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IoT-Based Disaster Management and Early Warning System

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Abstract - Disastrous events are cordially involved with the momentum of nature. As such mishaps have been showing off own mastery, situations have gone beyond the control of human resistive mechanisms far ago. Fortunately, several technologies are in service to gain affirmative knowledge and analysis of a disaster's occurrence. Recently, Internet of Things (IoT) paradigm has opened a promising door toward catering of multitude problems related to agriculture, industry, security, and medicine due to its attractive features, such as heterogeneity, interoperability, light-weight, and edibility. This paper surveys existing approaches to encounter the relevant issues with disasters, such as early warning, notification, data analytics, knowledge aggregation, remote monitoring, real-time analytics, and victim localization. Simultaneous interventions with IoT are also given utmost importance while presenting these facts. A comprehensive discussion on the state-of-the-art scenarios to handle disastrous events is presented. Furthermore, IoT-supported protocols and market-ready deployable products are summarized to address these issues.

Introduction

Natural disasters, including earthquakes, floods, hurricanes, and tsunamis, can cause devastating damage to life, property, and the environment. Their unpredictable nature makes early detection and timely response critical in reducing casualties and economic losses [1-6]. Traditional warning systems often rely on limited data sources and have delayed responses, making them less effective in rapidly evolving situations. In recent years, the integration of Internet of Things (IoT) technologies has revolutionized the approach to disaster management. IoT offers a robust framework for real-time monitoring, data collection, and early warning alerts by utilizing a network of interconnected sensors, devices, and communication platforms. These IoT-based systems enable continuous tracking of environmental parameters such as seismic activity, weather conditions, river levels, and ocean currents, providing vital information to predict natural disasters before they occur [7-11]. This research investigates the potential of IoT in developing early warning systems for natural disaster management. By leveraging IoT's capabilities in sensing, data analysis, and communication, these systems can offer more accurate and timely warnings, allowing communities to evacuate and prepare in advance. The paper also explores the challenges in implementing IoT solutions, including technical, economic, and social barriers, and suggests pathways for enhancing the efficiency and scalability of these systems globally [12-18]. Ultimately, IoT-based early warning systems promise to play a key role in disaster risk reduction and climate change adaptation.

BACKGROUND AND MOTIVATION

Disasters often take place in the vicinity of human livelihood. Most of the time, it is either natural (e.g., landslide, earthquake, tsunami, flood, forest- fire, and lightning) or man-made (e.g., industrial explosion, leakage in an oil pipeline, leakage in gas production, and terrorist attacks). Regardless the cause of incident, disaster leads to huge destruction in terms of economic and human lives. Some of the dangerous disasters in the history of mankind are Bhopal (India) gas accident (1984), Chansala (India) mining disaster (1975), 9/11 terrorist attack (USA), Chernobyl (Russia) nuclear accident (1986), Indian Ocean tsunami (2004), Nepal earthquake (2015), and Fort McMurray (Canada) forest re (2016). Around 11 million people have directly or indirectly got affected during last decade [19],[20]. In most of the cases, people have acted just like an observer. The main reason behind is the lack of knowledge and distribution of the latest technological advancement that could at least alert the citizen of the happening of possible disaster in respective location. Fortunately, the world has recently witnessed the origination of IoT that has already created a huge buzz in social, technological, political, and economic domains. Although IoT was coined in earlier 2000, IoT has recently grabbed huge attention in almost all areas of scientific and industrial fields such as smart-home, agriculture, industry, health care, entertainment, robotics, and transportation. IoT is formulated to establish seamless communication, monitoring, and management of smart embedded devices with its counterpart, i.e., analog objects or things. The IoT leverages heterogeneity, interoperability, distributed processing, and real-time analytics in parallel. Although Wireless Sensor Networks (WSNs) are widely deployed in disaster management, they lack in a multitude of socio-techno-economic perspectives. The WSN is fundamentally orientated to cater the vertical silos toward solving a problem. However, the following objectives are not properly discussed such as (i) managing heterogeneous embedded devices, e.g., different processor, memory space, operating system such as embedded Linux, iOS, and Android, (ii) managing heterogeneous protocols (e.g., discovery, data, infrastructure, semantics, communication, and security), (iii) providing efficient data analytics services, (iv) established middleware support, (v) user integration, (vi) real-time access, (vii) energy efficient algorithms, (viii) interoperability among associated enabled technologies, and (ix) cost. On the other hand, IoT is proven to be fundamentally capable enough to provide more significant, scalable, portable, and energy efficient solutions to various problems in the disaster management. Motivated by these issues, an overall understanding of how disasters are currently being monitored and managed by IoT becomes very important. In this study, several implementations of disaster management are found to be solely based on WSN, which is considered as a key part of IoT where geographically distributed nodes sense and act accordingly. Also, such WSN systems are normally equipped with various forms of topological structures (star, ring, tree, etc.) with smart sensor and processing units. The inter-nodal communication, as well as intra-WSN frameworks, rely upon either Transmission Control Protocol/Internet Protocol (TCP/IP) or standard Open Systems Interconnection (OSI) models. Hence, such WSN based systems become an essential part of getting associated with IoT-supported systems by their virtue. To achieve this goal, the article presents a detailed survey of the various aspects of IoT-empowered disaster management. The main contributions of this article are as follows: A systematic survey is presented on the IoT-based disaster management issues highlighting the key protocols with an aim to design efficient disaster countering approaches. Afterward, state-of-the-art application of IoT are dis cussed for disaster management systems. We provide a selective study on market-ready IoT-enabled off-the-shelf products (either open source or proprietary) solutions toward disaster management systems. Finally, the key challenges in IoT-based disaster management systems are highlighted, and possible future directions are suggested.

