

## Smart Emergency Window System for Rapid Evacuation in Disasters

Dahee Chun\*, Dawit Chun\*, Woohyeon Hwang\*\*

\*Student, School of Data Science &amp; Artificial Intelligence, TAEJAE University, Seoul, Korea

\*\*Professor, School of Robot &amp; Automation Engineering, Dongyang Mirae University, Seoul, Korea

## [Abstract]

This paper presents an efficient emergency operable security window system that addresses the limitations of conventional security windows during disasters. The system integrates a rack-and-pinion mechanism with IoT technology, enabling automatic release of window bars within three seconds upon detecting hazards. Experimental results demonstrate 89.5% reduction in evacuation time and 98% operational reliability compared to existing solutions. The dual-mode system combines sensor-driven automation with manual override capabilities, making it effective for vulnerable populations in multi-occupancy facilities. The design is expected to bring cost savings over time.

▶ **Key words:** Security Window, Emergency Evacuation, Smart Home, IoT, Automated Control, Disaster Response

## [요 약]

본 논문은 재난 상황에서 기존 방법상의 한계를 극복하는 효율적인 비상 개폐식 방법창 시스템을 제안한다. 랙-피니언 메커니즘과 IoT 기술을 통합하여 화재나 홍수와 같은 위험 감지 시 3초 이내에 창살을 자동으로 해제한다. 실험 결과, 기존 방법 대비 대피 시간을 89.5% 단축하고, 98%의 작동 신뢰성을 입증했다. 센서 기반 자동화와 수동 비상 해제 기능을 결합한 이중 모드 시스템은 다중 거주 시설과 취약 계층 보호에 효과적이며, 기존 건물 구조에 쉽게 장착할 수 있는 장점이 있다. 이 시스템은 장기적으로 비용 절감 효과를 가져올 것으로 예상된다.

▶ **주제어:** 방법창, 응급 대피, 스마트홈, 사물인터넷, 자동 제어, 재난 대응

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- First Author: Dahee Chun, Corresponding Author: Woohyeon Hwang
  - \*Dahee Chun (daheechun1@gmail.com), School of Data Science & Artificial Intelligence, TAEJAE University
  - \*Dawit Chun (dchun4748@gmail.com), School of Data Science & Artificial Intelligence, TAEJAE University
  - \*\*Woohyeon Hwang (priwoo@naver.com), School of Robot & Automation Engineering, Dongyang Mirae University
  - Received: 2025. 03. 05, Revised: 2025. 04. 08, Accepted: 2025. 04. 08.

## I. Introduction

Security windows are widely installed in underground residential facilities, commercial buildings, and corridor-type apartments to deter unauthorized access and protect valuable assets. Typically fabricated from steel and installed either within or on the exterior of the window frame (see Fig. 1), these windows perform well as security measures. However, their inherently closed structure poses a critical challenge during emergencies such as fires or floods: without specialized tools, the removal of window bars is extremely difficult, thereby hindering rapid evacuation.



Fig. 1. Installation of general security windows

Recent studies have addressed various aspects of emergency evacuation systems, highlighting both advancements and persistent gaps in the field. Jeong et al.[1] designed a safety mechanism for automotive power windows using Hall sensors, demonstrating the potential of sensor-based actuation in rapidly releasing window components. This approach showcases the feasibility of integrating smart technologies into traditionally mechanical systems for enhanced safety.

Comprehensive reviews on door lock security systems[2] and analyses of security bars[3] have underscored both the strengths and limitations of

current physical security measures. These studies emphasize the need for a balance between security and safety, particularly in emergency situations. Tarmizi et al.[4] proposed an innovative Emergency Exit Lockset for Grille Doors or Windows, offering promising ideas for enabling fast detachment of locking brackets under emergency conditions. Their design incorporates both manual and automatic detachment systems, addressing the critical need for reliable escape mechanisms.

On the evacuation systems side, several studies have proposed IoT-based and smart evacuation frameworks. Kanangkaew et al.[5] developed a real-time fire evacuation system integrating Building Information Modeling (BIM) and Augmented Reality (AR), while Nguyen et al.[6] presented a smart evacuation guidance system for large buildings. Both studies illustrate how modern information technologies can optimize evacuation routes and enhance safety during emergencies.

