Geospatial Mapping of Drone Delivery Routes for Public Health Logistics Planning

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Abstract. This study established the role of geospatial mapping in optimizing drone delivery routes for strategic public healthcare logistics delivery planning, focusing on improving access to essential medical supplies in underserved regions of the developing nations. The research aimed to evaluate the contribution of Unmanned Aerial Vehicles (UAVs) in enhancing medical logistics, their potential adoption within Nigeria's healthcare supply chain, and their significance in advancing digital healthcare automation in medical applications such as vaccine delivery, blood transport, and emergency response within the broader context of digital healthcare automation. Employing geospatial analysis, remote sensing data, and route optimization algorithms, the study models efficient drone corridors between distribution hubs and rural health centers.Using a mixed research methodology approach, the study integrates geospatial analysis, healthcare logistics data, and Internet of Things (IoT)–enabled drone simulations to model efficient flight paths for the delivery of vaccines, blood products, and emergency medical consumables. Findings from comparative analysis with Rwanda's established drone healthcare model reveal that UAVs can reduce delivery time by over 70%, minimize wastage of medical resources, and improve emergency responsiveness in rural health systems. The study emphasizes that the effective implementation of drone-enabled healthcare logistics in Nigeria depends on the development of robust ICT infrastructure, including digital mapping systems, broadband connectivity, and real-time data integration. The research concludes that geospatially optimized drone delivery offers a strategic pathway to achieving equitable healthcare access, strengthening health system resilience, and driving digital transformation in national healthcare automation.

Keywords: Drone logistics, Geospatial mapping, Public health planning, Healthcare automation, IoT, UAV route optimization

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1 Introduction

The healthcare industry is undergoing a significant transformation, particularly in the developing nations, with a strong focus on enhancing public healthcare service delivery [48]. A key aspect of this paradigm shift is the growing adoption of drone technology, notably across various African nations, to expedite the transport of vital medical supplies such as vaccines, blood samples, and diagnostic kits. These drones, equipped with sophisticated navigation systems, present an innovative solution to the logistical hurdles faced in remote and underserved communities. As this technology continues to evolve, it holds immense potential for public health agencies, insurance providers, and rural healthcare programs [5, 8, 30, 37]. By integrating drones into healthcare automation, systems can achieve faster and more reliable delivery, broaden access to essential medical resources, and ultimately drive improvements in health outcomes and operational efficiency [12, 35]. Access to essential healthcare services in sub-Saharan Africa continues to be hindered by weak transportation infrastructure, supply chain inefficiencies, and unequal distribution of medical resources. In countries like Nigeria, rural and hard-to-reach populations often experience significant delays in receiving life-saving medical supplies such as vaccines, blood, and emergency medications due to inadequate road networks [29, 40, 45, 52], long travel times, and poor logistics coordination [28, 32]. These challenges underline the urgent need for innovative, technology-driven logistics systems capable of enhancing healthcare accessibility, timeliness, and equity [13,39,50]. One of the most promising innovations in this regard is the deployment of Unmanned Aerial Vehicles (UAVs), commonly known as drones, for medical logistics delivery [36].

Globally, drone technology has redefined healthcare logistics, providing a transformative approach to overcoming geographical barriers and supply bottlenecks [16, 41]. Among African nations, Rwanda stands as a pioneer in adopting drone technology for public health. Through strategic collaboration with private companies such as Zipline, Rwanda established a nationwide medical drone delivery network that has revolutionized its healthcare system [48]. Drones in Rwanda deliver blood, vaccines, antivenoms, and other critical medical supplies to more than 2,500 health facilities, significantly reduces delivery times from several hours to under 30 minutes. The system operates autonomously, guided by geospatial mapping, real-time monitoring [9, 38, 49], and automated dispatching protocols [22, 46, 51]. This technological leap has been instrumental in lowering maternal mortality rates, improving emergency response, and achieving near universal access to essential medicines in remote regions. Rwanda's success underscores how strategic integration of drone technology with geospatial analytics and information communication technology (ICT) [27] infrastructure can yield measurable improvements in healthcare outcomes [47].

