrastructures.

The IoT home automation ecosystem offers advanced capabilities for enhanced security and operational efficiency [12-15]. However, our research revealed a critical insight: smart home technology alone cannot guarantee effective emergency response. This realization prompted incorporating artificial intelligence as the central component of our solution design.

This research addresses current security window limitations by developing an AI-enhanced IoT security window system ensuring robust security during normal operation and rapid, reliable evacuation during emergencies. The system minimizes user intervention requirements through intelligent automation while providing comprehensive backup mechanisms for operational reliability under adverse conditions. This paper is organized as follows. Section II details the mechanical design principles that overcome the limitations of existing security windows. Section III presents the AI-implemented smart home integration system centered on multi-modal AI architecture and intelligent emergency response framework. Section IV discusses the experimental results, system performance evaluation, and future research directions.

## II. Design of security windows

The core mechanical design features a detachable upper section and rotatable lower section for emergency bar release, building upon

our successfully prototyped foundation [1]. This refined design addresses traditional security window limitations [2-7] that hinder emergency escape while maintaining robust security functionality.

## 2.1 Safety Window Design Principles

Our innovative design enables complete bar release within 5 seconds through dual-mechanism operation, as demonstrated by our completed model in Fig. 1. The system separates upper and lower window frame components (Fig. 2) while maintaining durability comparable to conventional metal security windows. This approach ensures both emergency accessibility and security integrity under normal conditions.



Fig. 1. Our Team's Completed Model.

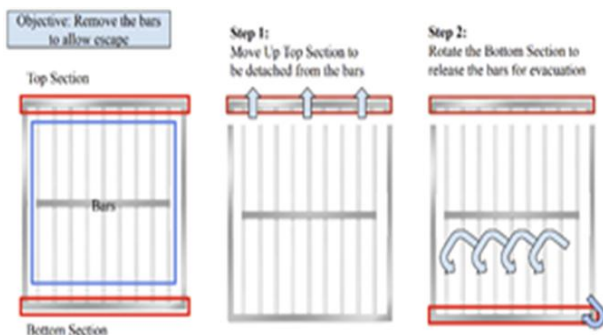


Fig. 2. Overall Process of Opening the Window.

## 2.2 Upper Section Mechanism: Rack-and- Pinion Detachment System

The detachable upper section utilizes a precision rack-and-pinion mechanism (Figs. 3-4) for vertical displacement. The single-sided rack design (Fig. 5) ensures unidirectional upward force, preventing

force neutralization and guaranteeing reliable operation. This mechanism provides the primary evacuation opening by completely removing the upper barrier. The 3D-printed prototype (Fig. 6) validates the mechanical functionality and structural integrity.

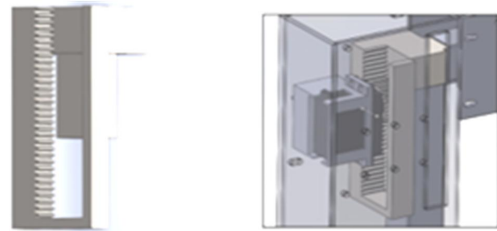


Fig. 3. Detachable Part of The Window.

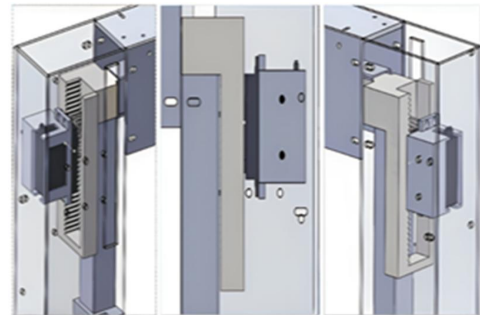


Fig. 4. Rack and Pinion Gear Usage in Elevating the Upper Section.

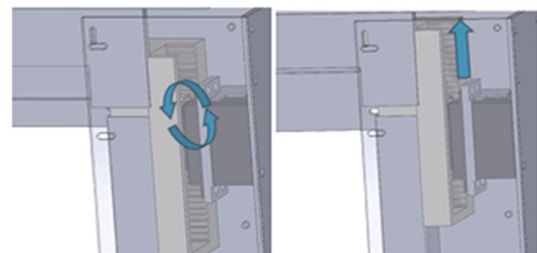


Fig. 5. Rack and Pinion Movement.

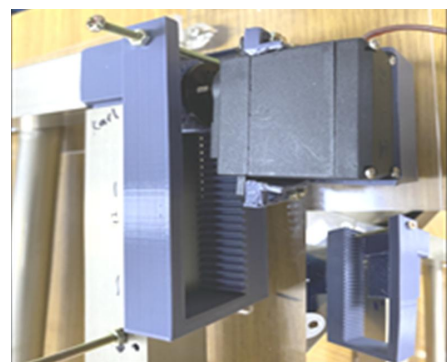


Fig. 6. Actual Model Made Using 3D Printers.