Literature Review

This section presents an overview of the existing literature relevant to the research presented in this paper. The role of the technology in disaster management that has been examined to investigate IoT can assist the personnel involved in relief operations post any natural disaster. There is a substantial literature available regarding the field studies about the emergency relief operations [21]. The methodology adopted by these studies includes the observations of training exercises, first-hand experience of real incidents, conducting interviews, and recursive refinement of initial prototypes [22] identified challenges related to victims, experts, and IT in developing intelligent systems for immediate relief response. The study focused upon designing a solution for identifying and monitoring patients in emergency scenario. The authors formulated the design paradigm to address the identified challenges and analysed different prototypes to propose guidelines for the realisation of such systems. Victim related challenges call for medical equipment communicating over wireless medium, e.g., wireless bio-monitoring system. The challenges concerning the experts led to the development of a real-time video model for providing situational awareness with the use of video camera, GPS and digital compass. IT related challenges indicate that the devices developed for managing emergency responses should also be employed for daily tasks, else the experts may fail to utilize them effectively. [23] Emphasized upon the use of participatory design in the emergency medical service. This is an inclusive and a recursive process that involves the practitioners and researchers for designing and evaluating a system. This work led to the formulation of a set of designs for supporting emergency medical services. Two of the proposed designs regarding remote access display and wireless bio-monitors are significant for our work. The main concerns of these paradigms are to enable remote access to the data collected by various sensors and infer situational awareness regarding the victims and the available relief resources. [24] recognized the following design issues in the context of emergency relief services, assessment of the situation through multiple sources of information, resource allocation, accountability of resources and personnel and communication support. The authors proposed a conceptual prototype for addressing the identified design issues. Their work deduced the following observations: first, in case of disasters, the activities should be focused upon the people and the surrounding environment; and second, redundancy is a crucial design principle for improving the reliability of the communication and providing efficient safety.

