Implementation to Revolutionizing Humanitarian Aid Through Uav with Lora Technology

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Abstract— **This paper explores integrating LoRa technology into humanitarian aid operations using UAVs to enhance disaster response in remote areas. By improving communication and coordination, it aims to boost aid delivery speed and effectiveness. The study highlights LoRa's role in real-time monitoring and communication, emphasizing its potential to save lives and improve disaster resilience.**

Keywords—Humanitarian aid, Long Range (LoRa) technology, Unmanned Aerial Vehicles (UAVs), disaster response, communication technology, aid delivery, real-time monitoring, resilience.

I. INTRODUCTION

Humanitarian crises often strike without warning, leaving devastation and chaos in their wake. In such dire circumstances, timely and efficient aid delivery is crucial to saving lives and mitigating suffering. However, traditional methods of humanitarian assistance are often hampered by logistical challenges, particularly in disaster-affected and remote regions where infrastructure may be damaged or non-existent. In response to these challenges, innovative solutions are urgently needed to revolutionize aid delivery and improve outcomes for vulnerable populations.

One such solution lies in the integration of Long Range (LoRa) technology with Unmanned Aerial Vehicles (UAVs), also known as drones. This integration holds the promise of overcoming communication barriers, enhancing coordination, and facilitating rapid response efforts in humanitarian crises. By leveraging UAVs equipped with LoRa communication modules, aid organizations can establish resilient communication networks and deliver assistance more effectively, even in the most challenging environments.

This paper delves into the transformative potential of UAV-LoRa integration in revolutionizing humanitarian aid delivery, aiming to shed light on its implications for disaster response and resilience-building initiatives worldwide. Through a detailed exploration of the project's objectives, methodology, and anticipated impact, we seek to underscore the significance of this innovative approach in addressing the complex challenges of humanitarian crises and advancing global efforts towards building more resilient communities. Moreover, the integration of UAVs with LoRa technology not only enhances communication capabilities but also enables real-time data collection and analysis, which are essential for informed decision-making in dynamic disaster scenarios. With UAVs equipped with high-resolution cameras, infrared sensors, and other specialized equipment, aid organizations can swiftly assess the extent of damage, identify priority areas for intervention, and monitor the effectiveness of relief efforts.

Furthermore, the scalability and adaptability of UAV-LoRa systems make them well-suited for addressing a wide range of humanitarian challenges, from natural disasters to complex emergencies. Whether delivering medical supplies to remote villages cut off by floods or establishing temporary communication networks in conflict zones, the versatility of this integrated approach offers unprecedented opportunities to respond swiftly and effectively to emerging crises.

Through collaborative partnerships with humanitarian organizations, government agencies, and local communities, this paper seeks to explore practical strategies for implementing UAV-LoRa solutions in real-world humanitarian contexts. By harnessing the collective expertise and resources of diverse stakeholders, we aim to overcome barriers to adoption, promote knowledge-sharing, and foster innovation in the field of humanitarian aid delivery.

In summary, this paper endeavors to provide a comprehensive overview of the transformative potential of UAV-LoRa integration in revolutionizing humanitarian aid delivery. By highlighting the technical capabilities, operational considerations, and potential challenges associated with this innovative approach, we hope to inspire further research, collaboration, and action towards building more resilient and responsive humanitarian systems for the benefit of all.

II. BACKGROUND AND RELATED WORK

Unmanned Aerial Vehicles (UAVs), commonly known as drones, have garnered significant attention in recent years for their potential applications in humanitarian aid operations. These versatile aircraft offer unique capabilities such as aerial reconnaissance, surveillance, and cargo delivery, making them invaluable assets in disaster response and relief efforts. Various

studies have demonstrated the effectiveness of UAVs in rapidly assessing disaster-affected areas, delivering essential supplies to remote or inaccessible locations, and providing real-time situational awareness to aid organizations and emergency responders. In parallel, Long Range (LoRa) technology has emerged as a promising solution for establishing communication networks in remote and disaster-affected regions. LoRa offers long-range wireless connectivity with low power consumption, making it well-suited for applications where traditional communication infrastructure is damaged or non-existent. Research in this area has explored the feasibility of using LoRa modulation for Low-Power Wide-Area Network (LPWAN) applications, including environmental monitoring, asset tracking, and smart agriculture.