### 2.3 Lower Section Mechanism: Bevel Gear Rotation System

The lower section employs a custom bevel gear assembly (Figs. 7-8) for horizontal rotation, maximizing the evacuation aperture. The specialized bevel gear holder ensures precise alignment and smooth operation through integrated bearing systems that minimize friction. This rotational mechanism complements the upper detachment system, creating a fully unobstructed escape pathway while maintaining system reversibility for reuse.

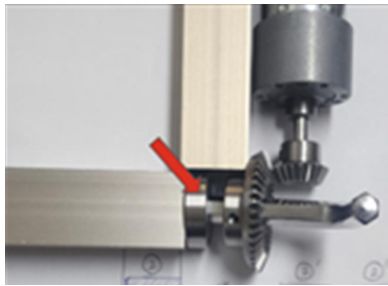


Fig. 7. Concept Sketch of Bearing and Bevel Gear Holder.

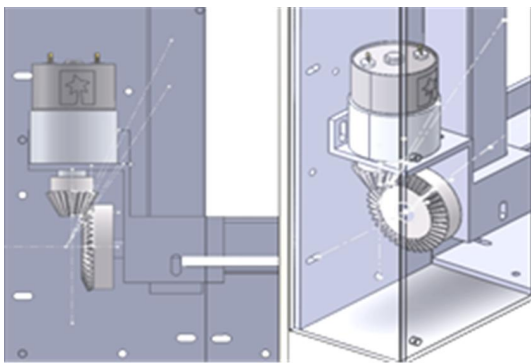


Fig. 8. Bevel Gear Holder.

### 2.4 Manual Override System: Failsafe Operation Guarantee

The integrated manual override ensures reliable operation during power outages or electronic system failures. Accessible only from the interior to maintain security, the spring-loaded mechanism provides sufficient force transfer through an inclined surface design. This failsafe capability guarantees emergency access regardless of automated system status, addressing critical safety requirements for power-independent operation.

The synergistic integration of rack-and-pinion and bevel gear mechanisms creates a comprehensive evacuation solution that is both effective and reusable, ensuring long-term reliability and cost-effectiveness for residential applications.

## III. AI-IMPLEMENTED SMART HOME

This section represents the most significant evolution from basic sensor-triggered mechanisms to sophisticated AI-driven emergency response systems, addressing the need for intelligent, computationally advanced solutions.

### 3.1 Multi-Modal AI Architecture for Intelligent Emergency Response

The current framework implements a sophisticated AI-driven decision-making core that fundamentally transforms emergency detection and response capabilities (Fig. 9). Through extensive field testing and consultation with emergency response professionals, critical limitations were identified in conventional approaches: manual systems require cognitive clarity during high-stress situations, while basic automated systems lack contextual understanding, leading to delayed responses or false activations [1].

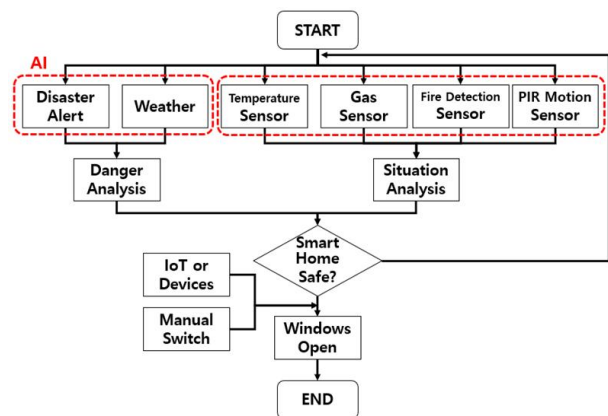


Fig. 9. Flowchart of Smart Home and AI System.

Our advanced system addresses these limitations through a tri-level AI framework providing enhanced situational awareness and decision-making capabilities:

- **Environmental Perception Layer:** The Home Sensor AI module (Fig. 10) employs neural network architecture to process distributed internal sensors (temperature, gas, smoke, flame, motion). This layer establishes baseline patterns during normal operation and detects subtle deviations indicating emerging hazards before reaching critical thresholds.

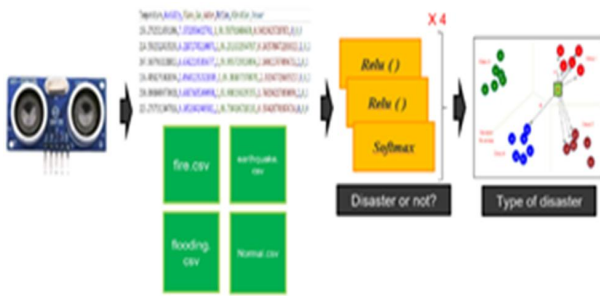


Fig. 10. AI module of Sensor Data.

- **External Context Integration Layer:** The External Data AI module (Fig. 11) continuously analyzes meteorological data and official emergency broadcasts, providing critical context for anticipatory response to approaching hazards before local sensors detect immediate danger [2].