IoT-based systems that track occupant locations and environmental hazards have further emphasized the benefits of integrating sensor networks into evacuation planning. Zualkernan et al.[7] proposed an IoT-based Emergency Evacuation System that utilizes wireless sensors to detect dangers and guide evacuees to safe areas. Ji et al.[8] developed an Intelligent Indoor Emergency Evacuation System using IoT-Enabled Wireless Sensor Networks (WSNs) for smart buildings, demonstrating improved response times and navigation efficiency.

Recent work on fire evacuation and control systems has shown how real-time data can guide occupants to safe exits in a dynamic environment. Mohammadiounotikandi et al.[9] presented a Fire Evacuation and Control System in Smart Buildings based on the Internet of Things and a hybrid intelligent algorithm, showcasing the potential of AI-driven approaches in emergency management. Fang et al.[10] explored Building Fire Evacuation from an IoT-Aided Perspective in the 5G Era, highlighting the potential of high-speed,

low-latency networks in enhancing evacuation systems.

Advanced simulation studies and architectural analyses have shown that the design and placement of emergency exit signs significantly influence evacuation speed[11]. Complementary frameworks, such as IoT-based emergency evacuation systems developed in PhD research[12] and comprehensive disaster response models for smart buildings[13], further validate the need for a holistic approach to emergency management.

Recent contributions on IoT and AI-based fire evacuation systems[14] and cellular automata-based evacuation modeling[15] offer additional insights into how intelligent guidance can shorten evacuation time and improve safety. These studies demonstrate the potential of combining advanced algorithms with real-time data to create more effective and adaptive evacuation strategies.

Recent advancements in IoT-based safety systems have introduced innovative approaches to hazard detection and response. Kok et al.[16] developed an energy-efficient IoT hazard detection system with adaptive monitoring that reduces power consumption while maintaining high detection accuracy. Alandjani[17] addressed cybersecurity challenges through a quantization-aware framework for IoT environments. Upadhyaya et al.[18] designed a multi-sensor system integrating thermal, gas, and motion sensors for real-time hazard detection, significantly improving response times compared to conventional systems.

Despite these advances, a notable gap remains in the integrated design of a security window that can be mechanically released rapidly during emergencies while interfacing seamlessly with smart home and IoT systems. This paper addresses this gap by proposing an innovative emergency operable security window system that combines a robust, synchronized rack-and-pinion mechanism for rapid mechanical release with an IoT-based smart home framework.

Our system is designed to automatically open the window within three seconds upon detecting hazards (e.g., fire or flood) and to enable real-time remote monitoring and control via a smartphone application. This integrated approach not only maintains building security during normal operations but also ensures rapid, safe evacuation during emergencies. By unifying mechanical reliability with smart connectivity, our system advances evacuation safety for vulnerable populations in high-density facilities, addressing limitations in current emergency signage design and evacuation protocols.

## II. Design of security windows

### 1. Definition of design problem

Existing operable security windows generally fall into two categories. The first type is designed for indoor operation (Patent application number: 1020160137280). These windows use a sliding door mechanism that enables manual operation for ventilation and emergency escape, are equipped with reinforced locking devices, and can be easily installed on various building types. However, they occupy indoor space and, despite the presence of springs between the window bars that facilitate movement, they are not robust enough for emergency conditions due to their vulnerability to high-impact forces.

The second type of security window is designed for exterior operation (Patent AN: 1020060060638). In this design, the window operates from the interior like a conventional door that is pulled open; it employs strong materials and locking devices and improves environmental factors such as wind, moisture, and noise. Although fabrication and installation are straightforward, these windows also occupy considerable space, are heavy and difficult to rotate automatically, and require additional locking mechanisms. Moreover, an automated function—such as using a servo motor

for rotation—is necessary but is not provided in the current design.

Table 1 provides a comprehensive comparison of existing patents, highlighting their key features, advantages, and limitations. As shown in the table, each design offers specific benefits but also presents notable drawbacks that limit their effectiveness in emergency situations.