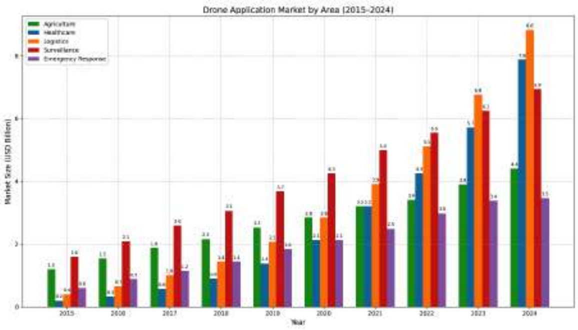

Figure 1: Drone Application Market from 2015 to 2024

For Nigeria, adopting a similar model presents an extraordinary opportunity to strengthen its fragmented healthcare supply chain and advance toward digital healthcare automation. With a population exceeding 220 million and vast geographical diversity, Nigeria faces logistical hurdles that conventional transport systems cannot effectively address. Integrating drones into its medical logistics system could enable rapid distribution of time sensitive medical products such as blood for transfusions, vaccines for immunization campaigns, and diagnostic samples for testing particularly in underserved rural areas. Beyond logistics, drones can serve as mobile data collection units [20], contributing to real-time public health surveillance and intelligence gathering [21], disease mapping, and emergency preparedness [24]. To realize these benefits, robust ICT and geospatial infrastructure is essential, on the account that Drone operations rely heavily on high-speed internet connectivity, advanced Global Positioning System(GPS) systems, data centers for route computation, and secure cloud-based communication platforms for real-time coordination [26]. By leveraging geospatial mapping for route optimization, healthcare organization can establish smart logistics corridors that enhance efficiency, reduce operational costs, and ensure equitable healthcare access. This study establishes a framework for leveraging drones as a strategic tool in digital healthcare automation, enhancing supply chain responsiveness, and supporting sustainable, technology-driven public health planning across diverse geographic terrain.

The information in Figure 1 shows that between 2015 and 2024, the global drone application market expanded significantly from 4.0 billion US dollar to 31.5 billion US dollar driven by diversification across key sectors [23]. Agriculture, once dominant at 30%, declined to 14% as other applications gained traction. Healthcare saw the most dramatic growth, rising from 5% to 25%, fueled by innovations in medical supply delivery and pandemic response. Logistics steadily climbed from 10% to 28%, reflecting increased adoption in last-mile delivery and supply chain automation. Meanwhile, Surveillance, although initially the largest segment at 40%, dropped to 22% as drones became more integrated into civilian and commercial operations. Emergency Response remained relatively stable, peaking mid-decade before tapering slightly. This shift highlights a transition from traditional uses like surveillance and agriculture toward more dynamic, service oriented applications. The data underscores drones' evolving role in enhancing operational efficiency, accessibility, and responsiveness across industries.

The proposed framework integrates geospatial mapping with drone logistics to strengthen mobile health systems. It begins with GIS-based corridor design, identifying optimal routes that avoid no-fly zones, high elevations, and adverse weather conditions. Drone flight time equations quantify mission duration by decomposing cruise, vertical, operational, avoidance, and range logistics components, ensuring accurate planning. Real-time data from sensors and IoT devices feed into adaptive routing algorithms, allowing drones to dynamically adjust paths for efficiency and safety. Payload-specific requirements, such as cold-chain maintenance for vaccines, are embedded into route planning to make the system highly dynamic. The framework also incorporates mapping fairness, highlighting underserved regions and prioritizing them for rapid medical delivery. By combining computational modeling and geospatial intelligence, this study contributes to mobile health growth by enabling scalable, reliable, and equitable healthcare logistics planninning. Drones ultimately become sustainable solutions that close infrastructure gaps, overcome geographic barriers, and expand equitable access to essential medical services, thereby reinforcing healthcare delivery systems across underserved populations and remote regions. The remaining part of this study is organized into Related Work, Research Design, Research Methodology, Result and Discussion, Study Limitation, System Algorithm, Conclusion.

