Journal of
Engineering Sciences
Faculty of Engineering
Assiut University
مجلة
العلوم الهندسية
كلية الهندسة
جامعة أسيوط
journal homepage: http://jesaun.journals.ekb.eg

Smart Staircase: Interactive Design for Social Distancing and Crowd Management

Received 30 July 2024; Revised 1 October 2024; Accepted 1 October 2024

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Keywords
Interactive Architecture, Smart Staircase, Crowd Management, IoT

Abstract: This study explores an innovative architectural framework that integrates design and technology to regulate crowd management and enforce social distancing protocols in public spaces. Grounded in the principles of functionality and humanism, architecture serves as a medium for societal adaptation. The primary objective of this research is to transform the management of vertical movement in densely populated public areas by implementing interactive staircase designs. Public access staircases, prevalent in environments such as university campuses, present significant challenges for crowd management and the control of social distancing. This study proposes the adoption of interactive staircases that not only facilitate physical distancing but also encourage physical activity. Employing a multi-stage methodology, this research combines empirical observation with advanced technological applications. The process encompasses a comprehensive literature review, on-site data collection through time-lapse photography and video recordings, and collaborative brainstorming sessions to develop interactive scenarios. The project leverages Arduino microcontrollers, ultrasonic sensors, and LED lights to create a responsive staircase environment. A 1:5 scale physical model is utilized as a prototype to test and refine these interactive elements, thereby integrating architectural design principles with smart technology. This approach aims to manage crowd flow and promote social distancing through dynamic, user-responsive illumination.

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https://doi.org/ 10.21608/jesaun.2024.308334.1359

1. Introduction

The recent global health crises have underscored the necessity for innovative architectural designs for public spaces. The emergence of this unusual problem has brought attention to weaknesses in conventional design frameworks, necessitating a shift towards adaptive solutions driven by technology. The architectural community should engage in the redesign of public spaces with the aim of mitigating health problems and enhancing performance and interaction. The integration of IoT sensors, artificial intelligence, and digital twins enables architects to construct dynamic spaces that can adjust to the requirements of users and the surrounding environment. Interactive components in architecture design have demonstrated significant efficacy in enhancing user engagement and achieving specific goals. Huang et al. (2012) demonstrated that the achievement of goals in physical rehabilitation therapies for children was significantly improved by using an interactive musical staircase[1]. One could utilize the concept of including interactive elements to influence behavior in order to address issues related to maintaining social distance and managing crowds in public spaces.

In the built Environment, several locations have been examined for the incorporation of technology in public spaces to manage the crowd in large gatherings. Dey et al. (2023) developed an interactive communication robot for crowd control and information dissemination in museums using crowd counting methods [2]. This approach highlights the potential of integrating crowd monitoring and interactive elements to enhance user experience and manage spatial dynamics effectively. Amidst the COVID-19 pandemic, numerous studies have investigated the necessity of technological interventions in public areas. Chowdhury et al. (2021) created a sophisticated artificial intelligence model to continuously observe and track adherence to COVID-19 protocols, such as wearing masks and maintaining social distance, during public gatherings. In their study, Ullah et al. (2021) introduced a video surveillance system that use artificial intelligence to ensure privacy while monitoring adherence to social distance protocols in public areas[3].

In their study, Nasajpour et al. (2021) explored the concept of utilizing Internet of Things (IoT) technology to enforce social distancing measures during epidemics. They proposed an end-to-end IoT architecture that might aid in maintaining social distance[4]. This strategy demonstrates the effective integration of smart technologies into architectural design to enhance public health objectives. Salama (2021) conducted a study on the impact of urban design on social behavior during the epidemic. The study focused on the relationship between boredom in public areas and urban form, social distance, and digital transformation[5]. This perspective highlights the importance of including psychological aspects into the design of public spaces to encourage social segregation. Soltani et al. (2022) examined the process of evacuating crowds in high-rise residential buildings that house individuals with varying abilities. They achieved this by integrating architectural strategies with managerial methods[6]. This study emphasizes the necessity of incorporating several user requirements in the design of staircases and crowd control.

The main goal of this study is to enhance the understanding and application of vertical circulation systems in public areas, particularly focusing on staircases in educational environments. The study seeks to transform the functioning and user experience of transitional spaces by combining architectural design principles with advanced interactive technology. The research aims to overcome the constraints of traditional staircase designs by creating a responsive system that can adjust in real-time to user behavior and spatial requirements by combining sensor-based technologies and illumination methods. The developed staircase prototype will be able to guide users, optimize crowd flow, and encourage compliance with social distancing regulations. This strategy seeks to not only improve the effectiveness of vertical movement but also to promote a more intuitive and captivating user interface in the constructed environment. Additionally, the project aims to add to the ongoing discussion on intelligent architecture and design that prioritizes human needs. It seeks to provide valuable insights that have the potential to transform our knowledge of how public spaces are used and how crowds are managed in the era following the pandemic.

2. Methods and tools

The methodology employed in this study combines empirical observation with technological implementation to create an innovative solution for crowd management on staircases. The study process employed a multi-stage methodology, commencing with an extensive literature survey to build a solid theoretical framework. Following that, an on-site observation was conducted utilizing quantitative data gathering methods, such as time-lapse photography and video recordings, to assess the usage patterns of the chosen staircase prototype. The project utilized brainstorming sessions to generate interactive situations, which were subsequently transformed into practical applications through the use of Arduino single-board microcontrollers for programming and control. Ultrasonic sensors were strategically positioned to detect the movement and closeness of users, while LED lights were incorporated into the steps of the stairs to offer visual feedback. This hardware design facilitated instantaneous responsiveness to user actions. In the implementation phase, the team constructed a physical model at a size of 1:5. This allowed them to test and improve the interactive parts. This methodology enabled the smooth integration of architectural design concepts with smart technology, resulting in a prototype that could actively control crowd movement and encourage social separation through dynamic, user-responsive lighting. The project's methodology is represented by a flowchart (Fig.1), which demonstrates the step-by-step process from initial research to prototype development and testing. This flowchart visually presents the study's integrated approach to designing interactive staircases.