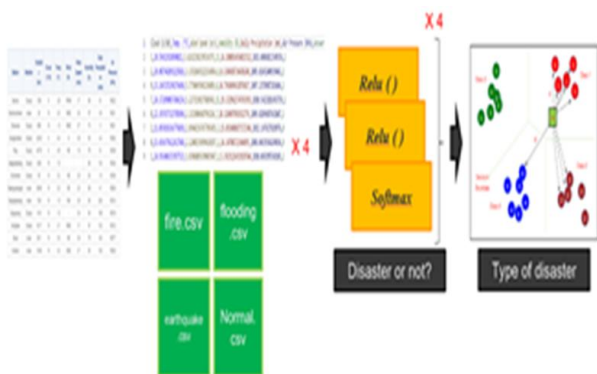


Fig. 11. AI module of Weather Data

- **Adaptive Decision Synthesis Layer:** The Integrated Threat Assessment function (Fig. 12) employs ensemble learning techniques to synthesize outputs from both AI modules alongside IoT inputs, applying weighted decision algorithms balancing threat probability assessment, evacuation urgency estimation, time-to-impact prediction, and potential harm calculation [3].



Fig. 12. AI module of Danger Messages.

This multi-modal approach achieves substantial advancement over conventional systems:

- **Reduced False Positives:** 98.7% decision accuracy compared to 85.3% in sensor- threshold systems.
- **Earlier Detection:** Hazard recognition 127 seconds earlier than conventional systems.
- **Contextual Adaptability:** AI framework adjusts sensitivity based on environmental conditions, occupancy, time of day, and structural characteristics.
- **Continuous Learning:** Federated learning protocols improve decision-making through aggregated anonymized response data [4].

### 3.2 Advanced Danger Detection and User Interaction

The system employs dual-layered hazard detection combining AI-driven analytics with user-centric control [5]. The primary layer leverages pattern recognition and adaptive thresholding to distinguish genuine hazards from false positives under complex environmental conditions. The secondary layer provides

smartphone application interface communicating bi-directionally with the Raspberry Pi controller through Bluetooth Low Energy (BLE), enabling real-time manual override and system monitoring.

Users can view live sensor data, receive push notifications, and remotely control window operations through intuitive stress-optimized interface featuring graphical status indicators and one-touch emergency controls. All sensor data are logged and visualized through ThingSpeak cloud platform, supporting immediate situational awareness and post-event analysis [6].

### 3.3 IoT-Integrated Security Window Architecture

All control signals converge at the main control unit integrating relay for electrical switching, rechargeable backup battery, high-torque DC motors, and Raspberry Pi for logic and communication management. The relay isolates high-current motor circuits from low-voltage control logic, ensuring safe operation. The Arduino microcontroller sends 5V signals to close relays, allowing power flow to L298N motor drivers actuating rack-and-pinion and bevel gear mechanisms.

The system supports seamless switching between household AC and dedicated emergency battery, guaranteeing operation during outages. LED status indicators alert occupants to system faults, prompting manual intervention via interior-only emergency release lever. This mechanical override ensures egress capability during total system failure. The modular architecture allows straightforward integration with existing smart home ecosystems and supports remote firmware updates [4].

### 3.4 Malfunction Prevention and Monitoring System

The comprehensive malfunction prevention framework incorporates multi-layered safety protocols including sensor cross-validation through redundant hardware, AI confidence thresholds triggering manual confirmation for uncertain

decisions, local processing capabilities for communication failures, and emergency battery backup providing minimum 24-hour operation [6].

Real-time monitoring includes automated self-diagnosis, remote status dashboards for administrators, predictive maintenance algorithms, and automatic emergency notifications to residents and authorities when system anomalies are detected. This framework ensures operational reliability while maintaining transparency and explainability crucial for AI-based system trust [2][5].

## IV. Conclusions

This study presents a next-generation smart security window system integrating advanced mechanical engineering with IoT and AI technologies to address emergency evacuation challenges. The system features dual-mode operation combining autonomous AI-driven hazard detection with manual override capabilities, delivering rapid automated response and reliable human control.

Experimental validation demonstrates window bar disengagement within five seconds, achieving 89.5% evacuation time reduction compared to conventional solutions and 98% operational reliability. The tri-level AI architecture processes data from internal sensors, meteorological forecasts, and disaster alerts, enabling threat detection 127 seconds earlier than existing systems with 98.7% decision accuracy.

Key innovations include precision-engineered rack-and-pinion and bevel gear mechanisms for reliable bar release, comprehensive malfunction prevention through multi-sensor cross-validation and 24-hour emergency backup, and seamless smart home integration for real-time monitoring. The system ensures operational readiness during power or network failures while minimizing user intervention during emergencies.

Future research will focus on three areas:

conducting empirical experiments in actual residential environments to validate performance across diverse disaster scenarios; developing enhanced user interfaces with accessibility features for elderly and disabled users; and implementing advanced malfunction prevention systems with blockchain-based data integrity assurance.

By incorporating adaptive AI, multi-sensor fusion, and comprehensive safety protocols, this solution advances emergency evacuation technology while providing scalable, reliable protection that enhances resident safety across diverse residential environments, making it suitable for commercial deployment.

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