Several studies in the available literature have considered the significance of proper awareness of the situation and apt decision-support systems for managing emergency situations in case of disasters [25]. This urged the attention towards the development of emergency-response information systems (EISs). EIS should be able to provide adequate situational awareness to the first responders for better planning of the relief operation. The decision-making failures of the humans during the disastrous events of Bhopal and the deaths of the rescue personnel during 9/11 can be attributed to the lack of situational awareness and intelligent decision-support systems. A number of research studies in the context of EIS development have considered the significance of enhancing the situational awareness of the first responder situational awareness for improving their capability of making apt decisions. Important studies, which proposed technical models for emergency relief response, have emphasized upon the ability of the information support to provide an insight into the situation faced by the responders for designing an effective EIS [26]. However, such systems do not require only static information such as the information system for office use. These EIS are designed to work in an extreme dynamic environment and hence require real-time information about the disaster impacts and the locations of the personnel and resources employed for the relief operations. Internet of things (IoT) The term 'Internet of Things' (IoT) was coined by Kevin Ashton in 1998 in his talk for Auto ID Centre at the Massachusetts Institute of Technology (MIT). However, it was formally introduced by the International Telecommunication Union (ITU) in the ITU Internet report in 2005 (ITU 2005). Semantically, IoT refers to a world-wide network of interconnected objects having unique identity and communicating using standard protocols (INFSO 2008). The 'things' in such a network refers to any virtual or real entity such as human beings, inanimate objects, intelligent software agents or even virtual data. The paradigm of IoT can be envisaged in conjunction with effective data collection strategies and the ability to share such data. The technology has adequate potential to realize complex decision support systems by delivering the required services in a more precise, organized and intelligent manner. The European Commission in its research roadmap has envisioned the IoT as an indispensable component of the future Internet (European Commission 2008). Refer to IoT as an add-on of the Internet to extend the coverage to the physical entities that can only support low-power computations [27]. However, debates that the IoT is a service provided by the Internet as any other existing web services. From the very onset of the conceptualization of IoT in 2005, the development of smart objects having sensing, communication and actuating capabilities have seen an accelerated growth. Such network-enabled smart objects have numerous applications in the areas of environment monitoring, healthcare, transportation and logistics, social networks etc. The applications of this new paradigm significantly rely upon the data gathered by the distributed smart objects and the communication infrastructure for the transmission of data. In the context of disaster management, IoT has the potential to become one of the enabling technologies. The key application areas include:

1. Disaster risk minimization and prevention: Monitoring disaster possibilities through satellite communication and geographic information system (GIS), designing early warning systems, use of social media for awareness creation.

2. Emergency response: Real-time communication for timely relief and response measures.

3. Disaster recovery: Online missing person search and fund management systems.

The dynamic nature of the requirements and environment during a relief operation emphasizes upon the ability to make efficient and precise decisions in minimal time. The IoT technology, having the potential for communicating instantaneous information updates, can be a key player for realizing dynamic workflow adaptations. proposed WIFA for assessing and managing the workflow dynamically. The work was further improved in the research by incorporating awareness about the status of the resource in terms of requirement and availability. developed an intelligent user interface for an efficient management of the activities involved in disaster management. Developed a conceptual model to identify the determinants of Radio Frequency Identification (RFID) in small and mid-sized enterprises [28]. The existing literature have not explicitly analysed the significance of IoT as a comprehensive technology for relief operations. Introduced the concept of employing IoT technology in the emergency management scenario. The work, however, lacks statistical analysis of the proposed constructs and qualitative tests of the proposed hypothesis. The main objective of our work is to obtain valuable insight into the workflow of the rescue operations post any natural disaster, what type of information is required, how IoT can cater these task requirements, and how the adoption of IoT can provide long-term strategic values. The paper specifically focuses upon how the adoption of IoT technology can enhance the relief operations in disaster management. Task-technology fit (TTF) developed the TTF approach for understanding the collabo ration between individual performance and information systems. A basic model of TTF. Here, task characteristics denote the activities performed by the individuals, while technology characteristics implies the technology utilized by the individuals for per forming the required tasks. Task-technology fit, hence, can be defined as the extent to which a technology catalyses the activities of an individual for performing the required tasks. One significant focus of TTF has been on individuals to assess and explain information systems success and impact on individual performance. TTF has been mainly considered for assessing the success of information systems and examining its impact on the individual performance. Performance impacts refer to the accomplishment of a set of tasks by an individual. Greater performance indicates the amalgamation of increased efficiency, improved effectiveness and better quality. TTF can, thus, provide the guidance for developing a technology to effectively cater the task requirements. TTF analyses the relationship between the tasks and technology fit by estimating user performance and technology utilization. 3 Disaster management scenario in India the workflow for disaster management in India is not similar to the approaches adopted by the other countries of the world. It is a well-established fact that the rescue operation requires