3. Implementing social distancing measures on public access staircases

The COVID-19 pandemic has radically changed the way we view and use public areas, requiring creative strategies for managing crowds and maintaining social separation. This shift has specifically affected vertical circulation features, such as staircases, which frequently function as crucial intersections in public buildings. The subsequent sections go into the wider framework of social distance in public areas and its implementation on staircases.

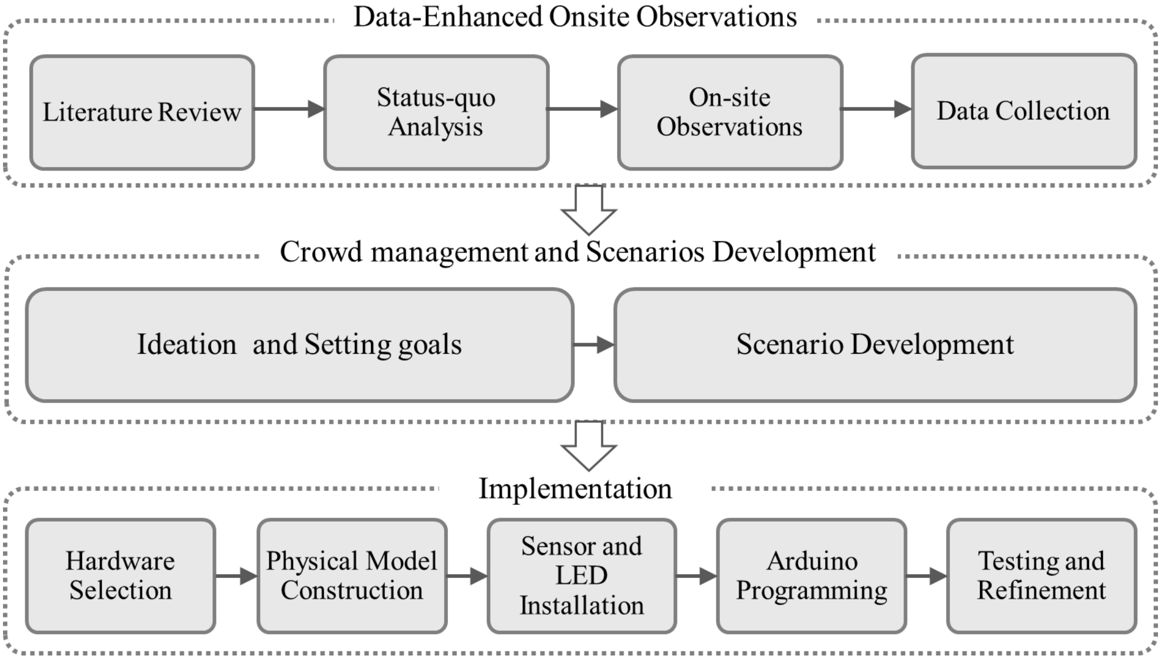

Fig. 1: Methodological Framework for Interactive Staircase Design

3.1. Utilization of social distancing measures in public spaces:

Social distance has become a vital public health tactic to reduce the transmission of contagious illnesses. Within the realm of public places, this notion goes beyond simple physical division and includes many adjustments in behavior and atmosphere. The International Association of Chiefs of Police (IACP, 2019) highlights the significance of organizing and controlling the assembly and movement of individuals in public spaces as a basic component of crowd management[7].

As seen in Fig. 2, Effective implementation of social distancing in public settings requires the use of various crowd management control strategies:

- Wayfinding Optimization: Conspicuous signage and markings enhance the ease of navigation and mitigate congestion resulting from confusion.
- Queue Management: Designated waiting spaces with clearly marked distances between participants in a queue aid in maintaining proper physical distancing.
- Flow Management: This comprehensive strategy includes space planning, arrangement, signage, and crowd management strategies to govern movement and avoid excessive crowding.
- Temporary closures: Implementing strategic barriers in specific places to ensure safety, facilitate cleaning, or carry out renovations, while also offering clear alternate routes to reroute pedestrian movement.
- Rapid Deployment: Rapid deployment of crowd management strategies in reaction to abrupt surges of individuals or unforeseen circumstances.

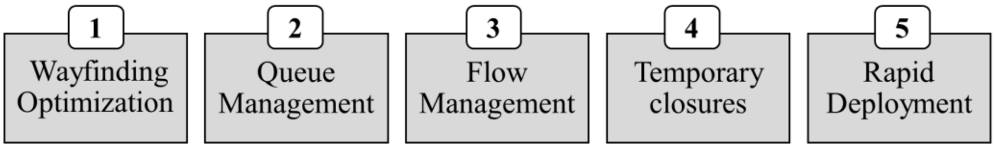

Fig. 2: The Five crowd management techniques

3.2. Implementation of Social Distancing Measures on Staircases

Staircases provide distinct difficulties for maintaining social separation because of their limited space and the complexities of upward travel. The National Fire Protection Association (NFPA, 2021) has established a set of recommendations specifically designed to ensure the maintenance of social distance on public access staircases[8].

- Unidirectional Flow: Enforcing the movement of individuals in a single direction to reduce the occurrence of face-to-face interactions.
- Designated Ascent and Descent: Allocating separate sides of the staircase for upward and downward movement to reduce cross-traffic.
- Improved Safety Measures: Implementing non-slip treads and clear markings to enhance safety and facilitate navigation.
- Practicing vertical distancing by ensuring a strict separation of 6 feet (equivalent to approximately 6 steps) between individuals while ascending or descending the stairs.
- Horizontal Spacing: Enforcing a distance of 2 meters between individuals whenever feasible. For narrower staircases, it is necessary to allocate a minimum space of 55cm for each person.

Figure 3 illustrates the concept of Prioritized Usage, which refers to giving priority to the use of staircases. This is an essential component in managing staircases effectively. This diagram demonstrates the need to prioritize individuals who are descending, particularly those who are using handrails. Research conducted by Cohen (2001) supports the prioritization of handrail use during stair descent. Their study revealed that handrail use was 10% higher during descent compared to ascend[9]. It is important to prioritize railing use during stair descent as falls during this activity might result in severe injuries or unintentional death.