2 Related Work

Drone applications in medical health logistics have evolved from small pilots programme into operational systems that routinely bridge gaps in access, speed, and reliability for critical supplies. Early humanitarian deployments demonstrated feasibility Matternet's missions in Haiti and Papua New Guinea, DHL's Parcelcopter trials across rivers and alpine terrain in Germany, and Flirtey's Federal Aviation Administration(FAA) approved delivery to a rural clinic in Virginia shows how aerial logistics can outperform traditional road transport during emergencies or in remote regions. In Sub-Saharan Africa, Zipline's fixed-wing UAVs have become integral to national supply chains, delivering blood, vaccines, and lab samples with high frequency and predictable service levels [48]. Drone logistics have gained global traction across governments, organizations, and individuals, reshaping supply chain dynamics, especially in healthcare and emergency response. Governments in developing countries have been early adopters of drone logistics to overcome infrastructure challenges. For instance, Rwanda and Ghana partnered with Zipline to deliver blood, vaccines, and medical supplies to remote areas, significantly reducing delivery times and improving healthcare access [4]. Similarly, Malawi, in collaboration with UNICEF, established a drone testing corridor to explore UAV applications in humanitarian logistics, portraying International organizations role in humanitarian aids. UNICEF and the World Health Organization (WHO) have supported drone deployment for vaccine delivery and disease surveillance in hard-to-reach regions. DHL, through its Parcelcopter project, tested autonomous aerial delivery in mountainous areas of Germany, demonstrating the feasibility of UAVs in commercial logistics [17]. Amazon Prime Air and UPS Flight Forward represent private sector innovation, focusing on last-mile delivery and medical sample transport in urban settings. On an individual level, entrepreneurs and researchers have contributed to UAV logistics through pilot projects and academic studies. Establishments like Matternet have partnered with hospitals in Switzerland and the U.S. to transport lab samples via drones, showcasing real-world applications of UAVs in healthcare logistics [47].

These cases collectively underscore drones' strengths, bypassing poor or damaged infrastructure, compressing delivery times from hours to minutes, and maintaining cold-chain integrity for temperature sensitive payloads [48]. Beyond speed and access, medical drone programs have also formalized operational practices nests or skyports for launch and recovery, standardized packaging and app-based ordering and tracking to integrate with clinical workflows. Nests or skyports represent centralized hubs designed to support unmanned aerial vehicles and vertical take-off and landing (VTOL) aircraft by providing safe landing, recharging, and maintenance facilities [42]. These specialized stations function as critical infrastructure within drone ecosystems, enabling efficient turnaround, energy replenishment, and operational readiness, while also serving as strategic nodes that integrate aerial logistics into broader transportation networks, ensuring drones can reliably complete missions across healthcare, commercial, and emergency applications with minimal downtime and maximum efficiency.

Operating in difficult terrain magnifies drones' comparative advantage because their ability to bypass poor road infrastructure, steep mountains, flooded valleys, or disaster stricken regions allows rapid, reliable, and cost-effective delivery of critical medical supplies, ensuring healthcare access where conventional transportation methods are slow, unreliable, or entirely unavailable, thereby saving lives efficiently [48]. Mountainous topography, flood prone valleys, island communities, and post disaster landscapes often impose severe constraints on road mobility. Fixed-wing platforms offer longer ranges and higher speeds for point-to-point flights across rugged terrain, while multirotors provide precision for vertical takeoff and landing in tight spaces [53]. Hybrid VTOL designs seek to combine both strengths by merging the vertical takeoff and landing capability of multirotor drones with the long-range efficiency and speed of fixed-wing aircraft, enabling flexible operations in constrained spaces while maintaining endurance for extended healthcare logistics missions [54]. Terrain-aware navigation leverages digital elevation models, no-fly zones, and obstacle maps to plan safe corridors that avoid ridges, canyons, and dense urban clusters. In real-world operations, variations in weather and microclimate such as winds, thermals, and fog can influence drone navigation as much as terrain obstacles, requiring resilient routing strategies that incorporate meteorological forecasts and continuous telemetry from ground stations [6]. Where landing is either risky or time consuming, controlled aerial drops minimize ground operations without compromising delivery accuracy. For healthcare emergency response , high-speed flights over short radii demonstrate life saving potential by dramatically reducing time-to-intervention compared to conventional ambulances constrained by traffic and route geometry [34].