Table 1. Patent Comparison (Application Number)

Patent A.N.	Type	Key Features	Limitations
1020160137280	Indoor Operation	Sliding mechanism, manual operation, reinforced locking	Occupies indoor space, vulnerable to impact
1020060060638	Exterior Operation	Door-like opening, strong materials, environmental protection	Heavy, difficult to automate, space-consuming
1020060112987	Foldable Grille	Detachable lower section, "javara" method	Narrow escape opening, complex manual adjustments
1020150028401	IoT Security Window	Smartphone alerts, intrusion detection	Limited remote operation, sensor reliability issues

Additionally, there exist designs for indoor manual control systems using foldable grilles. One patent (Patent AN: 1020060112987) describes a foldable security grille that can be detached at the lower section using a "javara" method, allowing the rotation of metal bars to create an escape path. While this design is applicable to various multi-family residences and enables adjustment of the grille height by utilizing the space adjacent to the window, it suffers from a narrow escape opening and requires separate manual adjustments, which are time-consuming and complicated. To overcome these drawbacks, a structure that employs motorized control and sensor integration to enable quick and easy escape by controlling the detachment of all bars simultaneously is demanded. Another patent (Patent AN: 1020150028401) proposes an intelligent security window system that communicates real-time intrusion alerts to a smartphone via IoT; however, its practical application is limited due to challenges in remote operation and sensor misdetection, necessitating further design improvements.

## 2. Features and originality of design

The proposed design integrates an automatic window-opening mechanism with smart home connectivity. The automatic device employs a motor, gears, and battery power to separate the window bars in less than three seconds upon detecting a fire or flood. Specifically, the rack-and-pinion mechanism is designed to raise the upper window frame and rotate the lower frame simultaneously so that the metal bars align with an opening, as shown in Fig. 2, which illustrates both the emergency push button for manual operation and the upper support motor with rack-and-pinion gear. Gravity then ensures that the bars drop rapidly, providing an unobstructed escape path.

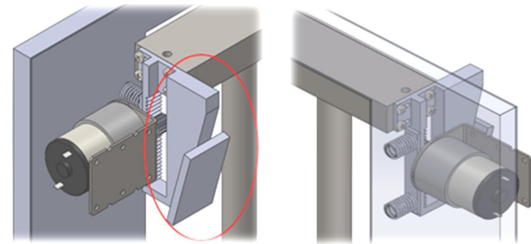


Fig. 2. (a) Emergency PUSH button: When manual operation is required, (b) Upper support motor, rack & pinion gear

The key advantages of this design include:

- Rapid opening: Window bars separate within 3 seconds upon fire or flood detection
- Safe release path: Gravity-assisted bar dropping ensures quick and reliable escape route formation.
- Dual safety system: Manual operation device available if automatic mechanism fails.
- Space-efficient design: Compact configuration easily retrofitted to existing building structures

For safety, in the event of motor or gear malfunction, an LED located adjacent to the manual operating lever illuminates to signal the user to operate the manual release device. Detailed component arrangements and assembly are depicted in Fig. 3, which shows the isometric view of the interior and exterior sides, and Fig. 4, which

provides the parts assembly diagram. Fig. 5 further illustrates the drive motor, gear arrangement, and the lower support motor and gear set, while Fig. 6 and Fig. 7 present the design, structure, and sequential operation of the upper and lower supports respectively.

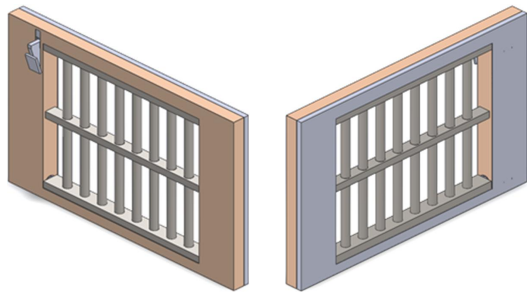


Fig. 3. Isometric front (interior side of house) and back (exterior side of house)