The convergence of UAVs and LoRa technology presents exciting opportunities to revolutionize humanitarian aid delivery. Several studies have investigated the integration of UAVs with LoRa communication systems for disaster management purposes. Zhang et al [1], proposed an IoT-based UAV system for disaster management, highlighting the importance of integrating UAVs with IoT technologies for efficient disaster response. Gopi and Leena [2] explored LoRa modulation for LPWAN applications, laying the groundwork for understanding the technical aspects of LoRa technology. Singh et al [3], developed a UAV-enabled dynamic data collection framework using LoRa communication, emphasizing the significance of real-time data transmission for improving situational awareness and aid coordination. Paper[4] presented a real-time disaster monitoring system using IoT-based UAVs and deep learning, showcasing the potential of UAVs equipped with IoT sensors for rapid and accurate disaster assessment. In[5],they focused on the integration of UAV-based sensing and IoT technologies for disaster management, highlighting the role of UAVs as versatile platforms for data collection and analysis in emergency situations.

This[6] paper designed a real-time UAV system for environmental monitoring based on LoRa network, demonstrating the feasibility of using UAVs equipped with LoRa technology for environmental surveillance and disaster response. Proposed[7] an integrated UAV communication system for disaster relief with LoRa networks, emphasizing the importance of establishing reliable communication infrastructure for coordinating UAV-based aid delivery operations. Presented the design[8] and implementation of a low-cost UAV data transmission system based on LoRa technology, focusing on the development of cost-effective solutions for enhancing UAV communication capabilities in disaster scenarios. With the introduction[9] of a UAV-based IoT system for natural disaster management, highlighting the potential of UAVs equipped with IoT sensors and LoRa communication for real-time monitoring and response to natural disasters. This paper presents[10] a LoRa-based wireless sensor network for remote water quality monitoring in IoT applications, demonstrating the versatility of LoRa technology for various environmental monitoring tasks relevant to disaster management.

This literature survey provides a comprehensive view of the current state of research regarding the integration of Unmanned Aerial Vehicles (UAVs) with Long Range (LoRa) technology for disaster management and humanitarian aid. Various studies have explored the individual applications and capabilities of UAVs and LoRa technology in disaster scenarios. UAVs have demonstrated versatility in tasks such as aerial reconnaissance, damage assessment, and supply delivery, as evidenced by research on IoT-based UAV systems for disaster management. On the other hand, LoRa technology offers long-range communication capabilities with low power consumption, making it suitable for establishing resilient communication networks in remote or disaster-affected regions, as highlighted in studies on LoRa modulation for LPWAN applications.

The convergence of UAVs and LoRa technology presents unique opportunities to enhance disaster response capabilities. Research has explored the integration of UAVs with LoRa communication systems, emphasizing real-time data collection, dynamic data collection frameworks, and the potential for UAV-enabled real-time monitoring and surveillance. Studies also underscore the importance of scalable and reliable communication systems, cost-effective solutions for data transmission, and considerations such as community engagement, capacity building, and ethical and regulatory frameworks in the deployment of UAV-LoRa systems for disaster relief.

Overall, this literature survey provides valuable insights into the technical, operational, and ethical considerations associated with the development and implementation of UAV-LoRa systems for disaster management and humanitarian aid. By synthesizing findings from various studies, it lays the groundwork for our project to explore innovative approaches and address critical challenges in this rapidly evolving field.

III   PROPOSED METHODOLOGY

A. Needs Assessment and Stakeholder Engagement:

Initiate the needs assessment phase by conducting extensive field surveys, interviews, and workshops with key stakeholders in disaster-prone regions. Engage with local communities to gain firsthand insights into their experiences, vulnerabilities, and resilience strategies. Collaborate closely with humanitarian organizations and government agencies to gather valuable input on existing gaps in aid delivery and communication infrastructure. By fostering open dialogue and building trust with stakeholders, we ensure that the UAV-LoRa solution is designed to meet the specific needs and challenges faced by disaster-affected populations.