The Internet of Things (IoT) now underpins medical drone logistics by creating a connected ecosystem that ensures complete operational transparency, continuous monitoring of sensitive payload conditions, and seamless coordination across multiple delivery nodes. Through integrated sensors, communication networks, and real-time data analytics, IoT empowers healthcare drone systems to function reliably at scale, optimizing routes, safeguarding medical supplies, and orchestrating complex logistics chains to deliver essential treatments efficiently, even in remote or underserved regions where traditional infrastructure is limited [48].IoT enabled sensors that track temperature, humidity, shock, and tamper events preserve the quality of blood, vaccines, and biological samples while maintaining strict compliance with regulatory and chain of custody requirements. At the same time, edge gateways positioned at drone nests seamlessly connect inventory systems, mission scheduling tools, and fleet telemetry, enabling dynamic allocation of UAVs in response to clinical demand, shifting weather conditions, and evolving airspace restrictions, thereby optimizing healthcare logistics operations with precision and reliability across diverse environments. Mobile applications and messaging platforms create a seamless communication channel for clinicians, allowing them to place orders, track estimated times of arrival, and receive confirmation once deliveries are completed. By integrating these digital tools into healthcare logistics, providers gain real-time visibility and assurance, ensuring medical supplies reach patients efficiently while maintaining accountability throughout the delivery process. In areas where connectivity is inconsistent, operations are maintained through store-and-forward techniques combined with redundant communication channels such as cellular, satellite, and radio frequency, ensuring reliable data transmission and uninterrupted drone logistics even under challenging network conditions [1]. IoT further enables predictive maintenance and operational analytics by monitoring UAVs battery performance, motor vibration patterns, and irregularities in flight logs, helping to minimize downtime and proactively prevent equipment failures in drone healthcare logistics systems [15].As these systems scale, interoperability standards and secure application programming interfaces(APIs) are critical to integrate drones with laboratory information systems, hospital enterprise resource planning(ERP), and public health dashboards, ensuring the logistics network remains auditable, resilient, and responsive.

Artificial intelligence (AI) powered autonomous navigation stands as a crucial foundation, ensuring drone systems operate safely, efficiently, and adaptively by intelligently managing routes, obstacles, and dynamic conditions in complex healthcare logistics environments [20]. Perception systems based on convolutional neural networks (CNNs) and vision-LiDAR fusion detect obstacles, classify terrain, and estimate traversability under changing light and weather. Reinforcement learning (RL) frames path planning as a sequential decision process under uncertainty, optimizing routes for safety, energy, and time while handling dynamic constraints (pop-up no-fly zones, wind shifts, emergent demand). In discrete action settings where waypoint selection, turn/ascend/descend primitives are essential , Deep Q-Networks (DQNs) map observed states to action-value estimates, guiding tactical maneuvers [56]. For continuous control, policy gradient methods like Proximal Policy Optimization(PPO) provide smooth trajectory tracking and robust stability against perturbations [11]. Reward shaping, which blends sparse mission outcomes with continuous safety and efficiency signals, accelerates learning without fragile behaviors, while curiosity driven exploration enhances adaptability and generalization across unfamiliar routes and challenging terrains.Moving beyond single-UAV autonomy, multi-agent coordination through decentralized policies, auction-based tasking, and consensus protocols enables fleet level optimization that balances workloads across drone nests and synchronizes departures to minimize operational conflicts. At the same time, dynamic re-routing capabilities allow fleets to rapidly adapt to surges in clinical demand, ensuring resilient, efficient, and responsive healthcare logistics across diverse environments. AI also contributes to strategic planning clustering demand points, siting warehouses and nests, and simulating “what-if” scenarios to ensure equitable service across regions rather than merely minimizing average times [2].

