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Empowering Local Authorities in Fire Services: The Intervention of Digital Twin Technology and Artificial Intelligence.

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Abstract: *It's a high time that, the local bodies who are solely responsible for protecting human lives and public as well as government property require a paradigm shift in their approach towards tackling the disaster management especially the fire disaster. With the fast-changing scenario of advancement and development in the life style of public at large and also due to accelerating urbanization, the problem of Fire Disaster has acquired a totally new and complex dimension which has further become more complicated owing to climate change and insurge of high-rise structures. Similarly, absence of exposure to new technological advancements to local bodies supporting staff who are responsible for combating the fire cases and the decision makers, who are responsible to bring necessary developmental changes in the available resources, has brought back the status of disaster management capabilities and thus the local bodies presently seem to be not equipped to face the disaster effectively and efficiently. It is, therefore essential to adopt and adapt newest technologies such as Artificial Intelligence, Digital Twin Technology, Machine Learning and Internet of Things (Iot) and apply these modern technology-oriented designs and tools to support and augment the skills already possessed by the local body representatives and who are already aware of the principles of disaster management but with the coupling of the newest and modern technology their capabilities can be more sharper and advanced which is the need of the hour.This paper is an attempt to highlight this need by which the present human resource at local bodies will be able to sharpen their skills of disaster management and will be more suitably armed to tackle the fire disasters more efficiently and effectively. It is expected that by adopting to these changes where the exposure to predictive analysis and risk management, data analysis, predictive modelling, early warning system, real-time monitoring, fire behavior prediction, and anticipation besides introduction to twin technology, can bring out sea changes positively in the management capabilities of local bodies.*
Keywords: *AI (Artificial Intelligence), Digital Twin, Predictive Modelling, Internet of Things, Machine Learning, Robotic Assistance, Real Time Monitoring.*

INTRODUCTION

Background to the Study

In the face of escalating urbanization and climate change, local bodies - city fire brigades are confronted with increasingly complex situations [1] and frequent challenges of various disasters and among them the challenge to face fire related disasters, acquires a multidimensional threat of human and property loss, thereby making these challenges very complex, complicated and at the same time it becomes very important to address them with precision and respond within a shortest possible time to ensure minimum loss of property and human lives. In order to deal with these challenges more efficiently, there is a need to think differently- afresh, explore and execute new strategies, taking help from the latest available technology. It may be emphasized here that; traditional firefighting and disaster management methods are often insufficient to address the rapid spread of fire and the unpredictable nature of emergencies.

Implementing the newest technology by the fire services not only empowers the first respondents - the local bodies- to tackle the situation with more confidence and bring the situation under control more quickly, but it also ensures that the chances of losing life of fire service personnel and the residents are eliminated to a great extent.

Artificial Intelligence (AI) presents an innovative solution to enhance the efficiency [2] [3], responsiveness and effectiveness of local bodies who are responsible for dealing with such situations, in managing various disasters and fire disaster in particular. This paper, is an attempt to explore how AI can revolutionize fire disaster management focusing on predictive analysis, real time monitoring smart dispatch system, robotic assistance, predictive maintenance, enhanced communication and post incident analysis, which is intended to zero down the probable cause/causes of the disaster. This paper also suggests the acceptance and use of Digital Twin Technology to enhance effectiveness of firefighting, training and rescue operation.

LITERATURE REVIEW

Theoretical Framework and Review of Literature

Internet of Things (IoT): It's a collective network of the connected device and the technology that facilitates the communication between the device and the cloud and also between the devices as the data inputs into a software platform where data updating in real time can be possible. Internet of things technology can be used in the following: heat, smoke and gas sensors in high-risk zones and critical structures and utilizing drones [4] and robotic surveillance for real time

monitoring. By enhancing the machine learning algorithms, the expenses associated with the sensors can be reduced [5]. With the help of visual algorithms various disasters can be detected.