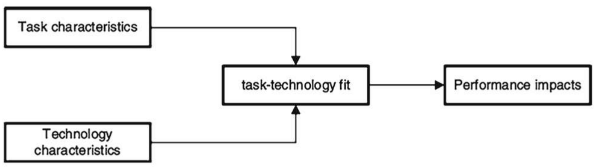

Fig. 1 Task-technology fit model

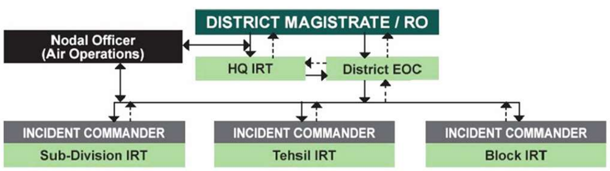

Fig. 2 Disaster response structure at district level

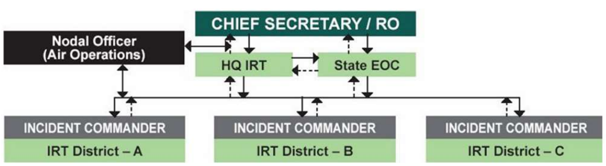

Fig. 3 Disaster response structure at state level.

an efficient collaboration of the local communities with the government officials and other organizations involved in the disaster management. The community dynamics in a country like India is quite complex. The disaster management manuals available on the web clearly depict the complex picture of the co-ordination of rescue personnel at different levels in India. Figures 2 and 3 outline the co-ordination of responses at various levels. The Government of India ordained the Disaster Management Act in December 2005, which envisaged the formulation of National Disaster Management Authority (NDMA) and State Disaster Management Authorities (SDMAs) to spearhead and implement a holistic and integrated approach for disaster management in India [29]. Manufacturers' Association for Information Technology (MAIT)—an IT industry association, which works in close coordination with the Government of India to strategies for Digital India, submitted a whitepaper in 2016 (Digital India Action Group 2016) with the aim to create an awareness about the potential uses of IoT in disaster management in India and to cover some of the requirements, issues and challenges related to IoT applications for disaster management. The whitepaper also discusses about a number of initiatives that have been taken by the central and state governments in the area of disaster management. A national disaster management framework has been developed by the ministry of home affairs. The framework comprehensively covers all aspects of disaster management including the institutional mechanism, disaster prevention, legal and policy framework, early warning systems, disaster preparedness and human resource development. United Nations Development Program (UNDP) has also joined hands in this effort of government of India and is implementing GoI-UNDP disaster risk management (DRM)

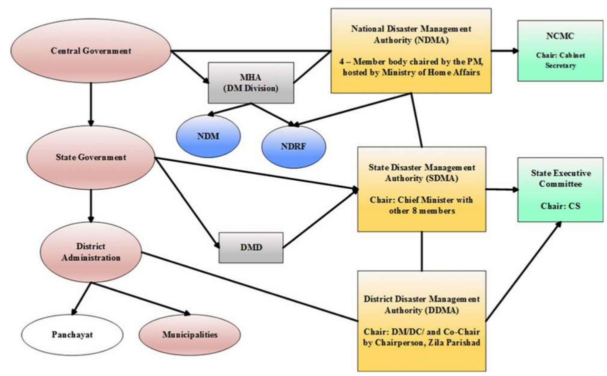

Fig. 4 Institutional framework for disaster management in India.

program in 169 most vulnerable Districts of 17 states in India. The Institutional framework for disaster management in India [30]. However, the framework discussed in the whitepaper does not incorporate the feedback of the affected people, the disaster management team and common masses. It is more of a technical blueprint and can be made more effective only if deployed with proper feedback of various stakeholders as visualizing the actual disaster scenario by technical people alone may not be sufficient. Hence, this work is very important to make any technical solution effective at ground level.

Methodology

This research employs a mixed-methods approach, combining both qualitative and quantitative techniques to develop and evaluate an IoT-based early warning system (EWS) for natural disaster management. The first phase involves designing an IoT framework, including the selection of appropriate sensors and communication technologies for monitoring environmental variables such as seismic activity, temperature, humidity, and rainfall.