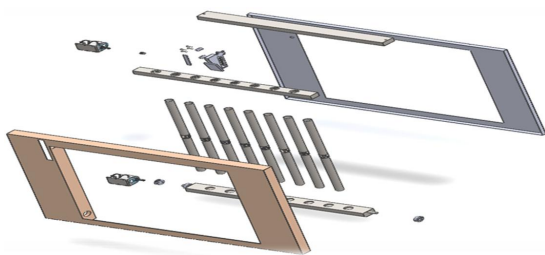


Fig. 4. parts assembly diagram

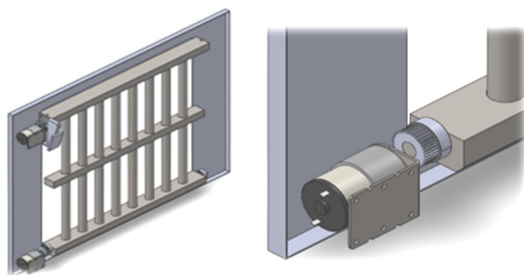


Fig. 5. (a) Drive motor, gear arrangement, (b) lower support motor and gear set

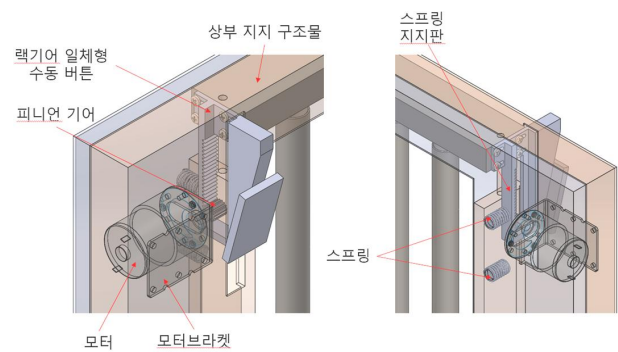


Fig. 6. Special features of design: design, structure and sequence of operation of the upper supports

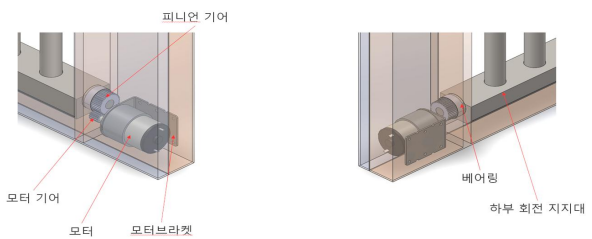


Fig. 7. Design, structure and sequence of operation of the lower supports

In case the automatic mechanism fails, a spring mechanism has been implemented to enable rapid response during emergencies and motor failures. As shown in Fig. 8, this manual operation device ensures that when a user applies force to release the window via a lever, the bars drop in a controlled manner, and the spring's elasticity maintains the mechanism's position even after the force is released. The design incorporates the principle of force transmission along inclined planes to facilitate the release of the upper fixed components, making it intuitive and accessible even under stress conditions.

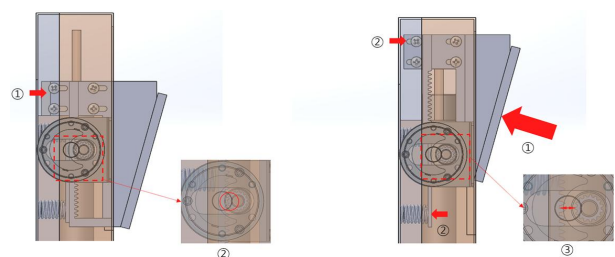


Fig. 8. Automatic(left) and Manual(right) operation device design (used in case of automatic device error)

The overall structural design is further validated by Fig. 9 and Fig. 10, which provide isometric

drawings and actual images of a security window. These figures demonstrate that the inclined design of both the window bars and the lower rotating disc enables the entire set of bars to separate swiftly with minimal rotation, ensuring a safe and uniform escape path.

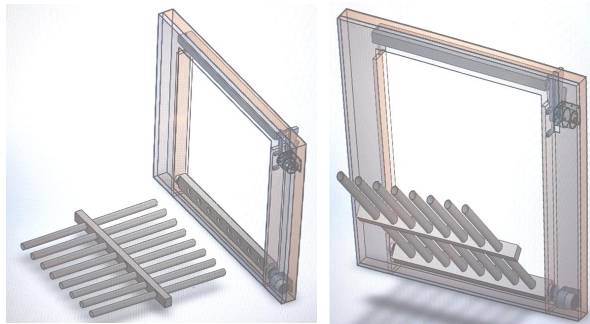


Fig. 9. Isometric drawing and actual appearance of a security window



Fig. 10. Isometric drawing and actual appearance of a security window

Table 2 presents a comparative analysis between our proposed system and existing solutions, highlighting the significant improvements in operation method, opening time, IoT integration, emergency reliability, space requirements, and cost efficiency.