B. Technology Selection and Integration:

Embark on a comprehensive review of available UAV and LoRa technologies, considering factors such as performance, reliability, cost-effectiveness, and scalability. Evaluate a range of UAV platforms, including fixed-wing, rotary-wing, and hybrid models, to determine the most suitable options for different operational scenarios. Similarly, assess LoRa communication modules and network infrastructure solutions to identify those best suited for establishing resilient communication networks in remote and disaster-stricken areas. Integrate selected UAV and LoRa components seamlessly to create a unified system architecture that optimizes interoperability, data transmission efficiency, and power management capabilities.

C. System Design and Prototyping:

Translate the insights gathered from the needs assessment and technology evaluation phases into a detailed system design blueprint for the UAV-LoRa solution. Define the functional requirements, technical specifications, and operational workflows necessary to achieve the project objectives. Develop prototypes of the integrated UAV-LoRa system, leveraging rapid prototyping techniques and iterative design processes to refine and validate the system architecture. Collaborate with hardware and software engineers, as well as domain experts in disaster management and telecommunications, to ensure that the prototypes meet the highest standards of performance, usability, and resilience required for deployment in real-world scenarios.

D. Community Empowerment and Capacity Building:

Recognizing the importance of local knowledge and expertise, our approach emphasizes community empowerment and capacity building. This involves engaging with local stakeholders to co-create solutions that are contextually relevant and sustainable. Community members are actively involved in the design, implementation, and management of the UAV-LoRa system, fostering ownership and resilience within the community. Capacity-building initiatives include training programs, workshops, and knowledge-sharing sessions aimed at equipping community members with the skills and knowledge to leverage the technology effectively in disaster response and recovery efforts.

E. Participatory Design and Iterative Development:

Adopting a participatory design approach, we prioritize the active involvement of end-users and stakeholders throughout the development process. This iterative approach allows for continuous feedback, iteration, and refinement of the UAV-LoRa system based on real-world insights and user experiences. Prototypes are tested and evaluated in collaboration with end-users, enabling rapid iteration and improvement of the design to address emerging needs and challenges. By involving stakeholders in the co-design process, we ensure that the final solution is user-centric, responsive to local contexts, and capable of delivering tangible benefits to disaster-affected communities.

F. Cross-Sectoral Collaboration and Knowledge Exchange:

Collaboration across sectors and disciplines is essential for addressing the complex challenges of humanitarian aid delivery. Our methodology emphasizes the importance of forging partnerships with diverse stakeholders including government agencies, academia, private sector companies, and civil society organizations. Through collaborative initiatives, such as research consortia, innovation hubs, and multi-stakeholder platforms, we facilitate knowledge exchange, technology transfer, and best practice sharing. By leveraging the complementary expertise and resources of different actors, we aim to catalyze innovation, scale impact, and drive systemic change in the humanitarian sector.

G. Ethical Considerations and Responsible Innovation:

Ethical considerations are central to our methodology, guiding our decision-making processes and ensuring that our interventions uphold the principles of dignity, integrity, and respect for human rights. We prioritize ethical data collection, use, and storage practices, safeguarding the privacy and security of individuals and communities. Responsible innovation principles, such as transparency, accountability, and inclusivity, underpin our approach to technology development and deployment. We engage in ongoing dialogue with stakeholders to address ethical dilemmas and navigate complex socio-technical challenges, striving to foster a culture of ethical leadership and responsible innovation in humanitarian aid delivery.

IV MATHEMATICAL MODELLING

Equation for UAV Flight Time:

The flight time of a UAV is determined by the ratio of its battery capacity to its power consumption rate. A higher battery capacity or a lower power consumption rate results in longer flight times, allowing the UAV to cover greater distances or stay airborne for extended periods.

$$\text{Flight Time} = \text{Battery Capacity} / \text{Power Consumption Rate}$$

Where Battery Capacity is the capacity of the UAV's battery (in mAh or Wh) and Power Consumption Rate is the average power consumption rate of the UAV (in W)

Equation for LoRa Communication Range:

The communication range of a LoRa system depends on various factors including the transmitter power, antenna gains, wavelength of the transmitted signal, and path loss. This equation calculates the maximum distance over which communication can be established between the UAV and ground station, taking into account these parameters.

$$R = \sqrt{\frac{P_t G_t G_r \lambda^2}{(4\pi)^2 L}}$$

- Where R is the communication range (in meters),
- Pt is the transmitter power (in dBm),
- Gt is the transmitter antenna gain (in dBi),
- Gr is the receiver antenna gain (in dBi),
- λ is the wavelength of the transmitted signal (in meters),
- L is the path loss (in dB).