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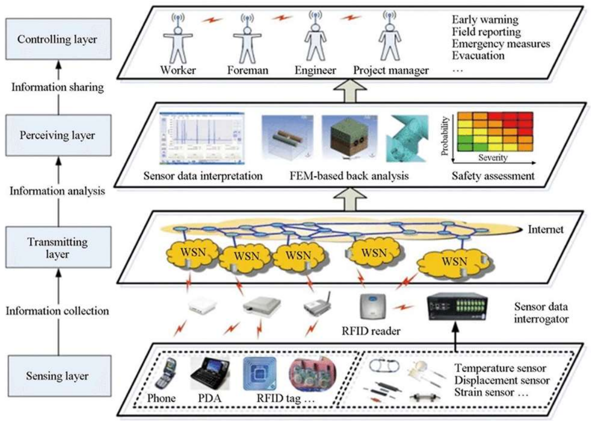

Fig. 5. IoT-based early warning system

The system architecture will integrate real-time data collection from interconnected devices, which will be transmitted via secure communication networks to a central processing unit for analysis. The second phase focuses on developing a machine learning model to predict natural disasters based on the collected data. Historical disaster data will be used to train and validate predictive algorithms, such as regression models and neural networks, to identify patterns that lead to specific disasters like earthquakes, floods, or wildfires. These models will be integrated into the IoT system for real-time prediction and alert generation. In the third phase, field tests will be conducted in selected disaster-prone areas to assess the system's reliability, accuracy, and response time. Data from sensors will be continuously monitored, and alerts will be tested for timely dissemination to local authorities and communities. The effectiveness of the system will be evaluated based on its predictive accuracy, communication reliability, and user response time. The research will also assess cost-efficiency and scalability for wider implementation [31].

Data Collection and Analysis

Data Collection: IoT-based systems utilize a network of sensors deployed in disaster-prone areas to continuously monitor environmental parameters such as seismic activity, weather conditions, soil moisture, river levels, and temperature fluctuations. These sensors are designed to collect real-time data and transmit it to a central data processing unit through wireless communication networks, such as 5G or low-power wide-area networks (LPWAN). The data collection process is continuous, providing up-to-date information that enables early detection of changes in environmental conditions that could lead to a disaster. Data Analysis: The collected data is processed using advanced analytics techniques, including machine learning algorithms, to detect patterns and predict potential disasters. Historical data, alongside real-time input, is used to train predictive models that forecast events like earthquakes, floods, hurricanes, or wildfires. These models analyse multiple factors such as seismic shifts, weather forecasts, and water levels to generate alerts for authorities and the public. Integration with Predictive Models: The integration of predictive models with the IoT framework allows for early detection of emerging threats, triggering alerts before the disaster occurs. Machine learning algorithms improve the accuracy of predictions over time, adjusting to new data and evolving environmental patterns. This continuous cycle of data collection, analysis, and prediction enables the system to provide highly accurate warnings, reducing false alarms and enhancing preparedness efforts. In this section, the focus is on ensuring that the IoT-based system efficiently processes vast amounts of data while maintaining high accuracy, reliability, and low latency in the prediction and communication of disaster events.