Artificial Intelligence & Machine Learning:

AI is the field of computer science which is applied and dedicated to resolving intellectual and psychological concerns such as learning, problem solving and pattern recognition. The capacity of fire prevention and fire suppression can be effectively enhanced by proper investment in the field of human resources, other fire equipment and technology. Artificial Intelligence is being applied after due research in the advanced countries. It also becomes important to consider the elements such as the cost, the budget in production, equipment management and maintenance of AI products. [6] The proper use of the Artificial Intelligence technology in fire detection, response to attend and fire investigation enhances the efficiency of fire services and Urban Local Bodies. This technology is useful in quick identification of fire outbreak and can be effectively applied for analyzing the fire incidents, predicting fire behavior. Furthermore, it can serve as a useful tool in planning of evacuation. Machine Learning is an AI technique that develops statistical models and algorithm and applies to computer system which performs tasks without specific and explicit instructions depending on patterns and inference. Knowledge of various stages of fire is vital parameter while attempting suppression of room fire. The Fire fighters who are experienced and knowledgeable can take a decision applying strategic tactics by ascertaining the correct stages of fire but this suffers from subjectivity. In order to have a correct judgement about the stages of fire, this technology of Machine Learning can be effectively utilized by the fire fighters to identify various stages of fire in case of the residential fire (Room Fire).[7] Digital Twin technology uses ML algorithms to process large sensor data and recognize the data patterns. AI coupled with Machine Leaning offers data insight regarding performance, maintenance, emission and efficiencies. Predictive analysis in fire services leverages data analytic and machine learning to anticipate fire outbreaks, identify high risk areas and optimize resource allocation which in turn increases safety and efficiency and overall performance of local bodies.[8]. Predictive analysis uses data, statistical algorithm and machine learning techniques to anticipate outcomes in future, based on past data. Risk assessment is a systematic process to identify, analyze and evaluate potential hazards and risks associated with a particular activity with a sole intention to find out the vulnerability and impact, coupled with the probability and further develop mitigation plans to ensure their overall impact is acceptable for the people and the property.AI can analyze data from different sources including Thermal Imaging Cameras, Infra-Red sensors to detect smoke, fire and heat sources in real time. With the AI technology, these risks can be predicted in advance with the help of predictive analysis. These modern techniques when applied to risk assessment and prevention the impact/ outcome of potential fire hazards can be minimized.

Real Time Monitoring:

Integrating AI with IoT (Internet of things) sensors enable real time monitoring of environment for signs of fire smoke and gas leaks. These sensors can be installed in residential, commercial and industrial areas to detect anomalies and trigger early warning [9]. AI enabled surveillance cameras and drones can further enhance monitoring capabilities, thereby facilitating fire brigades to assess situations remotely and dispatch appropriate resources promptly. This reduces response times and prevents small incidents from escalating into disasters.

Fire Behavior Prediction and anticipation:

AI models can predict fire growth and spread direction, intensity and other fine details required to analyze fire, based on factors like weather patterns, fuel moisture levels, and topography which facilitates evacuation planning, resource allocation and adopting fire suppression strategies by the local bodies. AI models can simulate fire spread and intensity based on environmental conditions, building material ventilation arrangements and other such factors. This can reveal important pattern of fire behavior in given circumstances, which then can be effectively applied to formulate suppression methodologies and firefighting strategies.

Data Analysis and Predictive Modelling

AI algorithms analyze vast datasets, including historical fire cases, conditions of environment [10] e.g. weather patterns, building layouts, occupancy pattern and their movement in order to identify area and situations with taller fire risk.

AI can create Predictive Modelling that can predict the probability of incident occurring which can be of great help to Fire Departments and Local bodies in allocating resources, prioritize schedule of fire inspections and thereby execute and implement prevention strategies. Machine learning algorithms can assess the probability of fire and recommend preventive measures. For example, Predictive Models can identify electrical grid faults [11] or flammable material storage sites, with which the Local bodies can take proactive steps to lessen the potential disasters outcomes. AI can also provide risk maps to guide allocation of resources and help engage readiness of staff in advance.

Early Warning Systems:

AI algorithm can analyze data from various sources including patterns of weather, structural details of the building, historical data of Fire Incidents and sensor data to identify potential fire hazards and predict when and where fire might occur. AI Powered systems can monitor conditions in real time situations which can detect potential fire hazards in

advance before it transforms into more severe situation [12] permitting early action by Local Bodies potentially preventing fire breakout and probable fire spread.

Autonomous System and Robotic Assistance:

At times approaching fire in order to suppress or operate suppression system becomes almost impossible due to adverse environment and extreme circumstances owing to intolerable heat, smoke and radiation hazards. In such situations an autonomous system comprising of Fire Fighting robots [13] [14] and drones equipped with AI capabilities can perform the job with substitution. AI driven Robots can navigate hazardous environment, assess fire situation locate trapped individuals and deploy extinguishing agents with precision where human intervention becomes risky [15.16,17] AI powered drones can be deployed to perform initial aerial survey and also to capture real time footage to identify hots spots in order to plan Fire Fighting strategy. Thus, it becomes very easy to take suitable and timely decisions by enhancing situational awareness.