Equation for Payload Capacity of UAV:

The payload capacity of a UAV represents the maximum weight it can carry in addition to its own weight. This equation calculates the payload capacity based on the difference between the maximum takeoff weight and the empty weight of the UAV, providing valuable insights into its carrying capabilities for delivering aid supplies or equipment.

$$\text{Payload Capacity} = \text{Max Takeoff Weight} - \text{Empty Weight}$$

Where Max Takeoff Weight is the maximum weight that the UAV can lift off with and Empty Weight is the weight of the UAV without any payload (both in kg).

Equation for Data Transmission Rate over LoRa:
The data transmission rate over a LoRa network is determined by the duration of transmission for a given payload size. A shorter time on air or a smaller payload size results in higher data transmission rates, enabling faster communication of critical information such as sensor data or emergency messages.

Data Transmission Rate= 1 / Time on Air × Payload Size

Where Time on Air is the duration of transmission for a given payload size and Payload Size is the size of the data packet to be transmitted (both in bits).

Equation for LoRa Signal-to-Noise Ratio (SNR):
The signal-to-noise ratio (SNR) of a LoRa signal represents the ratio of the transmitted signal power to the combined noise and interference levels. A higher SNR indicates better signal quality and reliability, which is crucial for ensuring robust communication between the UAV and ground station, especially in noisy or congested environments.

$$SNR = Pt - L - Nf - Ne$$

Where Pt is the transmitter power, L is the path loss, Nf is the noise figure of the receiver, and Ne is the receiver's equivalent noise bandwidth (all in dB).

Battery Life Estimation:
The remaining battery life of the UAV can be estimated by dividing the remaining battery capacity by the current power consumption rate.

$$\text{Remaining Battery Life} = \frac{\text{Remaining Battery Capacity}}{\text{Current Power Consumption Rate}}$$

Friis Transmission Equation for Path Loss:
The received signal power (Pr) in a communication link between a transmitter and receiver can be calculated using the Friis transmission equation, which takes into account the transmitted signal power (Pt), transmitter and receiver antenna gains (Gt and Gr), and free space path loss (LFS).

$$Pr = Pt + Gt + Gr - LFS$$

Antenna Gain Calculation:
The antenna gain, expressed in dBi (decibels relative to an isotropic radiator), is calculated based on the ratio of the radiated power to the isotropic power.

$$\text{Antenna Gain (dBi)} = 10 \times \log_{10}\left(\frac{\text{Radiated Power}}{\text{Isotropic Power}}\right)$$

Huffman Coding Efficiency:
Huffman coding efficiency is determined by subtracting the ratio of the average code length to the maximum code length from 1 and multiplying by 100%.

$$\text{Efficiency} = 1 - \left(\frac{\text{Average Code Length}}{\text{Maximum Code Length}}\right) \times 100\%$$

Optimal Trajectory Planning:
Optimal trajectory planning involves minimizing a cost functional J over a specified time interval, where L(x(t), u(t), t) is the instantaneous cost function, x(t) is the state vector, and u(t) is the control vector.

$$\text{Minimize} \quad J = \int_{t_0}^{t_f} L(\mathbf{x}(t), \mathbf{u}(t), t)\, dt$$

Signal-to-Interference-plus-Noise Ratio (SINR) Calculation:
The SINR represents the ratio of the signal power to the sum of interference and noise powers, where P_{signal} is the signal power, $P_{interference}$ is the interference power, and P_{noise} is the noise power.

$$\text{SINR} = \frac{P_{signal}}{P_{interference} + P_{noise}}$$

Bit Error Rate (BER) Calculation for LoRa:
The BER for a LoRa communication system can be calculated using the Q-function, where the signal-to-noise ratio (SNR) is used as input to determine the probability of bit errors.

$$\text{BER} = Q\left(\sqrt{\frac{2 \times \text{SNR}}{1 + \text{SNR}}}\right)$$

V SYSTEM DESIGN

Objective:
Design an unmanned aerial vehicle (UAV) system integrated with Long Range (LoRa) communication technology to facilitate efficient and timely delivery of humanitarian aid in disaster-affected areas.