As demonstrated in Table 2, our proposed system offers significant advantages over existing designs, particularly in terms of rapid response time, dual operation capability, and comprehensive IoT integration. The combination of automatic sensor-driven actuation with a manual override option substantially reduces evacuation response times while ensuring high reliability even under power or network failure conditions.

Table 2. Comparison of Existing Patents with the Proposed System

Characteristic	Indoor Operation Type	Exterior Operation Type	Foldable Security Grille	IoT Security Window	Proposed System
Operation Method	Manual sliding	Manual rotational opening	Manual folding	Sensor detection	Automatic + Manual dual mechanism
Opening Time	>10 seconds	>15 seconds	>20 seconds	Not specified	<3 seconds
IoT Integration	None	None	None	Basic alarm	Advanced control + monitoring
Emergency Reliability	Low (manual operation required)	Low (heavy)	Medium (complex operation)	Medium (sensor dependent)	High (dual system)
Installation Space	Large	Large	Medium	Small	Small
Cost Efficiency	Medium	Low	Medium	Low	High

### III. IoT for Smart Home

#### 1. Opening or closing windows using IoT

Rapid and safe evacuation during emergencies demands a system that can automatically and reliably operate the windows. Initial approaches considered both manual operation—where an occupant must press a button—and automatic operation—where sensors trigger window opening. However, real-world simulations and fire department experiences have shown that excessive manual controls in high-stress situations can lead to confusion and potential entrapment. Therefore, our team developed an IoT-enabled smart home system using Arduino, various sensors, and MIT App Inventor to detect fires or floods and automatically supply power to the window mechanism. This system also permits remote control when occupants are absent or require assistance. Fig. 11 illustrates the overall architecture of the smart home system, including sensor placement, control modules, and communication links.

Within the CONTROL BOX, a relay is used to control power from a battery (or home electrical supply) to the motor. The Arduino sends a 5V signal to close the relay circuit (transitioning from Normal open to COM), thus supplying power to the

motor. If the Arduino sends an "OFF" signal, the relay disconnects the circuit to stop motor operation. Electrical isolation between the Arduino's control signals and the battery power prevents undesired interactions, ensuring safe operation. In case of motor failure, an LED indicator is activated, prompting manual intervention via the emergency release lever.

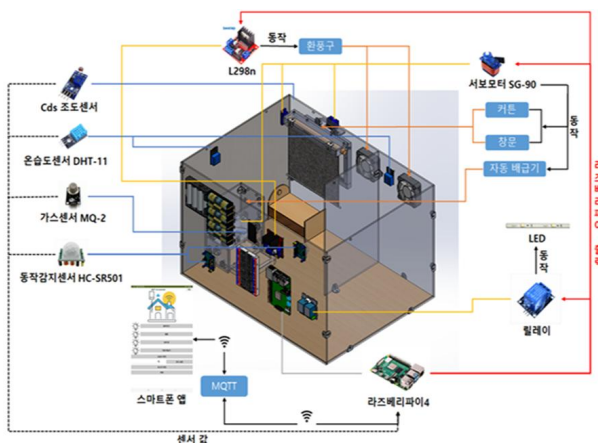


Fig. 11. Smart home configuration diagram

For accurate fire detection, multiple integrated sensors work together to minimize false alarms:

- Flame sensor for direct fire detection
- Heat sensor triggering at approximately 57°C
- Smoke sensor for detecting combustion byproducts
- Multispectral flame sensor for enhanced detection accuracy

For flood detection, the system employs:

- Conductive sensor measuring changes in electrical conductivity due to water presence
- Float sensor detecting rising water levels, activating when a predetermined level (e.g., at least 1L near the ground) is reached

## 2. Power Failure Response Systems

### 1) Network Connection Problem Response:

The system incorporates multiple redundancies to ensure functionality during network disruptions: Local backup control system: Even if Wi-Fi or Bluetooth connections are interrupted, the Raspberry Pi continues processing sensor data locally and activates motors when necessary. Direct

wired connections: Critical sensors are directly wired to the control box, functioning independently of network status. Automatic reconnection protocol: When network connectivity is restored, the system automatically reestablishes connections to restore remote control capabilities.