Additional strategies for enhancing social distancing on staircases include:

- Occupancy Monitoring: Deploying technologies that improve occupancy tracking, such as sensors mounted on rotating brackets, to promote and enforce safe social separation.
- Visual Cues: Utilizing labels and vibrant colors as indicators to clearly define safe distances and direct user actions.
- Capacity Restrictions: Establishing the maximum number of people allowed in a given space by considering high-density situations in order to avoid congestion.
- Sanitary measures: Reducing contact with handrails or promoting the use of gloves when contacting surfaces.

By employing interactive design and smart technology, the application of these recommendations can greatly improve crowd management and promote social distancing on staircases. By incorporating sensors, visual feedback systems, and real-time occupancy monitoring, staircases can be converted from possible congestion points into effectively controlled vertical circulation areas that prioritize user safety and public health.

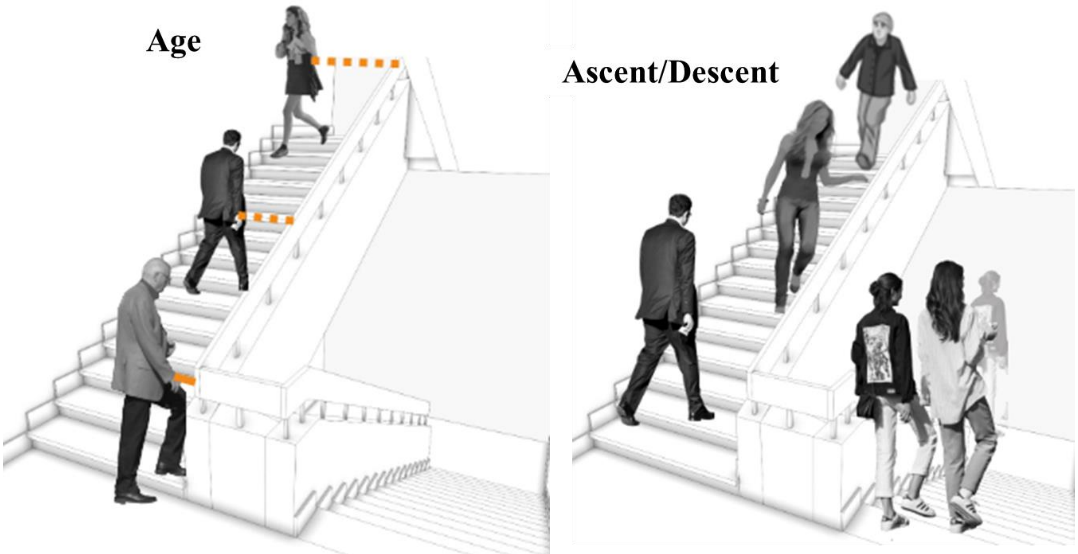

Fig. 3: Priority for Staircase Usage

4. Status-quo Analysis of the Selected Staircase

The chosen prototype for this study is a staircase located within the Architectural Engineering Department, Faculty of engineering at Ain Shams University. This vertical circulation element links the third-floor lecture halls to the fourth-floor design studios, serving as a critical junction for student movement throughout the day.

Observations were recorded for the staircase over five working days from 8:00 a.m. to 8:00 p.m. The documentation approach was a quantitative method, counting the number of students at the beginning of each two-hour interval during the first ten minutes. Photos and videos were also taken to capture staircase usage at different times. This update specifies that the student count was conducted during the first ten minutes of each two-hour period.

4.1. Usage Patterns and Behavioral Observations

The collected data revealed several noteworthy trends in staircase utilization:

a. Elevator Preference: Despite the availability of stairs, students exhibited a marked inclination towards elevator usage, even during periods of low staircase occupancy.

b. Directional Bias: The descending direction of the staircase experienced higher traffic volumes compared to the ascending direction.

c. Temporal Fluctuations: (Table 1) illustrates the variations in staircase occupancy throughout the week. Notably, the highest density was recorded on Mondays between 10:00 a.m. and 12:00 p.m., while the lowest occupancy occurred on Tuesdays from 2:00 p.m. to 4:00 p.m. Table 1 illustrates the number of students counted during the first ten minutes of each two-hour interval.

d. Alternative Usage: During peak hours, the staircase transformed into a multifunctional space. Students were observed not only ascending and descending but also utilizing the treads as impromptu seating areas, contributing to congestion.

e. Congregation Points: Stair landings and treads adjacent to landings emerged as popular spots for brief pauses and social interactions.
f. User Demeanor: Students traversing the staircase often displayed signs of fatigue or disengagement, suggesting potential opportunities for enhancing the user experience.

Table 1: Staircase Crowd Observation

	8:00 – 10:00	10:00 – 12:00	12:00-2:00	2:00 -4:00	4:00-6:00	6:00-8:00
Sunday	6	12	6	10	2	4
Monday	7	16	0	3	7	2
Tuesday	6	8	2	1	0	3
Wednesday	4	9	4	0	7	4
Thursday	5	0	5	3	5	2

4.2. Visual Documentation of Key Observations

Fig. 4 captures the stark underutilization of the staircase during off-peak hours, specifically on Tuesdays from 2:00 p.m. to 4:00 p.m. and Thursdays from 10:00 a.m. to 12:00 p.m. This visual evidence underscores the potential for optimizing staircase usage during these periods.

Fig. 4: Underutilized staircase on Tuesdays from 2:00 to 4:00 p.m. & Thursdays from 10:00 to 12:00 a.m.

In contrast, Fig. 5 illustrates the staircase at its maximum occupancy, recorded on Mondays between 10:00 a.m. and 12:00 p.m. This image not only depicts high foot traffic but also showcases the phenomenon of students repurposing stair treads as seating areas, exacerbating congestion issues.