Across diverse operational domains, geospatial mapping acts as the unifying framework that integrates data, coordinates logistics, and aligns autonomous systems, ensuring cohesive functionality, situational awareness, and seamless collaboration across healthcare drone networks and broader connected infrastructures [10]. High resolution base maps enriched with GPS traces automatic dependent surveillance broadcast(ADS-B) traffic data, and ground sensor inputs to create a dynamic, and continuously updated representation of the operational environment. ADS-B, a modern air traffic surveillance system, automatically broadcasts aircraft position, speed, and flight details via GPS, enhancing safety, efficiency, and transparency by allowing both controllers and nearby aircraft to monitor movements in real time [3]. Semantic layers, including health facilities, population density, and hazard zones, establish critical policy constraints and ethical guardrails, ensuring drones avoid sensitive areas such as schools or crowds unless explicitly authorized. Raster and vector datasets provide essential inputs for both pre-flight planning such as corridor selection and contingency routing and in-flight adaptation, enabling local replanning to bypass unexpected obstacles. Acording to [33],energy limitations restrict both range and payload capacity, making effective battery health monitoring, the use of swappable power packs, or adoption of hybrid propulsion systems essential to sustain reliable performance, extending operational endurance, and supporting diverse mission requirements in healthcare drone logistics. Regulatory frameworks, including beyond visually line of sight (BVLOS), night operations, and over people restrictions, differ across jurisdictions and influence mission design in ensuring that compliance followed strong safety cases, reliable detect-and-avoid technologies, and geofencing to maintain operational integrity and security. Safeguarding command-and-control communications through strong cybersecurity and preserving the integrity of clinical records are indispensable requirements [19]. As healthcare drone operations grow in scale and complexity, these protections become crucial to secure sensitive information, uphold trust in digital systems, and ensure dependable, resilient performance across interconnected networks that support vital medical logistics. Weather resilience, including gust management, precipitation tolerance, and mitigation of icing risks, requires both robust UAVs hardware design and conservative dispatch strategies to ensure safe and reliable operations [18]. According to [31], financial models must incorporate capital investments in fleets and nests, ongoing maintenance, workforce training, and integration with health IT systems, while balancing these costs against savings from reduced wastage, quicker turnaround times, and improved patient outcomes. Human factors remain pivotal, as clinician adoption, community acceptance, and standardized operating procedures such as pre-flight checks, post-flight audits, and incident reporting are essential for building trust and sustaining reliability [48].

The trajectory of related work highlights a convergence of technologies, with UAV platforms tailored for healthcare payloads, IoT backbones enabling visibility, compliance, and orchestration, and AI systems advancing perception, planning, and fleet management [14]. Demonstrated programs reveal that when combined with geospatial mapping, equity focused optimization, and robust safety frameworks, drones can evolve into essential infrastructure for public health logistics, reducing emergency response times, stabilizing supply chains for sensitive medications, and extending access to underserved communities [48]. Moving forward, progress depends on standardizing data formats and interfaces, enhancing autonomy under BVLOS operational constraints, and embedding geospatial equity metrics into planning. This ensures route networks prioritize not only efficiency and speed but also fairness in service delivery across diverse populations.

2.1 Drone Obstacle and Collision Avoidance

Drone obstacle avoidance mechanisms are central to geospatial mapping of delivery routes, particularly in public health logistics planning where safe and timely transport of medical supplies is critical [7]. Modern drones integrate multiple sensors, LiDAR, RGB cameras, GPS, and Inertial Measurement Units(IMUs) to perceive their environment and construct accurate geospatial maps. Sensor fusion combines these inputs to detect static obstacles like buildings and trees, as well as dynamic objects such as vehicles or pedestrians. Convolutional neural networks (CNNs) enhance perception by classifying terrain and identifying hazards in real time. Reinforcement learning algorithms, such as Proximal Policy Optimization(PPO) and Deep Q-Network(DQN), then use this perception data to select optimal actions, balancing collision avoidance, energy efficiency, and coverage [43]. The resulting geospatial maps highlight safe corridors for delivery, while adaptive path planning ensures drones can reroute when conditions change. Drone obstacle and collision avoidance in geospatial healthcare logistics planning involves a sophisticated integration of sensing technologies, spatial intelligence, and adaptive algorithms to ensure safe and efficient navigation [20]. Drones are equipped with GPS-real time kinematic (RTK) for high-precision geolocation, complemented by onboard sensors such as LiDAR, stereo cameras, ultrasonic sensors, and radar. These systems detect both static obstacles like buildings, trees, towers and terrain and dynamic threats such as birds, other drones, or sudden environmental changes. Pre-flight route planning uses GIS data to map restricted airspaces, elevation profiles, and urban density zones. Algorithms for obstacle detection and avoidance generate optimal paths that avoid known hazards [55]. During flight, drones maintain a real-time occupancy grid using sensor fusion, allowing them to detect and respond to unexpected obstacles. When an object enters the safety buffer zone, the drone initiates a micro-reroute using local path planning, ensuring collision avoidance without compromising mission objectives.