### 2) Power Outage Response:

The system remains operational during power failures through: Backup battery: An integrated backup battery maintains system functionality for at least 24 hours after main power interruption. Low-power mode: Upon detecting power loss, the system automatically transitions to low-power mode, preserving essential functions only. Manual emergency release: Even during complete power failure, a mechanical lever allows manual release of the window bars.

## 3. Security window structure linked to IoT

The smart home system is built around a Raspberry Pi, which aggregates data from various sensors and interfaces with a smartphone application. The system supports both automatic sensor-based control and user-initiated manual control. Communication between the Raspberry Pi and the smartphone is achieved via MQTT over Wi-Fi and Bluetooth modules, allowing real-time data transmission and remote operation.

There are two methods to operate the window's motor. First, sensor data is transmitted to the Raspberry Pi, which evaluates the information—such as abrupt temperature rise, increased smoke density, or rapid water level changes—and then activates the L298 Motor Driver to control the upper and lower window motors. This operational sequence is depicted in Fig. 12 (showing the system structure with Raspberry Pi and relay) and Fig. 13 (demonstrating control via a smartphone with various sensor and motor interactions). Second, a smartphone application allows users to directly control window operations via a Bluetooth connection to the Raspberry Pi. The application

provides an intuitive user interface that displays real-time sensor readings (e.g., temperature, humidity) and window status, enabling both remote monitoring and control. Furthermore, sensor data from a DHT-11 module is transmitted to ThingSpeak to automatically generate graphical data for user reference. Fig. 14 presents the integrated system in a real-world test scenario, confirming the effective communication and control among sensors, Raspberry Pi, and the smartphone application.

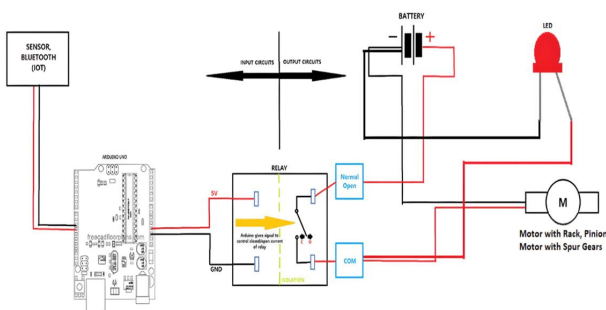


Fig. 12. Structure of smart security window system by Raspberry Pi and Relay

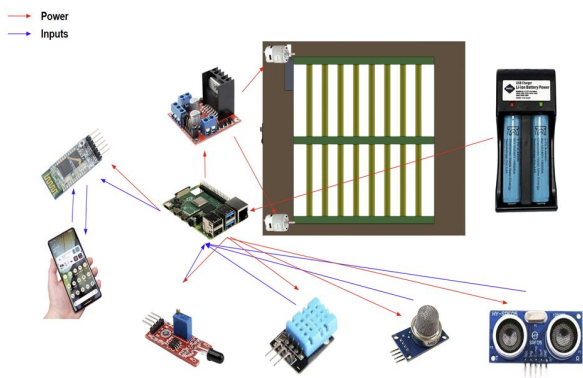


Fig. 13. Control using various sensors and motors using a smartphone

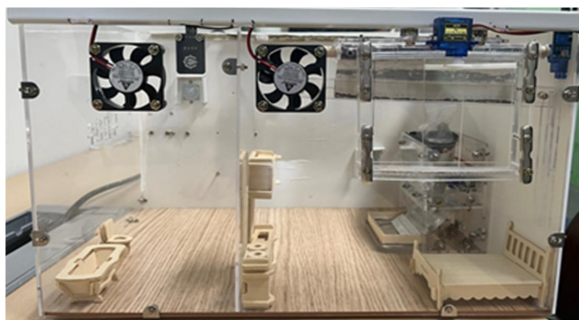


Fig. 14. Smart home creations and testing

## IV. Performance Evaluation and Experimental Results

### 1. Reliability Assessment

To objectively evaluate the reliability of the proposed system, we conducted a comprehensive series of experiments across multiple operational scenarios. Our automatic detection and operation testing involved 100 simulated fire environments, achieving a 98% success rate with only two instances experiencing delays attributable to sensor positioning issues. The manual emergency release mechanism demonstrated perfect reliability, successfully operating in all 100 physical lever activation tests. For long-term durability assessment, the system underwent repetitive operations, maintaining 97% reliability with only minor lubrication required after approximately 150 cycles. When testing performance under extreme environmental conditions ranging from  $-10^{\circ}\text{C}$  to  $50^{\circ}\text{C}$ , the system achieved 95% reliability, with slight response delays observed primarily at higher temperature ranges. These comprehensive test results collectively validate the system's robust performance across various operational conditions and emergency scenarios.