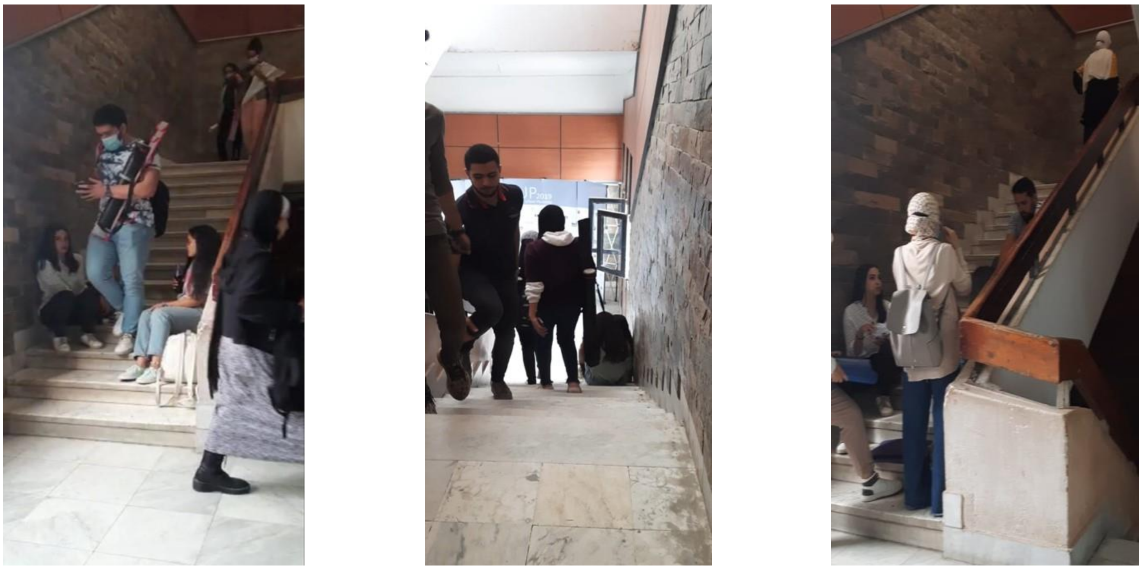

Fig. 5: Highest density on the staircase recorded on Mondays
from 10:00 to 12:00 p.m., with students using treads for seating

Fig. 6 presents a paradoxical scenario where students queue for elevators despite the adjacent staircase being unoccupied. This behavior was particularly prevalent on Tuesdays from 10:00 a.m. to 12:00 p.m., highlighting a potential area for intervention to encourage staircase use.

Fig. 6: Students waiting for elevators despite empty stairs
on Tuesdays from 10:00 to 12:00 a.m.

4.3. Implications for Design Intervention

The status-quo analysis reveals several critical issues that the proposed interactive staircase design must address:

- Underutilization during off-peak hours
- Overcrowding and improper use during peak periods
- User preference for elevators over stairs
- The need for designated resting or social interaction spaces near the staircase

These findings provide a solid foundation for developing targeted design interventions that can enhance the functionality, safety, and appeal of the staircase while promoting more efficient crowd management and social distancing practices.

5. Crowd management and Scenarios Development

The core concept behind this interactive staircase design is to manage the movement of large groups of people, specifically in the context of vertical movement within educational institutions. The project intends to maximize user flow, encourage social separation, and improve overall safety by utilizing intelligent technologies and incorporating flexible design components.

The main goal of crowd management in this context is to control the movement of people on publicly accessible staircases, with a specific focus on:

- Accident prevention
- Social distancing enforcement
- Efficient crowd flow optimization

This approach aligns with established crowd management principles, such as those outlined by the International Association of Chiefs of Police (IACP, 2019), which emphasize the importance of planning and directing public movement in shared spaces[7].

The innovative aspect of this project lies in its application of interactive elements to a traditionally static architectural feature. By integrating sensors and visual cues, the staircase becomes a dynamic system capable of responding to real-time user behavior and environmental conditions.

5.1. Adaptive Crowd Management through Interactive Illumination

The fundamental idea behind this interactive staircase design centers on the efficient management of crowds by leveraging advanced technology to optimize the movement of users and improve safety. The system functions based on the following principles:

- User Tracking: Each individual ascending or descending the staircase is identified as a distinct moving target. The system pinpoints their precise location on the stairs and registers the moment they initiate their climb or descent.
- Illuminated Personal Zones: As illustrated in Fig. 7, the design incorporates a unique feature where each user is defined by a colored zone created through strategically placed LED lights. This visual element serves both aesthetic and functional purposes.
- Path and Speed Indication: The illuminated zone around each user serves as a dynamic indicator of their trajectory and velocity. This visual cue aids in maintaining appropriate distances between individuals and helps regulate overall traffic flow.
- Scenario-Based Color Adaptation: The color of each user's zone is not static but adapts in real-time based on various usage scenarios. This color-coding system provides immediate feedback to users, promoting safe navigation and efficient space utilization.

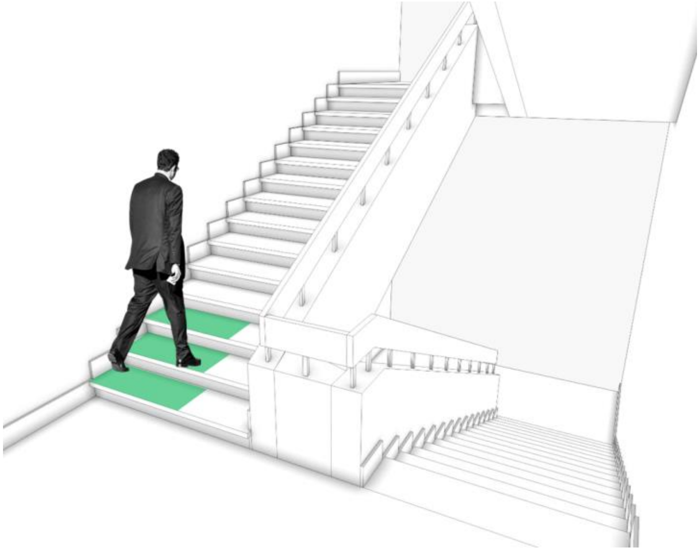

Fig. 7: Each user is defined with a colored zone.

By implementing this intelligent, responsive lighting system, the interactive staircase aims to transform a traditionally static architectural element into a dynamic, self-regulating environment. This approach not only enhances the user experience but also addresses critical concerns such as social distancing and accident prevention in high-traffic vertical staircase.

