A Human-Centric Approach Using Design Thinking Principles for Stampede Prevention

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***Abstract*—The risks associated with stampedes in crowds are quite serious owing to the speed at which crowds can become dense and the lack of preventive measures for managing such situations. Existing methods for monitoring crowds are usually very late and reactive, which means they are inefficient at identifying emergencies and responding to them. This paper explores a simple but effective approach for detecting stampedes. The current model was developed based on Design Thinking principles. The proposed solution consists of the following components: drones, a structural similarity index measure for detecting abnormalities rapidly, special tags for sensing crowds, and measuring crowd stability. There are two stages involved in the process rapid image analysis and further sensor-based data collection for determining whether there could be an emergency situation. The current solution was tested in a simulation environment known as Vadere. It proved to be very effective as it was able to detect the inappropriate behaviour of the crowd in advance and give an alarm around two to three minutes prior to any occurrence and it took just under one second for all this to happen. We have implemented effective techniques that ensure low utilization of the computer resources without compromising on accuracy. This research emphasizes the importance of understanding human psychology while developing any product as it enables us to develop practical solutions that can be applied anywhere.**

***Index Terms*—Design Thinking, Stampede Detection, Crowd Monitoring, UAV, SSIM, RFID, Entropy Analysis, Real-Time Systems.**

I. INTRODUCTION

As the infrastructure develops and becomes easily accessible, there will be larger meetings like religious festivals, political meetings, and sports, which are likely to form dense crowds, leading to a stampede situation, which is a quick process with minimal opportunity for intervention [1]. However, traditional crowd monitoring technologies using CCTV [2] and Computer Vision techniques [3] can work well within controlled scenarios, although such technologies tend to be highly computationally intensive and often lack the capability for real-time prediction in dynamic and dark environments, being primarily reactive, i.e., more concerned with post-incident analysis than prevention.

Although there is a rising need for predictive and holistic crowd management systems, most systems available in the market are too complex to use, lack scalability, and do not have practical application [4].

In this paper, the approach taken is Design Thinking, which incorporates user needs, practical limitations, and scalability into the design process. The system uses UAV monitoring, SSIM image recognition [5], RFID sensors [6], and entropy stability measures [7] to provide a scalable and practical stampede detection solute

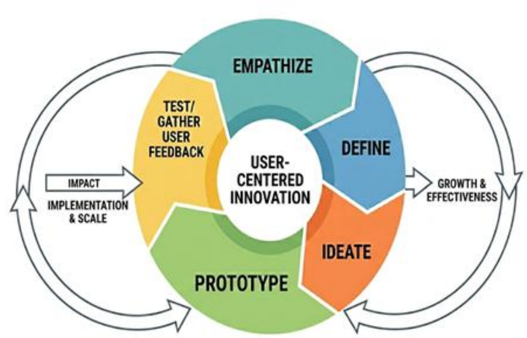


Fig 1: Design Thinking Cycle

II. RELATED WORK

Crowd management and stampede prevention have attracted significant research attention due to the increasing frequency of large-scale public gatherings and the associated safety risks. Existing studies can broadly be categorized into operational strategy-based approaches, technology-driven crowd monitoring methods, review and best-practice frameworks, and integrated intelligent systems.

Early studies primarily focused on operational planning and security strategies for managing large crowds. Real-world case-based analyses, such as the management of the Prayagraj Kumbh Mela, emphasized coordinated governance, zoning, access control, surveillance deployment, traffic regulation, and emergency preparedness to mitigate stampede risks. These works demonstrated the importance of inter-agency coordination and infrastructure planning but relied heavily on manual supervision and reactive control mechanisms. While effective at an administrative level, such approaches lack predictive intelligence and real-time adaptive decision-making capabilities [8].