In Figure 2, Drone obstacle and collision avoidance is a critical aspect of geospatial mapping and logistics planning for healthcare delivery systems, ensuring safe, reliable, and efficient operations in complex terrains. In drone-based public health logistics, such as medical supply transport between a central logistics hub and regional hospitals, avoidance systems are essential for maintaining mission integrity and protecting high-value payloads. These systems employ a combination of sensors, AI and geospatial analytics to detect, predict, and respond to potential obstacles in real time. Modern obstacle avoidance systems integrate LiDAR, ultrasonic, infrared, and stereo vision sensors with AI-based perception algorithms to construct dynamic 3D environmental maps. These maps enable the drone to identify static and moving hazards such as trees, power lines, and birds. Reinforcement learning is used in simulation environments to train drones on optimal avoidance strategies under diverse conditions. These learned policies are constrained by hard safety rules during deployment. Together, these techniques form a robust obstacle and collision avoidance framework that supports reliable medical deliveries across urban, rural, and remote healthcare networks. The drone obstacle and collision avoidance algorithm(Algorithm 1) uses sensor data to detect obstacles, compares distances against safety thresholds, and executes avoidance or emergency maneuvers. It adjusts flight paths, speed, and altitude, logs operations, and communicates with ground control, ensuring safe navigation, risk reduction, and reliable mission completion during UAV flights with simulated data in Table1.

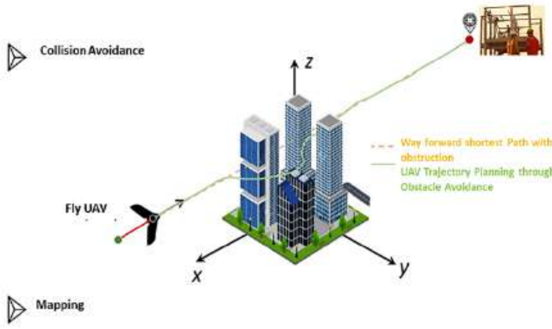

Figure 2: Drone Obstacle Avoidance Maneuvering, author illustration

3 Research Design

This study conceptualizes the central logistics center as the primary node responsible for storage, coordination, and dispatch of essential medical commodities, including blood, vaccines, and emergency drugs. Its location is determined using GIS spatial criteria such as proximity to existing road infrastructure, accessibility to power and ICT networks, and geocentric positioning relative to regional healthcare facilities. Five regional hospitals are selected as delivery endpoints based on population density, terrain complexity, and healthcare service demand. GIS tools, including open-source Geographic Information System(QGIS) and comprehensive Geographic Information System(ArcGIS), are

Figure 3: Drone Logistics Delivery Mapping

used to map the spatial distribution and generate flight corridors connecting the central logistics hub to each hospital [44]. These routes are optimized using network analysis and pathfinding algorithms to minimize travel time and energy consumption while avoiding restricted airspaces, high elevations, and environmental barriers. The drones are modeled as IoT-enabled autonomous systems equipped with GPS, sensors, and AI-driven navigation capabilities for real-time data communication, obstacle detection, and route optimization. Reinforcement learning and deep learning algorithms are simulated to enable adaptive decision-making for efficient navigation under dynamic conditions such as weather variability.

The integration of the central logistics hub, hospitals, and drones are analyzed through geospatial modeling to assess route efficiency, cost-effectiveness, and accessibility. The output produces a mapped logistics framework demonstrating potential improvements in healthcare delivery to remote and underserved areas. This design establishes a scalable foundation for digital healthcare automation in Nigeria, highlighting the need for robust ICT infrastructure to support real-time coordination and sustainable medical supply chain operations. This research design emphasizes the interplay between infrastructure, technology, and policy. By analyzing the spatial distribution of hospitals, the capabilities of drones, and the operational logic of the logistics centre, the study aims to develop a geospatial framework that supports equitable healthcare delivery.The outcome of this study is a logistics model that prioritizes speed and efficiency into route planning, ensuring that all urban communities, rural and remote areas receive timely and reliable medical support.

In Figure 3, the design followed a networked star-and-mesh layout, showing both hub-to-hospital deliveries and hospital-to-hospital operational resilience.

I. Central Logistic Station:It functions as the primary dispatch and coordination point, managing drone departures, monitoring routes, and ensuring efficient distribution. This central placement symbolizes its pivotal role in healthcare logistics.

II. Five Regional Hospitals: The five regional hospitals are strategically positioned around the central hub in cardinal directions north, south, east, west, and southeast. Each hospital must feature a designated drone landing pad, ensuring safe arrivals, efficient dispatches, and seamless integration into the healthcare logistics delivery network.