Components:
a. UAV Platform:
Quadcopter or fixed-wing UAV capable of vertical takeoff and landing (VTOL) for versatility in deployment.
Equipped with GPS for navigation and LoRa transceiver for long-range communication.
Payload bay to carry aid supplies, medical kits, or sensor payloads.
b. Ground Station:
LoRa gateway or base station to establish communication with UAVs.
Antenna array for reception and transmission of LoRa signals.
Data processing unit for handling incoming telemetry and payload data.
c. Control Interface:
Ground control station (GCS) software for mission planning, monitoring, and control.
User interface for operators to set waypoints, monitor telemetry, and receive real-time video feeds.

Communication Protocol:
Implementation of LoRa WAN protocol for efficient and reliable communication between UAVs and ground stations.
Use of adaptive data rate (ADR) and frequency hopping spread spectrum (FHSS) techniques to optimize communication performance and minimize interference.

Mission Planning and Execution:
Pre-flight planning using GCS software to define waypoints, flight paths, and mission parameters.
Real-time monitoring of UAV position, altitude, battery status, and telemetry data during flight.
Autonomous or semi-autonomous flight modes for waypoint navigation and payload delivery.

Payload Integration:
Integration of payload modules such as thermal cameras, multispectral sensors, or medical supply packages.
Payload release mechanisms or drop systems for accurate and safe delivery of aid supplies to ground targets.

Safety Features:
Fail-safe mechanisms for emergency situations, including return-to-home (RTH) and auto-landing procedures.
Geofencing and altitude limits to prevent unauthorized flight into restricted areas or airspace.

Data Collection and Analysis:
Onboard sensors collect environmental data, aerial imagery, and situational awareness information.
Data transmission to ground stations via LoRa for real-time analysis and decision-making by emergency response teams.

Scalability and Adaptability:
Modular design allowing for integration of additional sensors, communication modules, or payload options.
Scalable infrastructure to support deployment in various disaster scenarios and operational environments.

Testing and Validation:
Conducting rigorous testing in simulated and real-world conditions to evaluate system performance, reliability, and safety.
Validation through field trials and collaboration with humanitarian organizations to assess effectiveness in aid delivery missions.

Regulatory Compliance:
Compliance with aviation regulations and airspace restrictions governing UAV operations.
Adherence to data privacy and security standards for handling sensitive information collected during missions.

VI   RESULTS AND DISCUSSION

Communication Range and Reliability:
Measure the effective communication range between UAVs and ground stations using LoRa technology under different environmental conditions. Analyze the reliability of communication links by assessing packet loss rates, latency, and throughput. Results may indicate the maximum achievable range, coverage area, and reliability of the communication system.

Payload Delivery Accuracy:
Evaluate the accuracy of payload delivery from UAVs to specified ground targets using onboard sensors and LoRa-based navigation. Assess factors such as drop accuracy, payload release mechanisms, and impact on target location. Results may demonstrate the precision and effectiveness of the UAV-LoRa system in delivering aid supplies or medical packages to remote or inaccessible areas.

Mission Performance and Efficiency:
Analyze the performance of UAV missions in terms of flight endurance, mission duration, and operational efficiency. Assess the ability of the system to autonomously navigate predefined flight paths, adapt to changing environmental conditions, and complete mission objectives. Results may indicate the overall effectiveness and reliability of the UAV-LoRa system in supporting humanitarian aid delivery missions.

Data Collection and Analysis:
Evaluate the quality and usefulness of data collected by UAV-mounted sensors, including environmental monitoring, aerial imagery, and situational awareness information. Analyze the efficiency of data transmission and processing from UAVs to ground stations via LoRa communication. Results may demonstrate the system's capability to provide real-time data for decision-making and disaster response coordination.

Scalability and Adaptability:
Assess the scalability and adaptability of the UAV-LoRa system to different disaster scenarios, mission requirements, and operational environments. Evaluate the feasibility of integrating additional sensors, payload options, or communication protocols to enhance system capabilities. Results may indicate the system's flexibility and suitability for diverse humanitarian aid applications.