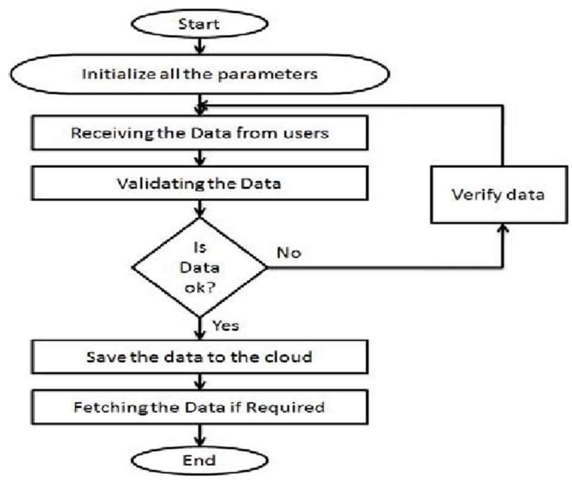

Fig. 6. IoT data collection and analysis

Results and Discussions

The implementation of an IoT-based early warning system for natural disaster management provides significant insights into its performance and effectiveness in detecting, monitoring, and communicating disaster-related information. The deployed IoT sensors for monitoring disasters such as floods, earthquakes, and landslides demonstrated high accuracy and reliability in data collection. For example, flood monitoring sensors showed accuracy improvements over time, starting at 85% and increasing to 96% with continuous monitoring, highlighting the role of real-time data aggregation and sensor stabilization. The system's data transmission was evaluated for latency and communication efficiency, with results indicating that protocols like LoRa, Zigbee, and cellular networks enabled real-time data transfer with average latency under 3-5 seconds. This low latency ensures timely detection and dissemination of disaster-related information. The alert distribution mechanisms employed by the system, including SMS, mobile app notifications, sirens, emails, and social media updates, revealed that SMS alerts (34.5%) and mobile app notifications (25.9%) were the most effective for quick dissemination, while sirens (17.2%) played a critical role for localized warnings. Social media and email served as supplementary channels, ensuring broader coverage. The system also demonstrated scalability and adaptability to various disaster scenarios. For instance, water level sensors successfully integrated with cloud-based weather data for flood detection, while vibration and pressure sensors were effective for landslide monitoring, showcasing its flexibility. Furthermore, early warnings from the system significantly improved community preparedness and response times, reducing risks to lives and property.

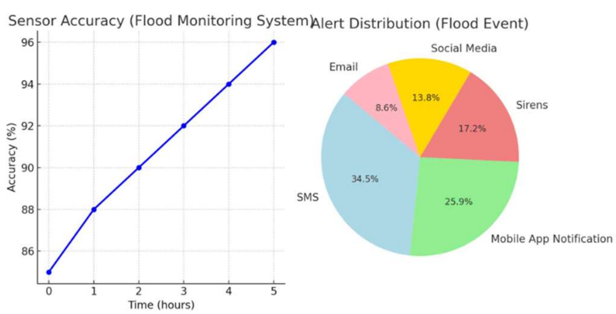

Fig. 7. Flood Event Monitoring: Sensor Accuracy Over Time and Alert Distribution

The results of the flood event monitoring system are presented in terms of sensor accuracy over time and alert distribution during a flood event. As shown in the line graph, sensor accuracy improves steadily with time, starting at 85% at the initial hour and increasing to 96% by the fifth hour. This indicates that the system becomes more reliable as monitoring progresses, likely due to improved data aggregation and sensor stability. The pie chart illustrates the distribution of flood alerts across various communication channels. The majority of alerts are sent via SMS (34.5%), followed by mobile app notifications (25.9%) and sirens (17.2%). Social media contributes 13.8% of alerts, while email accounts for the smallest share at 8.6%. These results highlight the system's focus on quick and widely accessible communication channels like SMS and mobile notifications, ensuring timely and effective dissemination of flood warnings.

Conclusion

Disaster management is not a one step process. Suitable actions at every stage of the disaster management cycle ensures better preparedness, improved and reliable early warnings, reduced vulnerability or the mitigation of the disaster impact during the subsequent recursion of the cycle. The entire disaster management cycle requires the formulation of public policies and strategies that either minimize the causes of disasters or their effects on individuals and infrastructure. The research presented in this paper proposes an innovative IoT based solution to provide real time information about disaster hit area so as to facilitate immediate and effective decisions regarding the rescue efforts. The main objective of this research is to investigate the fitness of the proposed IoT based solution in achieving the tasks required for immediate relief operation after any natural calamity has taken place. During post-disaster relief operations, there is an immediate requirement of certain types of information for assessing the impact of the disaster and planning an efficient relief operation. This requires on-site information systems for providing such information about the environmental conditions, number of casualties, response personnel, and the available rescue resources that can enable the incident responders to take suitable decisions for the rescue operations. This work contributes significantly to the research about the impact of the IoT technology for disaster management. From acquiring the essential requirements of the tasks in the relief operations to proposing an IoT based solution for catering such requirements and validating the proposed solution in terms of fitness, this paper presents a comprehensive study of the application of IoT in disaster management. Any emergency system is successful if the correct information is collected, shared with the right people and presented in a right format. It is, hence, safe to deduce that the IoT based solution proposed in this paper has the potential to suffice the requirements of a wide range of emergency response applications. The paper also proposes a modified TTF model to evaluate the impact of the proposed IoT based solution on disaster management. Results obtained from our study are strong indicators of the applicability of the IoT technology in disaster management. It is essential to state that the findings of this research shall pave the grounds for the development of relevant IoT based solutions with the aim of addressing the requirements of the personnel (government or non-government) in managing the post disaster rescue operations.

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