With the advancement of sensing and computation technologies, research shifted toward technology-assisted crowd monitoring and modeling. Several studies provided comprehensive reviews of crowd modeling techniques, including microscopic, macroscopic, and mesoscopic models, along with flow-based, entity-based, and agent-based approaches. These models enabled pre-event planning, evacuation analysis, and congestion estimation. In parallel, vision-based systems using CCTV and image processing became dominant for crowd density estimation, motion analysis, and anomaly detection. However, these systems often suffer from limitations such as occlusion, lighting conditions, scalability issues, and privacy concerns [9].

To overcome the limitations of vision-only systems, researchers explored wireless and RF-based crowd sensing, including RFID, Wi-Fi, Bluetooth, mobile phone footprints, and device-free RF sensing. These methods improved coverage in non-line-of-sight environments and enabled crowd flow estimation at larger scales. Additionally, social media and web data mining techniques were investigated for situational awareness and post-event analysis [10]. Despite their potential, these approaches face challenges related to data reliability, device dependency, latency, and integration into real-time control systems [11].

More recent studies adopted a conceptual and managerial perspective, analyzing crowd management challenges, crowd typologies, ethical concerns, legal responsibilities, and sustainable practices [12]. These works highlighted the importance of understanding crowd behavior, communication effectiveness, medical preparedness, and infrastructure design. While valuable for policy formulation and event planning, such studies remain largely qualitative and lack algorithmic depth, real-time analytics, and system-level validation [13].

Decision-support approaches were also introduced to rank and prioritize crowd management strategies, offering structured evaluations of safety measures, surveillance techniques, and emergency protocols [14]. Although useful for strategic planning, these approaches typically do not incorporate live crowd data, predictive modeling, or dynamic feedback mechanisms.

The most recent advancement is represented by integrated intelligent frameworks that combine artificial intelligence, computer vision, Internet of Things (IoT), and cloud computing. Notably, the Integrated Intelligent Crowd Control and Management (IICCM) framework proposes a holistic architecture incorporating crowd vision, health monitoring through wearables, evacuation planning, and cloud–IoT reliability [15]. This framework demonstrates how deep learning models, such as CNNs, Vision Transformers, and GANs, can be used for large-scale crowd analysis, abnormal behavior detection, early crowd prediction, and health-aware decision-making [7]. While comprehensive, such frameworks are complex, resource-intensive, and still lack extensive real-world validation under diverse crowd scenarios [16].

From the reviewed literature, it is evident that most existing approaches address isolated aspects of crowd management, such as surveillance, modeling, health monitoring, or strategy planning. There remains a critical research gap in integrating predictive crowd behavior analysis with simulation-based validation and real-time decision support, particularly for stampede risk estimation. Moreover, limited work explicitly connects simulation outputs with live sensing data to quantify stampede likelihood and proactively guide intervention strategies.

Motivated by these gaps, the present work aims to bridge operational planning, intelligent sensing, and simulation-driven analysis by proposing a unified framework for early stampede detection and prevention, supported by predictive modeling and validated through crowd simulation.

Approach	Cost	Real Time Monitoring	Early Prediction	Complexity
CCTV Based Monitoring	High	Yes	No	High
RFID Based Monitoring	Moderate	Yes	Sometimes	Moderate
Deep Learning System	Very High	Yes	Yes	Very High
Proposed System	Low	Yes	Yes	Low

Fig 2: Comparison of existing crowd monitoring approaches

III. DESIGN THINKING METHODOLOGY

The Design Thinking approach, which is a human-centric process based on the needs of the users and addressing real-world issues with implementable solutions [17], is used to design the suggested stampede prevention and detection system, which is not like typical engineering because it might be too complicated and unrealistic for real-world implementation. There are five major steps involved in the Design Thinking process: empathize, define, ideate, prototype, and test [18].

3.1. Empathize

When in the empathize stage, the knowledge about the general public, event organizers, and emergency authorities dealing with the situation is taken into account, including the realization that people who attend big events may be oblivious of the dangers around them, causing them to go into panic mode and behave unpredictably amid congestion, which makes monitoring of large groups of people in real time by authorities and guaranteeing their safety by organizers challenging.