5.2. Scenario Development

This section will present an overview of all the possible scenarios that can occur on the chosen staircase. The three anticipated scenarios are described in the following chart (Fig. 8).

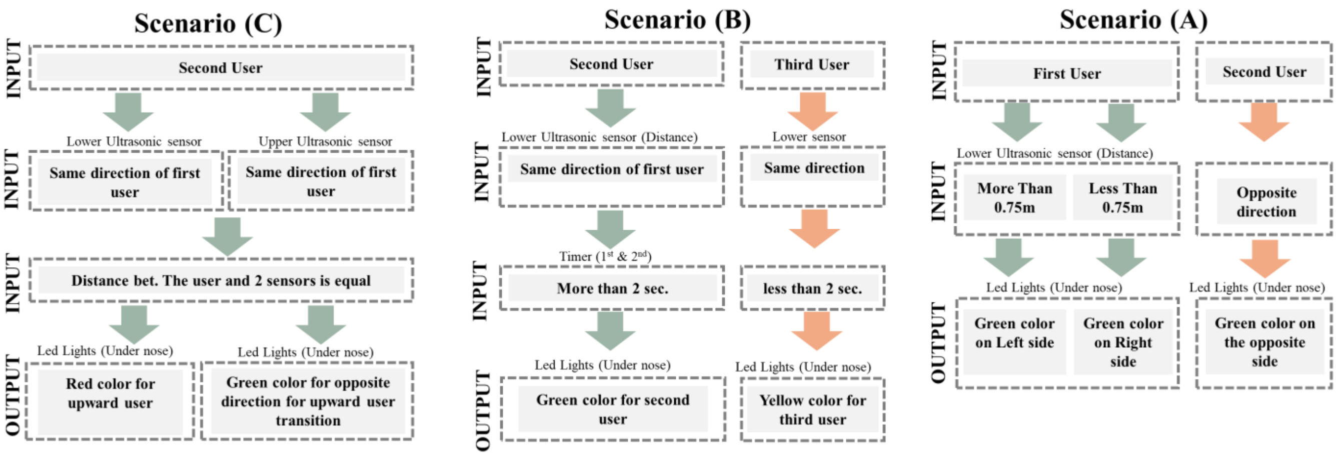

Fig. 8: The three possible scenarios

5.3. Scenario A

When the initial user uses the stairs, the relevant sensor will calculate the distance between the user and the sensor. If the distance exceeds 0.75m, a green light will be displayed on the left side of the stairs. If the distance is below 0.75m, a green light will be seen on the right side of the stairs, as depicted in Fig. 9.

Fig. 9: Scenario A

When the second user uses the stairs, the corresponding sensor will calculate the distance between the user and the sensor. If the second user's location is directly opposite to the first user's location, a green light will also appear at the second user's location.

5.4. Scenario B

When a user utilizes the stairs, the corresponding sensor will calculate the distance between the user and the sensor. If the current user's position matches the previous user's location and the time difference between the two users is greater than 2 seconds, a green light will be displayed at the second user's location, as depicted in (Fig. 10).

Fig. 10: Scenario B

When a user utilizes the stairs, the associated sensors will calculate the distance between the user and the sensor. If the current user is at the same area as the previous user and the time difference between them is less than 2 seconds, a yellow light will be displayed at the second user's location, as depicted in (Fig. 10).

5.5. Scenario C

When two users ascend or descend the staircase, but they are moving in different directions. The sensors will measure the distance between the users and themselves. When the distance between the two users and their associated sensors is the same, the user who is facing upwards will be displayed in red, while the other user will be displayed in green. This is seen in (Fig. 11).

Consequently, the user who is moving in an upward manner will be required to change lanes to the opposite lane. Consequently, the updated location of the user moving in an upward direction will be indicated by a green colour, as depicted in (Fig. 12).

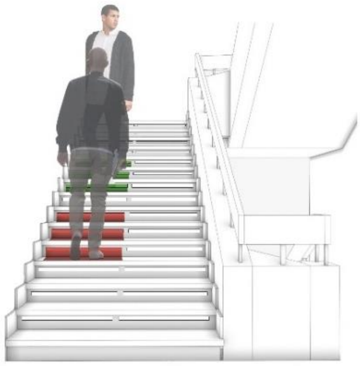

Fig. 11: Scenario C – Initial Condition

Fig. 12: Scenario C – Updated Condition

6. Implementation of the Interactive Staircase Design

The realization of the interactive staircase concept involves a multifaceted approach, integrating various technological components and design principles. This section elucidates the implementation stages, from the initial experimental setup to the creation of a scaled physical model, demonstrating the practical application of the crowd management system.

6.1. Stair's Experimental Settings

The experimental Settings of the staircase, as depicted in (Fig. 13), comprises a strategic division of the stair flight into five distinct zones. Each zone encompasses three steps and is equipped with LED lights bifurcated into two lanes. Sensor placement is crucial, with one sensor positioned at the commencement of each zone, except for the fifth zone, which features sensors at both its inception and terminus. This arrangement facilitates precise user detection and movement tracking throughout the staircase.