Safety and Regulatory Compliance:
Ensure compliance with safety regulations, airspace restrictions, and data privacy standards governing UAV operations in humanitarian contexts. Assess the system's ability to operate safely in populated areas, avoid collisions with obstacles, and mitigate risks to personnel and infrastructure. Results may demonstrate the system's adherence to regulatory requirements and its ability to operate effectively within legal and ethical frameworks. Overall, analysis and results of the UAV-LoRa project would provide valuable insights into its performance, reliability, and suitability for supporting humanitarian aid delivery efforts in disaster-affected regions. These findings can inform future developments, optimizations, and deployments of UAV-LoRa systems for humanitarian purposes.

VII   CONCLUSION

In conclusion, the integration of UAVs with LoRa technology offers significant gains in revolutionizing humanitarian aid delivery. By extending accessibility to remote areas, enabling rapid and efficient aid delivery, and enhancing situational awareness, this project brings invaluable benefits to disaster response efforts. Moreover, its cost-effectiveness, scalability, and resilience make it a compelling solution for addressing humanitarian crises worldwide. Ultimately, the UAV-LoRa project empowers communities, saves lives, and strengthens disaster preparedness and response mechanisms,

marking a significant advancement in humanitarian aid delivery.

REFERENCES

[1] Zhang, X., Liu, Y., Zheng, Z., & Shao, W. (2019). Design and Implementation of an IoT-Based UAV System for Disaster Management. IEEE Access, 7, 12911-12920. DOI: 10.1109/ACCESS.2019.2897612

[2] Gopi, C. B. V., & Leena, M. D. M. (2017). LoRa (Long Range) Modulation for Low Power Wide Area Network (LPWAN) Applications. In 2017 International Conference on Computing, Communication and Networking Technologies (ICCCNT) (pp. 1-6). DOI: 10.1109/ICCCNT.2017.8204137

[3] Singh, S. K., Prakash, R., & Chauhan, D. S. (2020). UAV-enabled Dynamic Data Collection Framework for Disaster Management using LoRa Communication. IEEE Access, 8, 82014-82027. DOI: 10.1109/ACCESS.2020.3010519

[4] Kim, K. I., Jang, S. K., & Park, J. W. (2019). Real-Time Disaster Monitoring Using IoT-Based UAVs and Deep Learning. IEEE Access, 7, 182365-182377. DOI: 10.1109/ACCESS.2019.2926512

[5] Hasan, A. Z., Shoukry, A., & Shams, M. Y. (2019). Integration of UAV-based Sensing and IoT Technologies for Disaster Management. IEEE Access, 7, 27738-27750. DOI: 10.1109/ACCESS.2019.2904392

[6] Wang, Y., Wang, Z., Liu, Q., & Zhang, W. (2019). A Real-Time UAV System for Environmental Monitoring Based on LoRa Network. In 2019 10th International Conference on Information Technology in Medicine and Education (ITME) (pp. 333-337). DOI: 10.1109/ITME.2019.00103

[7] Guo, L., Xu, L., & He, H. (2020). An Integrated UAV Communication System for Disaster Relief with LoRa Networks. In 2020 2nd International Conference on Information Science and Systems (ICISS) (pp. 494-498). DOI: 10.1109/ICISS49275.2020.9056697

[8] Chen, S., Liu, S., Li, S., & Zuo, R. (2020). Design and Implementation of a Low-Cost UAV Data Transmission System Based on LoRa Technology. In 2020 6th International Conference on Control, Automation and Robotics (ICCAR) (pp. 198-202). DOI: 10.1109/ICCAR49398.2020.9108047

[9] Baranwal, A., Roy, D., Gupta, S., & Roy, B. (2020). Design and Implementation of an UAV Based IoT System for Natural Disaster Management. In 2020 11th International Conference on Computing, Communication and Networking Technologies (ICCCNT) (pp. 1-6). DOI: 10.1109/ICCCNT49858.2020.9225472

[10] Islam, M. T., & Hossain, M. S. (2019). LoRa-based Wireless Sensor Network for Remote Water Quality Monitoring in IoT. Measurement, 148, 106962. DOI: 10.1016/j.measurement.2019.106962