According to real-life observations, stampedes usually result from unexpected variations in crowd density, bottle-necks at entry and exit points, as well as lack of information on time, all made worse due to panic and misinformation. This phase brings out the lesson that a solution must have the capability to provide situational awareness, instability detection, and alert dissemination.

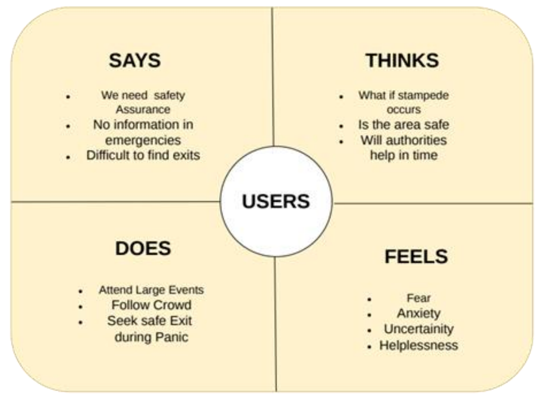


Fig 3: Empathy Map for crowd safety stakeholders

3.2. Define

With the help of empathy stage findings, the problem statement is formulated as follows: there are no prediction systems working in real time that could identify the possibilities of a stampede and warn about such hazards. At present, existing crowd monitoring systems are mostly reactive, computationally costly, and inefficient under resource-limited conditions.

The core objectives of design are to come up with a system capable of predicting future cases of stampedes several minutes before the actual occurrence. It should have low computational complexity, be affordable, real-time, and capable of being used in large-scale events.

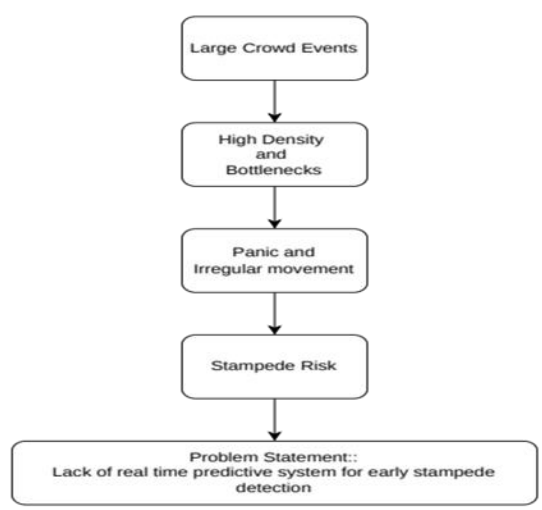


Fig 4: Problem Definition flow for stampede risk

3.3. Ideate

The ideation stage involved considering various crowd monitoring and stampede detection techniques like computer vision based on deep learning, sensor based monitoring and simulation models, along with their pros and cons like high computation demand, expensive, and inability for real-time application, and a hybrid and light approach to these techniques was suggested by incorporating them together like using Unmanned Aerial Vehicle (UAV) for aerial monitoring over larger areas, SSIM for fast image comparison, RFID sensoring for acquiring real-time crowd parameters, and entropy calculation for stability measurement.

Fig 5: Ideation and solution concept

3.4. Prototype

During the prototype stage, the ideation of the solution takes shape in terms of a functional architecture of the system. The system will be developed as a modular system, with a UAV module capturing real-time video images of the environment and processing these images using the technique of SSIM, analyzing them for similarities with stampede videos. If the similarities exceed the threshold, then the analysis moves on to the RFID sensor readings, which will measure the density, motion, pressure, heartbeats, and stability of the crowd. Using these readings, a probability score will be calculated, after which the entropy value will be calculated based on the probability score.

Such an approach makes it possible for the system to make quick initial assessments and conduct reliable analyses with minimal computational burden.