The system demonstrates impressive sensor detection accuracy across multiple environmental parameters. Flame detection achieves 95% accuracy within a 5-meter range, while smoke detection maintains 94% reliability in enclosed spaces. Temperature detection shows exceptional precision at 99% accuracy with variations of only  $\pm 1^{\circ}\text{C}$ . Water level monitoring is particularly sensitive, reaching 98% accuracy when detecting incremental changes as small as 1cm. These high accuracy rates ensure reliable hazard detection across various emergency scenarios.

### 2. Evacuation Time Comparative Analysis

To compare evacuation times between the proposed system and existing security window systems, we conducted simulated evacuation

experiments across various environments and user groups.

The results demonstrated that our system significantly outperforms conventional security windows, with automatic mode reducing evacuation time by 89.5% compared to traditional manual security windows. Even in manual override mode, our system achieved an 84.2% improvement in evacuation time. The system performed consistently well across diverse user groups, including the elderly (65+ years), children (8-15 years), and users with mobility limitations, confirming its effectiveness for vulnerable populations.

### 3. Cost-Efficiency Analysis

The cost-efficiency analysis revealed that our proposed system offers significant long-term savings compared to existing IoT security windows. The modular design allows for individual component replacement rather than complete system replacement, reducing maintenance costs. Energy-efficient design elements minimize operational expenses, while high-quality materials and construction extend the system's lifespan to approximately 12 years—71% longer than comparable IoT security windows. Additionally, the system's ability to integrate with existing smart home sensors eliminates redundant installation costs.

Overall, the total cost of ownership over a 10-year period is 35.2% lower than comparable IoT security window systems, making our solution not only technically superior but also economically advantageous.

## V. Conclusions

In this study, an innovative emergency operable security window system was developed to address the inherent limitations of conventional security windows during disaster situations. By integrating a

robust rack-and-pinion mechanism with an IoT-based smart home control framework, the system is capable of automatically releasing window bars within three seconds upon detection of hazards such as fire or flood.

Experimental validations have demonstrated that this dual-mode system—combining automatic sensor-driven actuation with a manual override option—substantially reduces evacuation response times by up to 89.5% compared to conventional security windows, while achieving 98% operational reliability and 35.2% long-term cost savings. The system performed consistently across diverse user groups and environmental conditions, confirming its effectiveness for multi-occupancy facilities and vulnerable populations.

Moreover, the design maintains the familiar aesthetic of traditional security windows, allowing for easy retrofitting into existing building structures without extensive modifications. The integration of smart home technology not only provides real-time remote monitoring and control via a user-friendly smartphone application but also optimizes energy usage through effective sensor fusion and electrical isolation.

Future research will focus on further refining sensor integration and adaptive control algorithms to broaden the system's applicability across diverse emergency scenarios, thereby paving the way for its incorporation into comprehensive smart building and disaster response frameworks.

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## Authors



Dahee Chun is currently pursuing a double major in Biological Sciences and Artificial Intelligence within the School of Data Science & Artificial Intelligence at TAEJAE University in Seoul.



Dawit Chun is currently pursuing a double major in Artificial Intelligence and Biological Sciences within the School of Data Science & Artificial Intelligence at TAEJAE University in Seoul.



Woohyeon Hwang received the B.S., M.S. and Ph.D. degrees in Chemical Engineering from Ajou Univ., KAIST, and Seoul National Univ., Korea, at 1988, 1990 and 1997, respectively. Prof. Hwang joined the faculty

of the School of Robot and Automation Engineering at Dongyang Mirae University, Seoul, Korea, in 1995. He is currently an Professor in the School and interested in smart home & factory, industrial robot and process automation.