Digital Twin Technology:

The years old traditional Fire Protection system which depends upon alarm system, detectors and pressure information from sprinkler system are only effective for an early fire detection and alarm but offer very meager assistance in fire prevention. In such a system real time monitoring, rescue and evacuation cannot be possible. In order to enhance building fire safety, introduction of digital twin technology can be revolutionary in Fire Safety management of structures and various occupancy. A digital twin is a virtual model of a physical structure. It covers the life-cycle data and uses real time data sent from the sensors installed on the structure to simulate the behavior and monitor operation. Digital Twins can replicate almost each and every object right from the small object, structures, equipment, engines and other heat sources and even cover complete cities. According to NASA, the digital twin is an integrated multi physics, multi scale, probabilistic simulations of an as-built system that uses the best available physical models, sensors updates, fleet history etc.to replicate the life of its corresponding twin. In summary we can say that every information related to the physical manufactured product and its digital twin shall be identical. [18] The Digital Twin Technology permits the overall monitoring of the performance of the object digitally twinned, identify potential faults which can be utilized to arrive at better informed decisions about maintenance of the object and its life cycle. The digital twin works by digitally replicating a real physical asset in the virtual environment including its functionality, features and behavior. A real time digital representation of the original object is created using smart sensors installed on the object that collect data from the targeted object. [19,20]

Digital Twins are quite different to simulations; both are virtual based simulations but pure simulations are used to depict off line optimizations and designs. While simulations are basically used to study “what if” scenario, whereas, Digital Twins are more technical and technologically more intricate. These are virtual environments with which one can interact and update in real time situations in order to take suitable and timely decisions. Digital Twin uses various technologies to offer digital model of an original real physical asset. As far as the building fire safety is concerned, the digital twin is designed and decided based on Building Information Model (BIM) at the time of design stage itself. It connects all sensors and transmits data through Internet of Things (IoT) and connects the virtual model.

Functions and utility of Digital Twin:

Fire Risk Information: The model is regularly fed with the information of enhancement or curtailment of Fire Load and inclusion of dangerous goods via transportation inside the building. Remote Real Time Monitoring: Based on virtual representation the Digital Twin enables remote real time monitoring. Digital Twin unites all needed virtual information with virtual models. It also fuses historical and real time data and predicted data to track the past, monitor the present and predict futuristic possibilities. It can understand the present situation and optimizes the decision-making process.

Interconnection with HVAC system: The digital twin when integrated with existing HVAC system of the building and sensors in more voluminous structures, real time monitoring fire scenario and hidden scenes can be monitored, which in turn can enhance the response time and suppression efforts by the fire services. Actual Fire Scene Information: The traditional detectors can be of very minimal help in dissipating information about real time fire situations at the fire site as they have limitations owing to heavy and dense smoke and rapid and vast flame spread. The digital Twin technology can be of immense support in deriving this vital information which surely help Fire Services in strategic planning at the early hours of fire breakout. Fire Forecasting: The digital Twin technology can be employed to forecast fire evolution including Flash-over, Fire Travel in various parts of the building, Fire deterioration of environmental conditions for the people and fire service respondents who are exposed to fire and probable structural collapse.

Emergency Response and Incident planning:

Digital Twin for Emergency Response and Incident planning is virtual representation of real-world environment, systems or assets used to simulate, analyze and optimize response to emergencies. These facilitate data driven decisions in critical situations. This includes: Disaster preparedness and Simulations, Real-time Incident Monitoring and response, Traffic and evacuation., Crisis Communication, Infrastructure and facility safety monitoring, Post event analysis and learning.