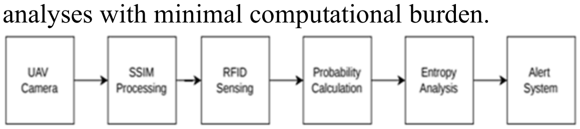


Fig 6: Prototype of the defined solution

3.5. Test

Testing evaluates the feasibility and strength of the system design in a simulation environment, whereas validation will be carried out by creating scenarios of crowd simulations through the Vadere crowd simulation software and testing its capabilities with respect to high density, bottlenecks, and panicking behavior by providing simulated data inputs to the designed system.

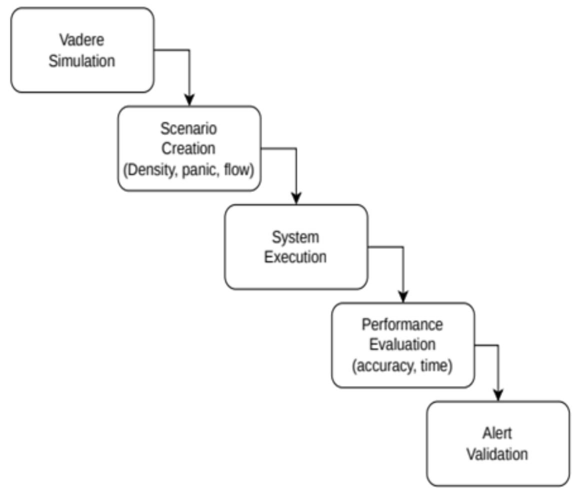


Fig 7: Test phase implementation

The outcome shows that the system is able to identify any likely occurrence of a stampede with up to 2-3 minutes notice and processes that in under one second. The trial phase proves that the Design Thinking approach to problem-solving will create a system that is efficient and feasible at the same time.

3.6. Importance of Design Thinking

The use of Design Thinking ensures that there is an actualization of the system to solve these real-life problems such as the uncertainty of crowd behaviours, lack of infrastructure, and fast decision making compared to conventional ways in which complex algorithms are used; thus, the use of Design Thinking guarantees that there is an easy-to-use and scalable model of the system, despite its size, so that it can work efficiently under the challenging conditions of big crowds. Moreover, the repetitive process of Design Thinking would ensure that there is constant testing and improvement of the system through the Design Thinking process, thus making it very efficient. Design Thinking application in this scenario can help bridge the gap between the theory and the practice of developing the solution because reality is usually much more complicated and not necessarily technical compared to the engineering approach. The real-life problems connected with the stampede detection involve the unpredictability of crowd behavior, low infrastructure capabilities, and timeliness of decisions taken by the authorities. The project incorporates Design Thinking to resolve the problem. The first phase of empathy makes sure that all the requirements of the stakeholders are met; in this situation, it implies taking into account the problems related to the safety of the public and challenges faced by the authorities; the second phase helps define the problem clearly, for example, the late reaction and the absence of alarm systems; the third phase is aimed at finding easy ways to cope with the issue.

IV. PROPOSED METHODOLOGY

The suggested technique provides a unique, light weight, and efficient system of crowd stampede prevention and control using aerial surveillance, image similarity computation, crowd data obtained by sensors, and entropy-driven stability calculation. This system runs through a continual monitoring process for identification of any anomalous activity in crowds in time. The approach is based on a two-step algorithm that integrates rapid visual inspection with sensor analysis.

This involves data gathering at the beginning of the process by capturing images of the crowds with the use of an unmanned aerial vehicle (UAV) that gathers the aerial frames of the crowd at a specific frame rate. With this method, we can be able to obtain a complete image of the crowd's distribution, density, and patterns for wide area coverage since there would be no need to install fixed surveillance systems in large-scale crowds.