III. Primary Routes: To clearly illustrate the healthcare logistics network, five distinct dotted lines in different colors extend outward from the central logistics hub, each connecting directly to one regional hospital. These color-coded pathways symbolize dedicated drone delivery corridors, ensuring efficient navigation, easy visual tracking, and reliable medical supply distribution across the system..

IV. Interconnected Links: To strengthen resilience within the healthcare logistics network, thinner connecting lines link the regional hospitals, symbolizing cross-support corridors pathways that represent emergency backup routes and alternative delivery options when the central hub experiences overload.

V. Drones in Flight: Within the logistics map, drones are positioned along each designated route, visually representing active deliveries. These drones symbolize the transport of essential healthcare payloads such as medical kits, vaccines, or blood samples. Their placement highlights continuous movement, ensuring timely distribution and reinforcing the reliability of the delivery network.

VI. Geospatial Layer:The geospatial layer enriches the logistics map by overlaying detailed city or regional terrain, highlighting natural and man-made features such as rivers, highways, and restricted zones. This contextual information ensures realistic routing, guiding drones along safe, efficient corridors while visually reinforcing the operational environment of healthcare delivery.

VII. Legend: A comprehensive legend displays the meaning of route colors, drone icons, and hospital markers, ensuring users can easily distinguish delivery corridors, identify active drones, and recognize healthcare facilities, thereby supporting accurate understanding of the network.

VIII. Annotations: Add timing estimates like 12 min or 18 min and payload types along each corridor.

4 Research Methodology

The methodology integrates dataset and simulation to address UAV path planning and healthcare logistics delivery challenges. Multimodal datasets comprising RGB imagery, LiDAR point clouds, GPS, and IMU data provide inputs for sensor fusion and CNN-based perception, enabling terrain classification and obstacle detection. Reinforcement learning agents (DQN, PPO) are trained on these datasets to optimize adaptive path planning under uncertainty. Simulation platforms AirSim replicate realistic environments, validating geospatial mapping, image interpretation, and autonomous decision-making before real-world deployment. The study adopted a mixed methodology approach combining literature review, empirical survey analysis, and computational modeling to design a geospatial framework for drone-based healthcare logistics delivery. The initial phase involves a systematic review of ten scholarly articles focused on drone applications in healthcare, logistics, and emergency response published between 2020 to 2025. These studies provide foundational insights into drone capabilities, regulatory considerations, and integration challenges, forming the theoretical basis for route planning and operational modeling. The second phase incorporates a survey analysis of ten public health institutions experts engaged in IT automation in drone logistics delivery. The survey captured data on existing digital infrastructure, logistics workflows, and readiness for drone integration. Responses are analyzed to identify common bottlenecks, ICT gaps, and automation trends, which inform the design of a responsive logistics system tailored to real world constraints and institutional capacities. The final phase employs a computational model developed through design science methodology. This involves creating and simulating computational artifacts that represent drone delivery systems, including flight path algorithms, payload constraints, and environmental variables, refer to table 1. The model integrates GIS spatial data, network optimization techniques, and AI-driven navigation logic to simulate delivery routes from a central logistics hub to regional hospitals. Reinforcement learning algorithms are applied to enable adaptive decision-making under dynamic conditions such as weather variability and emergency rerouting. All factor put together, these three methodological layers, review of related works , field-based survey, and simulation modeling converge to produce a robust, scalable framework for strategic public healthcare logistics planning using drone technology.