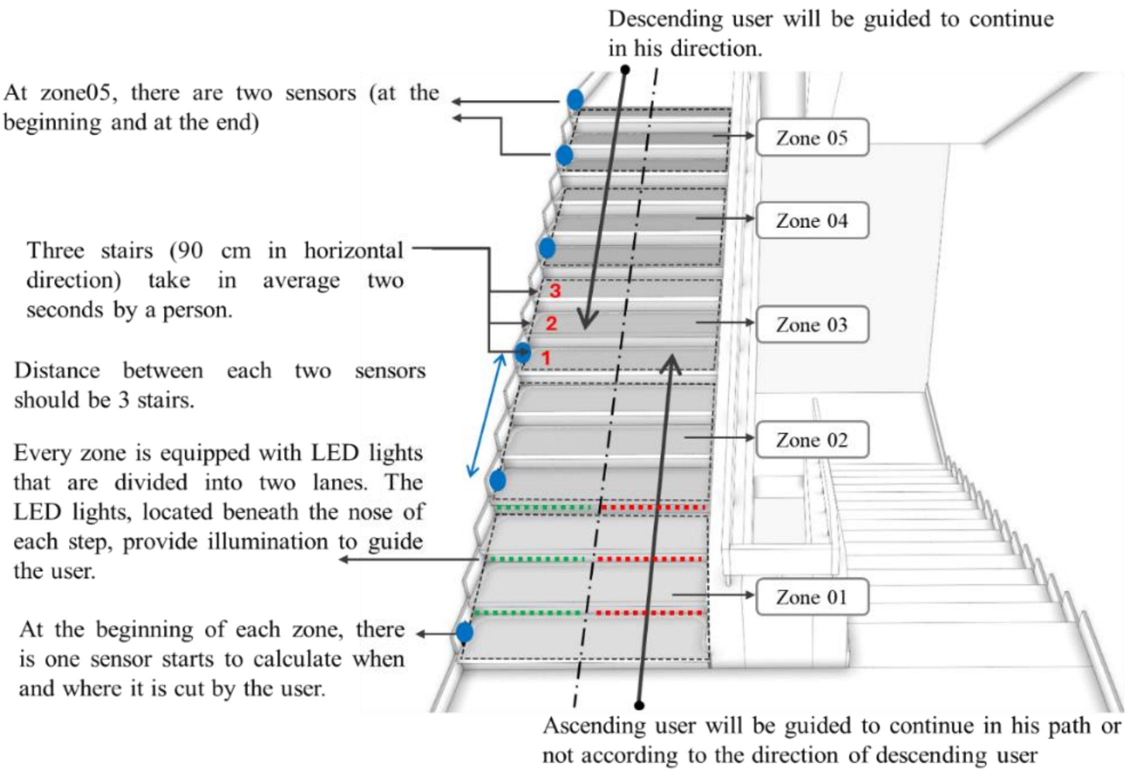

Fig. 13: The experimental Settings of the staircase

6.2. Color Coding Concept

The color-coding scheme, illustrated in (Fig. 14), serves as a visual communication system for users navigating the staircase. Green illumination denotes a user's zone without intersection, promoting a sense of calm and facilitating decision-making. Red signifies proximity to another user moving in the opposite direction, demanding immediate action. Yellow indicates closeness to another user moving in the same direction, stimulating analytical processes and logical reasoning. This chromatic system, grounded in color psychology principles (Wright, 1998), enhances user responsiveness and spatial awareness.

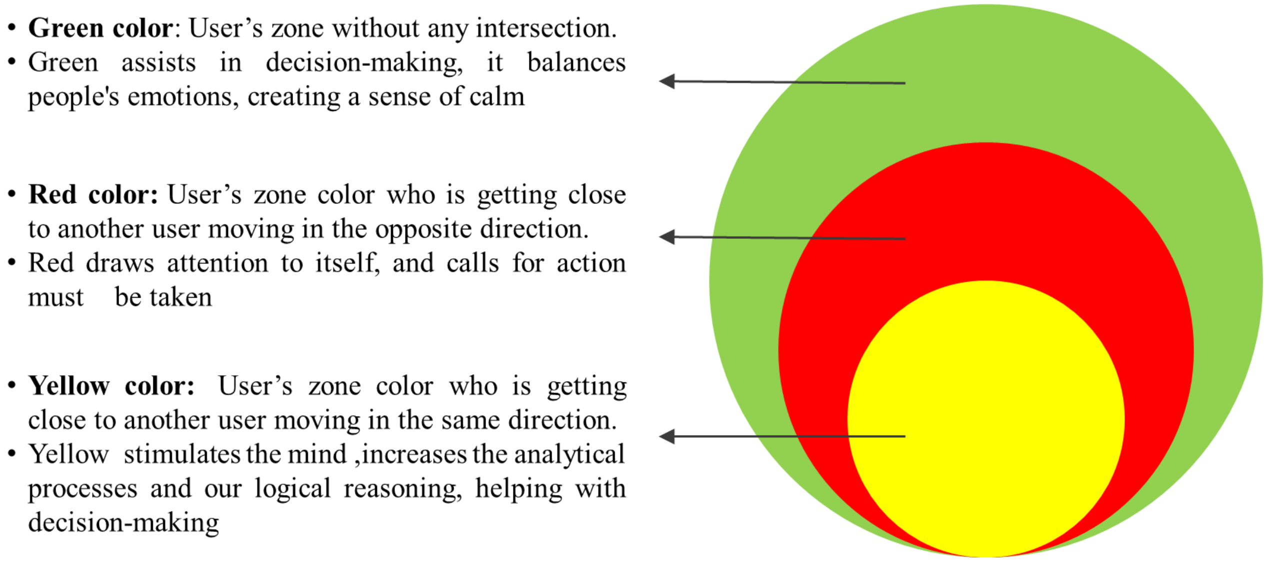

Fig. 14: The color-coding scheme

6.3. Technologies and Sensors Utilized

The implementation relies on ultrasonic sensors for distance measurement and user detection. These sensors emit high-frequency sound waves and calculate the time taken for the waves to return, determining the user's position. An Arduino board, programmed using the Arduino Integrated Development Environment (IDE), processes the sensor inputs and controls the LED outputs. The system's logic flow is delineated in the coding flow chart (Fig. 15), illustrating the decision-making process based on sensor inputs and predetermined time intervals.