The second method utilizes Structural Similarity Index Measure (SSIM). The system will make use of the structural similarity measure to compare the structural characteristics of incoming video frames against those stored in a database containing reference images, where each reference image symbolizes an example of stampedes, and compares the statistical structural similarity of the current frame to the reference images. If there is a high degree of statistical structural similarity between the live frames and reference images (for instance, over 40%), the system will identify the live frame as abnormal and move onto the next phase, while frames that have a low statistical structural similarity to the references will be ignored.

In the case that an emergency event is recognized, the RFID sensor analyzing module will be triggered to conduct a series of analyses based on the use of RFID sensor bands which measure various crowd parameters, such as density, speed, crossing, reversal, pressure, heart rate, stability, and height, thereby providing a clearer idea about the root cause of the instability event.

Afterward, the sensor data is analyzed using a parametric approach that uses a probability score based on crowd parameters, where reverse, cross, and pressure movements are given greater weight because these movements can effectively predict disorder. This process provides a consistent and efficient risk analysis approach that is responsive to shifts in crowd behavior. Finally, the calculated probability score is used to obtain an entropy value that acts as an indicator of stability. When the value of entropy exceeds 0.94 or falls below 0.06, the system perceives such a scenario as being unstable, and when entropy levels exceed the specified threshold, an alarm is triggered.

In case of a detected risk scenario, the alert generation module activates certain warning systems, such as hooters, visual warnings, and alerts to authorities to begin the necessary process to control the crowd movements and avoid the situation evolving into a stampede. The alerting system should work in real-time mode, because the system must react fast in order to solve critical issues in time.

The suggested approach was examined in the Vadere crowd simulation model, which simulates various crowd behavior in dense situations, bottleneck events, and situations of panic. These simulated scenarios were used as an input for the analysis using the proposed approach, and the findings show that the system could detect unstable situations and warn about the upcoming stampede 2-3 minutes ahead of time, with low processing time (less than one second).

To conclude, the discussed method is able to find an optimum point between computational burden and prediction accuracy by merging simple image processing with data fusion from various sensors and entropy-based decision-making, while its modular nature allows achieving scalability and flexibility, which makes this system useful in the context of mass gatherings and limited resources. The effectiveness of the described technique proves that it is possible to solve sophisticated problems, like stampedes prevention, with the help of multiple data streams and basic data analysis.

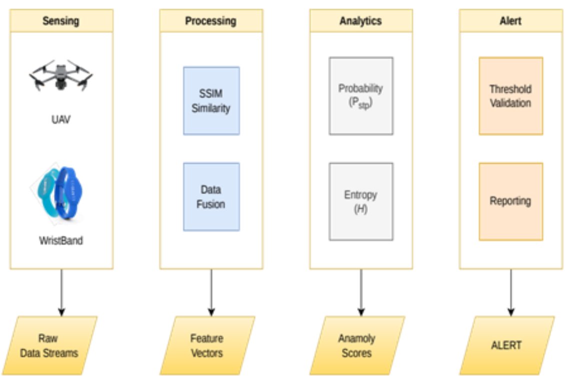


Fig 8: Modular Division of the proposed system

V. MATHEMATICAL MODEL

The proposed stampedes detection algorithm includes probability estimation using sensors, entropy evaluation of stability, and image similarity. The models of mathematical methods enable the system to detect abnormal crowd behavior and predict the likelihood of stampedes.

5.1. Structured Similarity Index Measure

In order to determine the degree of similarity between the real-time UAV video frames and reference images indicating the occurrence of stampedes, Structural Similarity Index Measure (SSIM) [19] can be used for comparison of the images, where the structure within the image, rather than individual pixels, is considered for comparison, unlike conventional methods which only consider pixel-based comparisons.