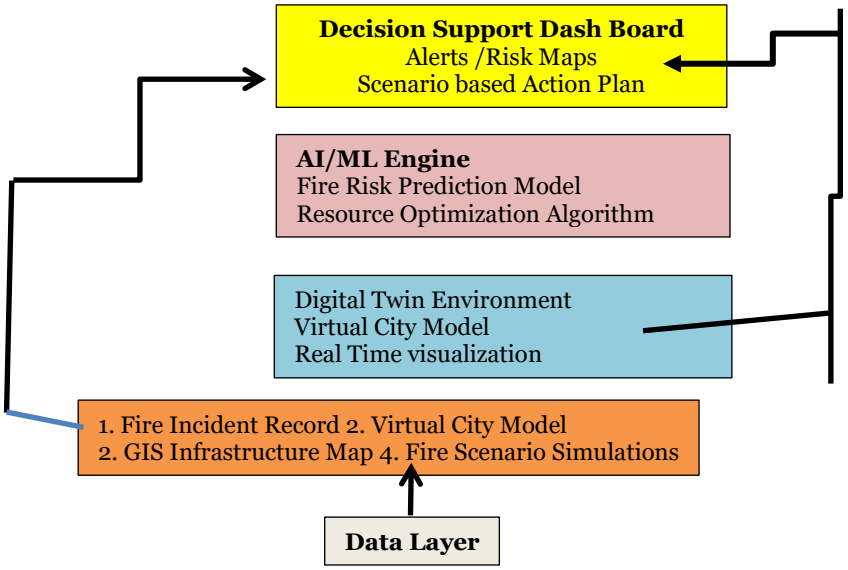
RESEARCH DESIGN

This paper is based on a conceptual research design, which is appropriate for models, frameworks-that can be empirically tested latter.
Type: Qualitative and simulation -informed conceptual.
Scope: Focused on Nagpur City
Data Sources: Secondary Data (Govt. Reports, Fire Service Manuals, Academic Papers, Smart City documentation.

PROPOSED RESEARCH METHODOLOGY

1. Proposed Methodology for future Implementation: While this paper lays down the conceptual groundwork, the following steps are planned for future field-based research:
2. Diagnostic Study: The field visits will be conducted to NMC (Nagpur Fire Brigade- Stations) and data is planned to be collected through interviewing the fire officers and staff about current procedure, technologies used and challenges being faced. Past Fire Incident report data shall be analyzed.
3. AI/ML Model Development: The data regarding fire incidents is proposed to be used to build machine learning model and later on the algorithm can be applied to identify high risk areas and predict fire outbreaks.
4. Digital Twin Prototype: The Virtual Model of a selected fire prone area is proposed to be created and simulation of fire scenario, emergency response and emergency routes is proposed to be carried out.
5. Evaluation and Feedback: The Evaluation and feedback is proposed to refine the model if needed.
6. Road Map: A suitable Road Map shall be suggested in order to integrate into Municipal Disaster Management System.
7. Flow Diagram of the proposed System

Fig. No.1



RESULTS & DISCUSSION

1. Expected Results: Although the present paper is conceptual in nature the implementation of the proposed framework is expected to bring many trans-formative results for the Nagpur Fire Services and also similar urban bodies engaged in similar cities.
2. Improved Fire Risk Prediction: The application of machine learning can help identify high risk zones based on historical fire incidents data, urban density, weather patterns and type of infrastructure.
3. Enhanced Emergency Response: By integrating AI-based resource allocation tools and scenario planning, the framework can reduce decision making and optimize the deployment of firefighting personnel and equipment.
4. Simulation and Planning using Digital Twin: The Digital Twin environment will allow authorities to simulate various fire situations, test response plans, and conduct virtual training for firefighters. These can be achieved without real world risk.
5. Data Driven Governance: The adoption of these technologies can improve inter departmental coordination between the fire services, municipal authorities, police, NDRF and health services through a shared decision support dashboard.
6. Policy Inputs for Smart Cities: The research will generate a model that could influence Fire Safety field in India's Smart City and Disaster Management policies.
7. Significance of the Research Study: The study is more significant in many ways:
8. Urban Fire Safety Modernization: This will help to fulfill the need for Indian cities to modernize their emergency services. This is more important owing to rapid modernization and consequent enhanced disasters risks.

9. Capacity Building for Urban Local Bodies: The proposed system enhances operational efficiency and at the same time takes care of capacity building by offering training tools and facilitates planning and strategic analysis.
10. Scalability and Adaptability: This study is planned for Nagpur as a focus point but can be considered for several similar local urban bodies responsible for managing Fire Disasters with minimum efforts.

CONCLUSION

The urban structure in the city is acquiring much more complexity day by day as the development in every aspect is taking its shape as per the expectation of growth. The consequence of ever-growing risk of fire related disaster necessitates the shift from old conventional methods and modes of fire service to more advanced and intelligent substitutes. This conceptual research study has put forth and proposed technology oriented frame work that integrates Artificial Intelligence (AI) Machine Learning (ML) and Digital Twin technologies for transforming the nature of fire services of Nagpur city.

By suggesting to shift from current reactive practices to predictive, data driven system, the paper contributes to both academic literature and suggests practical governance. Though the current work is exploratory in substance the future research may include empirical data collection, prototype development, stakeholder validation and showcasing implementation possibilities.

The findings and proposed model can definitely serve as a blue print for policy makers fire service administration, urban planners and technology developers interested in building resilient and smart emergency services. This can be equally applicable and executable in similar urban centers in India and abroad.

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