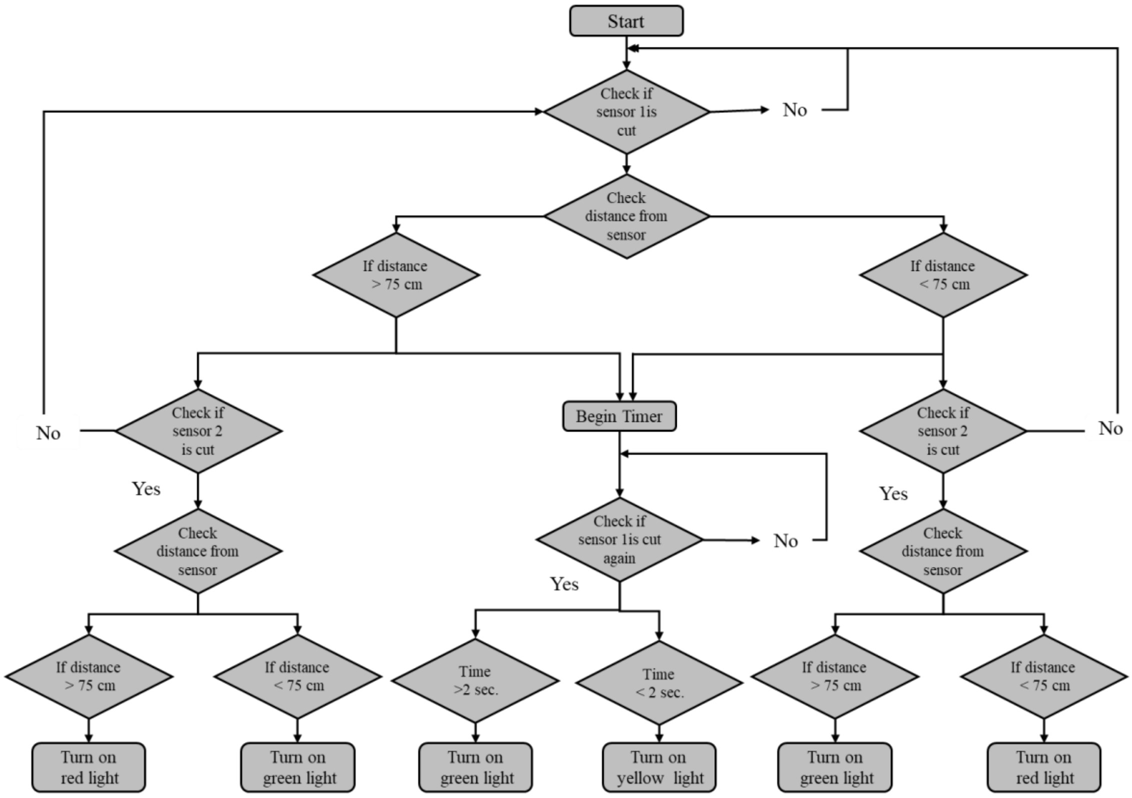

Fig. 15: Flowchart of the decision-making process based on sensor inputs

6.4. Operational Dynamics of Crowd Management

The crowd management system's functionality is predicated on the interplay between sensor inputs and LED outputs. When a user enters a zone, the corresponding sensor measures their distance and triggers the appropriate LED response. The system distinguishes between users based on time intervals and distances, illuminating green, yellow, or red lights accordingly. This dynamic response mechanism encourages users to adjust their speed and position, thereby optimizing crowd flow and maintaining safe distances.

6.5. Scaled Physical Model Implementation

To validate the concept, a 1:5 scale physical model of the selected staircase was constructed (Fig. 16 & 17). This model incorporates one ultrasonic sensor on the side of the first zone and green and yellow single-piece LED lights fixed in the risers of the first three steps. The Arduino board and IDE were utilized to program the interaction between the sensor input and

LED output. This scaled model serves as a proof of concept, demonstrating the feasibility of the interactive staircase design and its potential for full-scale implementation.

The implementation of this interactive staircase design represents a convergence of architectural innovation and smart technology. By integrating real-time sensing capabilities with intuitive visual cues, the system offers a novel approach to crowd management in vertical circulation spaces. This implementation not only addresses the immediate concerns of social distancing and crowd flow optimization but also lays the groundwork for future developments in interactive architectural elements.

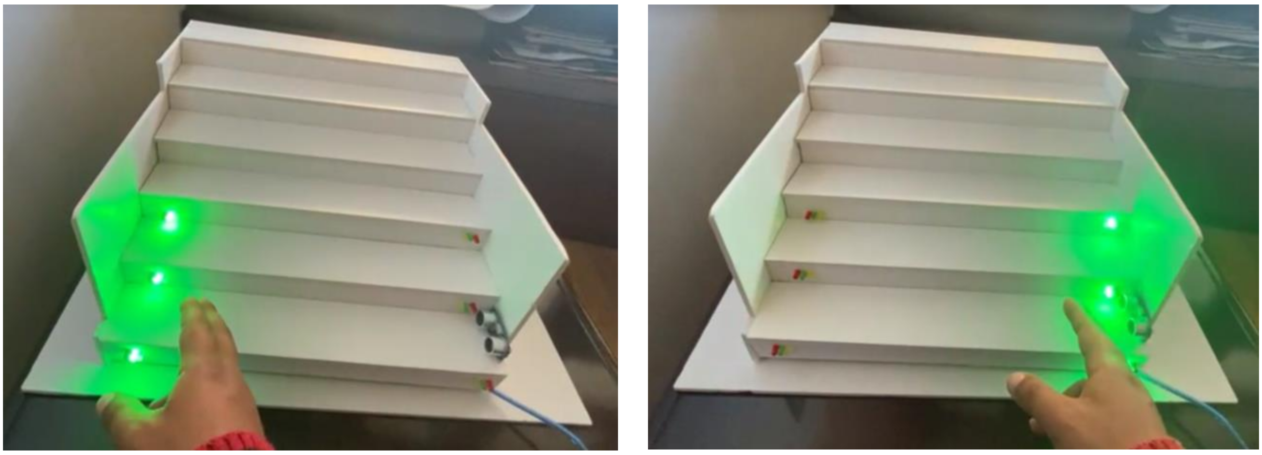

Fig. 16: On the right, green LED lights illuminated when sensor waves were interrupted for over 2 seconds. On the left, green LED lights activated under the same condition.