In order to classify the abnormal behavior, the proposed system will compare each incoming UAV frame against a number of reference images depicting stampede cases, and if the SSIM score exceeds a certain threshold (such as 0.40), then the frame will be classified as abnormal crowd behavior.

$$\text{SSIM (x, y)} = \frac{(2\mu_x\mu_y+C1)(2\sigma_{xy}+C2)}{({\mu_x}^2+{\mu_y}^2+C1)({\sigma_x}^2+{\sigma_y}^2+C2)}$$

where covariance, mean (μ), and variance (σ2)

5.2. Probability Model for Stampede Prediction

Once the detection of the anomaly is made by the SSIM, the next stage of calculation will be estimating the probability of the occurrence of the stampede based on various crowd parameters like physical and behavioral properties, through the use of the RFID sensors. The probability calculation model used is such that: High density, pressure, and movements mean a higher risk, while high reverse and crossing movements increase the risk.

Low movement speeds and high variation of heights mean a compressed crowd.

The result of such a calculation will produce a probability score that acts as a normalized measure of risk in the crowd.

$$\text{stp} = \text{K} * \frac{dt(RMCM)^2prst^2HB}{mshv}$$

5.3. Entropy Based Stability Assessment

The probability score generated is then translated into entropy [20], which is a notion in information theory used to measure uncertainty and chaos within the crowd system, with entropy being represented by the formula below:

The system sets threshold values such that moderate entropy values suggest orderliness and stability. Very low or very high entropy values imply chaos and instability. If entropy values cross the threshold values below, the system labels the scenario as high-risk and raises an alarm.

$H(S) = \Sigma\, p_i \log_2 (p_i)$

$H<0.06 \rightarrow$ Highly unstable (risk of stampede)

$H>0.94 \rightarrow$ Chaotic condition (high disorder)

5.4. Interpretation of the Model

This multi-level technique employs SSIM for fast visual examination, uses a probability function for capturing dynamic aspects of crowds, and relies on entropy analysis to measure the stability of the whole system, resulting in highly accurate and efficient crowd detection at a lower computational cost.

VI. EXPERIMENTAL SETUP

The purpose of the experiment is to evaluate the viability and functionality of the stampede detection system. In order to recreate realistic crowd conditions without compromising the viability of the experiment, it employs a combination of hardware, software, and artificial data.

6.1. Hardware Configuration
Our system is cost-effective and scalable, using a lightweight hardware setup:
6.1.1 Unmanned Aerial Vehicle (UAV):
The unmanned aerial vehicle (UAV) that is fitted with a high-definition camera collects live video footage from above the crowd. The bird's eye view enables surveillance of large crowds from afar.
6.1.2 RFID Wristbands:
Sensors within low cost RFID tags are used to gather real time data pertaining to crowd metrics like crowd density, pressure, motion, and physiologic factors. Wristbands allow for local and constant data acquisition without much computation.
6.1.3 Processing Unit:
A standard desktop computer is used for processing video frames and sensor data. The system is designed to operate efficiently without high-end computational resources.

6.2. Software Tools and Libraries
Implementation of the algorithm uses readily available software technologies:

- Programming language: Python 3
- Libraries:
  - NumPy for performing numerical calculations
  - PIL (Python Imaging Library) for performing operations on images
- Operating system: Windows-based

Using lightweight libraries makes sure that algorithms run fast and in real time.

6.3. Datasource and inputs
The algorithm works through a process that involves both visual and sensor input.

- Visual Input: Frames from the UAV video taken in real-time
- Reference Pictures: Defined reference pictures for stampede scenarios
- Sensor Input: Parameters based on RFID, which include density, velocity, pressure, and stability

This combination provides for multi-modal analysis of crowd behavior.

VII. SIMULATION ENVIRONMENT

The simulation technique is adopted in the validation process of the suggested methodology because of the problems associated with the collection of stampede data from reality. Controlled experiments become possible under realistic crowd conditions through simulation.

7.1. Simulation Tool
Simulation of Pedestrian Dynamics and Crowds is done using the Vadere simulation platform. Vadere simulation platform is a freely accessible software package that allows for advanced simulation modeling approaches such as the social force model [21].