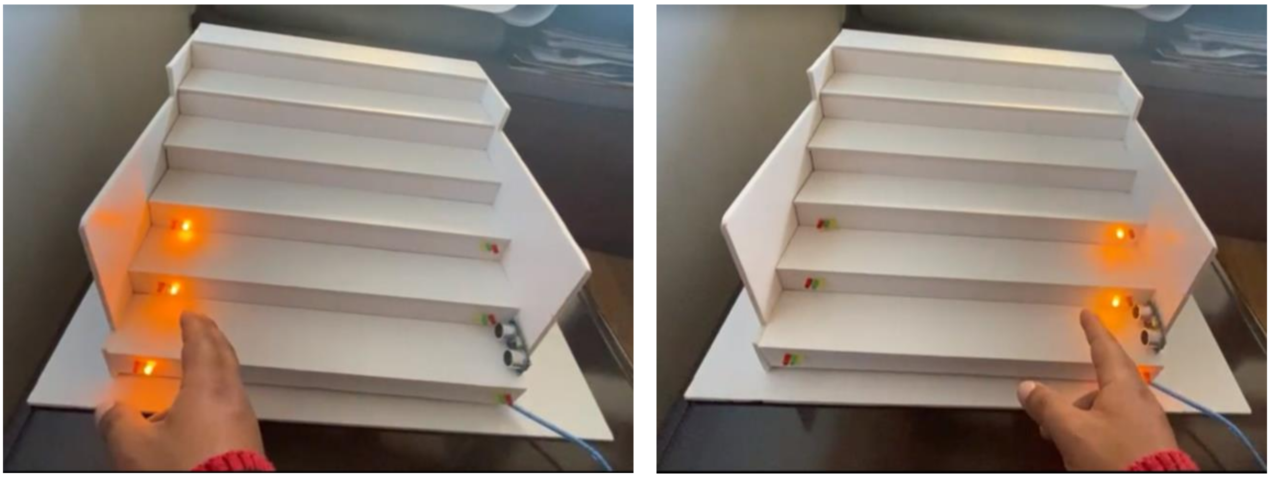

Fig. 17: On the right, yellow LED lights illuminated when sensor waves were interrupted for less than 2 seconds. On the left, yellow LED lights activated under the same condition.

7. Results

The implementation of the interactive staircase design yielded several noteworthy outcomes:

- User Behavior Modification: The color-coded LED system demonstrated efficacy in guiding user movement. Green illumination, signaling unobstructed paths, facilitated smooth traffic flow. Yellow lights, indicating proximity to other users moving in the same direction, prompted individuals to adjust their pace. Red illumination, warning of potential collisions with users moving in opposite directions, successfully encouraged lane changes.

- Sensor Accuracy: Ultrasonic sensors exhibited high precision in detecting user presence and movement. The system accurately distinguished between users based on time intervals and distances, with a threshold of 2 seconds and 75 cm respectively. This granularity allowed for nuanced crowd management strategies.
- Real-time Responsiveness: The Arduino-based control system demonstrated rapid processing of sensor inputs and corresponding LED outputs. The lag between user detection and light activation was imperceptible, ensuring timely visual cues for staircase users.
- Scalability: While the proof-of-concept focused on a single zone of three steps, the modular nature of the design suggests feasibility for full-scale implementation. The successful integration of hardware and software components in the 1:5 scale model indicates potential for broader application.
- User Engagement: Observational data suggested increased user attentiveness to their surroundings when interacting with the illuminated staircase. The dynamic lighting appeared to heighten spatial awareness among participants.
- Flow Optimization: In scenarios simulating high-density usage, the system effectively segregated ascending and descending traffic, potentially mitigating congestion points observed in the status-quo analysis.
- Adaptability: The programmed scenarios demonstrated the system's capacity to respond to varying crowd densities and movement patterns, suggesting adaptability to diverse usage contexts.

8. Discussion/Conclusions

The interactive staircase project represents a significant stride in reimagining vertical circulation spaces as dynamic, responsive environments. By integrating sensor technology with intuitive visual cues, the design addresses critical issues of crowd management and social distancing in public spaces.

The color-coding system, grounded in established color psychology principles (Wright, 1998), proved effective in influencing user behavior. Green illumination fostered a sense of safety and encouraged forward movement, aligning with Wright's assertion that green balances emotions and creates calm. The use of yellow to signal caution and red to indicate immediate action required demonstrates a nuanced application of color theory in architectural design.

The prioritization of descending users, as implemented in the system's logic, aligns with research by Cohen (2001)[9], which highlighted increased fall risk during descent. This feature underscores the potential for interactive architecture to enhance safety in addition to optimizing flow.

The project's focus on staircases as critical junctions in public buildings addresses an often-overlooked aspect of architectural design. As Yang et al. (2012) noted, staircase dimensions significantly impact pedestrian flow under both normal and emergency conditions[10]. The interactive system's ability to adapt to varying crowd densities suggests potential applications in emergency evacuation scenarios, meriting further investigation.

The successful implementation of the Arduino-based control system demonstrates the feasibility of integrating smart technology into existing architectural elements. This approach offers a cost-effective alternative to major structural renovations, potentially extending the lifespan and enhancing the functionality of older buildings.

However, several limitations warrant consideration. The reliance on visual cues may pose challenges for visually impaired users, necessitating the exploration of multi-sensory feedback mechanisms. Additionally, the system's effectiveness in extreme crowd densities or emergency situations requires further testing.

Future research directions could include:

1. Long-term studies on user adaptation and behavior change in response to interactive architectural elements.
2. Integration of machine learning algorithms to predict and preemptively manage crowd flow patterns.
3. Exploration of energy-efficient lighting solutions to enhance the system's sustainability.
4. Investigation of potential applications in other vertical circulation elements, such as escalators or moving walkways.

In conclusion, the interactive staircase project demonstrates the potential for smart, responsive architectural design to address contemporary challenges in public spaces. By leveraging technology to create intuitive, user-centric environments, architects and designers can significantly enhance the functionality, safety, and experience of built spaces. As urban populations continue to grow and public health concerns persist, such innovative approaches to crowd management and social distancing will likely play an increasingly crucial role in shaping the future of architecture and urban design.

Acknowledgments

This research is based on a pilot study that was completed as a primary requirement of a postgraduate course titled “ARC616 - Interactive and Responsive Architecture” in Fall 2021. We are thankful to our postgraduate students (Amira Diaa Eldin, Ehab Medhat, Hager Magdy, Hala Medhat, Marwa Said, Meral Omar, Merna Ibrahim, Noha Al-Shafaey, Noha Abou Elezz, Shireen Al-Sharkawy, Waad Waheed, Mohamed Alfy) who contributed greatly to the research efforts.

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