7.2. Scenario Design
To evaluate the system's performance based on varying conditions, various scenarios for crowds are created using simulation. These include:

- Crowds with high density
- Bottlenecks at entry and exit points
- Reverse movement due to panic
- Cross movements

Stampedes are more prone to happen in real-life cases; therefore, these scenarios will be used to mimic real-life cases.

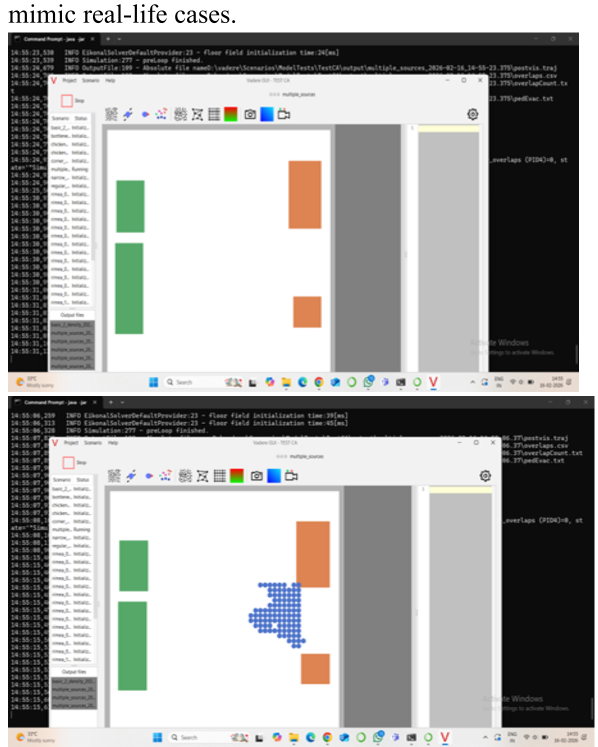


Fig 9: Screen Shots of a Sample Scenario

7.3. Data Generation

Some essential crowd-related parameters that would be generated through the simulation include:

- Density distribution
- Movement and velocity
- Inter-personal interaction force

These values would serve as inputs for the proposed crowd-detection system, particularly for validating the entropy and probability models.

7.4. Integration with Proposed System

For performance evaluation of the proposed method, the data is fed into the system. The identification of instability is based on entropy calculations, probability calculation, and SSIM-based screening.

7.5. Purpose of Simulation

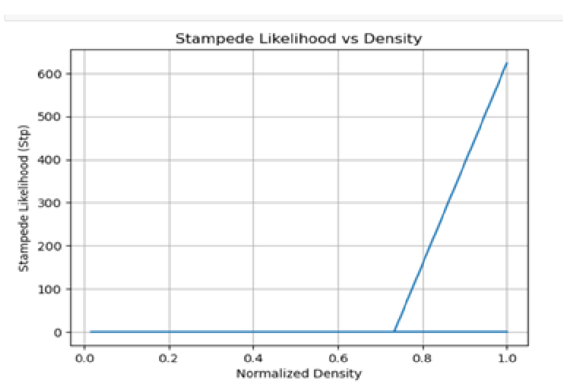
The simulation environment plays several roles:

- Allows for the safe experimentation with extreme crowds
- Ensures consistent experiment conditions
- Tests system functionality prior to its implementation in the real world.

7.6. Validation Outcome

The results obtained from the simulation demonstrate that the system can detect strange crowd behavior and trigger an alarm at an early stage. The reliability and effectiveness of the system are ensured through the use of simulation together with the proposed approach.

VIII. RESULTS AND DISCUSSION



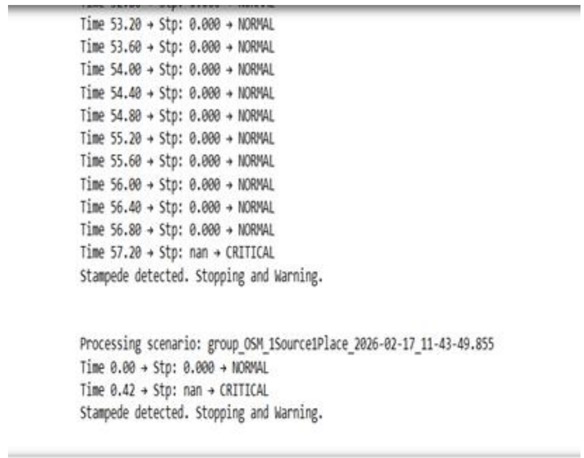


Fig 10: Result of the proposed system

The simulations generated by Vadere software for creating crowds are employed for evaluating the proposed approach for detecting stampedes in crowd environments. The evaluation process involves the use of crowds in scenarios such as high-density crowds, bottlenecks, and chaotic movement.

In order to identify anomalies in the crowd, the SSIM-based module performs well in identifying anomalous behavior when compared with the reference image. Although frames where there is congestion go beyond the set threshold, frames indicating normal situations have a low value of similarity.

Some of the key crowd indicators like density, flow, and pressure are recorded using RFID sensors in this particular study. In dangerous situations, these factors show substantial variations, hence resulting in high likelihood levels. The extreme entropy indicates unstable conditions, and this method also evaluates the stability of crowds. The processing duration is less than one second, and the system manages to produce alerts up to two to three minutes before stampedes occur. It is thus clear how the proposed method works in real-time.

From the results obtained from the experiment, the system manages to identify crowd instability successfully and promptly. The actual implementation of this system can be enabled by combining the use of lightweight methodologies and multiple sources of information.

IX. DESIGN THINKING IMPACT ANALYSIS

The development process of the suggested approach was significantly influenced by the implementation of the Design Thinking framework. It became easier to comprehend the real-life problems such as panic attacks, insufficient early warning systems, and complicated crowd surveillance through the empathy stage. At the define stage, it was ensured that the need for developing a real-time and lightweight prediction model was emphasized.

In the ideation stage, overly complicated designs were not considered, and the decision was made to use a very efficient design involving UAV surveillance, SSIM analysis, and RFID sensors. This could be accomplished through a flexible and efficient design in the prototype stage, and simulation-based validation would be assured in the testing phase. Considering all these facts, Design Thinking assisted in the creation of an implementable solution.

X. ADVANTAGES

- Ability to detect and provide early warnings in real time
- Lower computational cost than deep learning approaches
- Uses information from various sources, enhancing accuracy
- Easily scalable for crowd monitoring at a larger scale
- Effective in resource-limited settings

XI. LIMITATIONS

- System validation uses simulations only
- Needs to be tested in the real world to work fully
- Relies on the accuracy of sensor data
- Threshold values may have to be adjusted depending on situations

XII. SOCIETAL IMPACT

Through ensuring safety among people attending social activities, the proposed mechanism would have a huge benefit for society. This is because it makes it easy for those in charge of ensuring the safety of the people to be able to monitor the movement and also get early warning that could lead to stampede. Due to the affordable and scalable nature of the device, it can easily be applied in underdeveloped countries where there are no advanced facilities.

XII. CONCLUSION

This paper proposes a lightweight and efficient stampede detection system developed using the Design Thinking approach. This system can detect instability in crowds in real-time through the use of UAV surveillance, SSIM analysis of images, RFID sensor systems, and stability analysis based on entropy. The results indicate that the proposed technique can provide an early warning system with minimal computational costs, thus making it feasible for practical deployment.

XIV. FUTURE WORK

In future, efforts will be made to implement the system and apply it during big events. The accuracy of the system will further be enhanced by using more data feeds and better prediction algorithms. Communication will be facilitated by making connections between the system and the mobile alert systems for better communication.

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