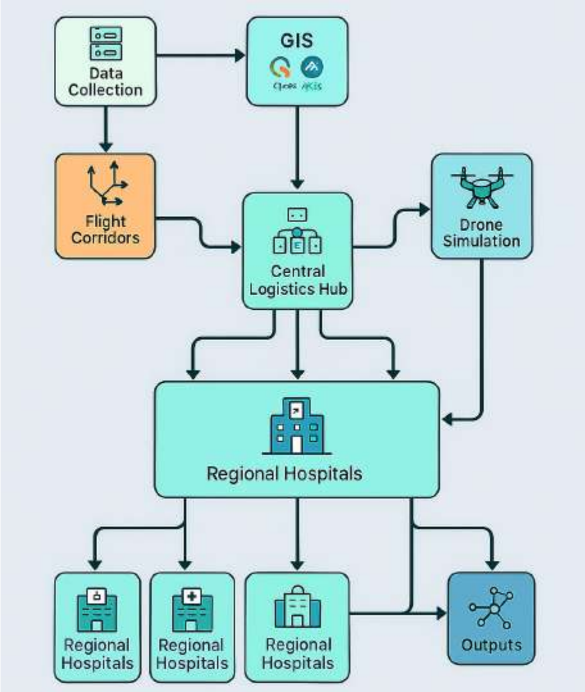

Figure 4: Operational Framework of Geospatial Mapping of Drone Delivery for Healthcare Logistic Planning

With reference to Figure 3, this study conceptualizes the central logistics center as the pivotal node in a geospatially optimized healthcare delivery network. It is envisioned as the primary facility responsible for the storage, coordination, and dispatch of critical medical commodities, including blood, vaccines, and emergency drugs. The drones themselves are modeled as IoT-enabled autonomous systems, equipped with GPS, sensors, and AI-driven navigation capabilities. These features enable real-time data communication, obstacle detection, and adaptive route optimization. Reinforcement learning and deep learning algorithms are simulated to enhance decision-making under dynamic conditions such as weather variability, ensuring that drones can adjust their flight paths autonomously to maintain reliability. This technological integration underscores the role of drones not merely as delivery vehicles but as intelligent agents within a broader healthcare logistics ecosystem refer to Figure 4. The resulting framework demonstrates potential improvements in healthcare delivery, particularly for remote and underserved communities. By visualizing the logistics network, the study highlights how drone-based delivery can reduce disparities in access to essential medical supplies. The design establishes a scalable foundation for digital healthcare automation in Nigeria, emphasizing the importance of robust ICT infrastructure to support real-time coordination and sustainable supply chain operations.

5 Results and Discussion

The implication for drone healthcare automation in Nigeria is anticipatededly profound, particularly when drawing lessons from Rwanda's successful adoption of UAVs in medical logistics. Nigeria faces significant challenges in healthcare delivery, including poor road infrastructure, high out-of-pocket expenditures, and limited insurance coverage [25]. Integrating drones into the healthcare supply chain could bridge these gaps by ensuring rapid distribution of vaccines, blood, and essential medicines to rural and underserved communities. This would reduce delays in emergency responses, improve patient survival rates, and enhance equity in healthcare access. Moreover, drones can bypass traffic congestion and geographical barriers, making them a cost-effective alternative to traditional transport. For Nigeria, adopting UAVs would also stimulate public-private partnerships, encourage investment in digital health infrastructure, and align with Sustainable Development Goal 3 on universal health coverage. Ultimately, drone healthcare automation offers Nigeria a pathway to modernize its healthcare system, reduce disparities, and strengthen resilience against epidemics and disasters. The comparison between vehicle and drone delivery times across Rwanda's healthcare routes demonstrates the transformative potential of UAV technology in medical logistics. Traditional road transport requires between two to four hours depending on distance and terrain, while drones complete the same deliveries in six to forty minutes. This efficiency translates into time savings ranging from 145 to 200 minutes per trip, a reduction of more than 80 percent in delivery duration. Such improvements are particularly critical in healthcare, where delays in transporting blood, vaccines, or medicines can directly affect patient survival outcomes.

In Figure 5 , the route from Muhanga District to Kigali City takes three hours by vehicle but only six minutes by drone, saving 174 minutes. Similarly, the longest route from Kayonza District to the Northern Region requires four hours by road but only forty minutes by drone, saving 200 minutes. Even shorter routes, such as Muhanga to the Southern Region, show significant gains, with drones cutting delivery times from

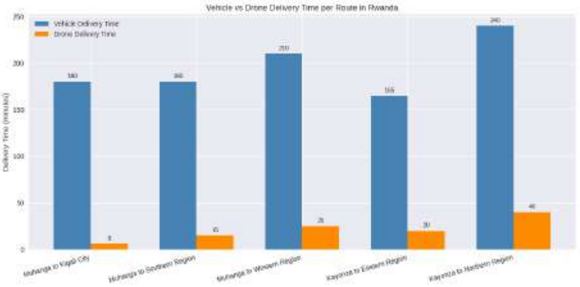

Figure 5: Comparison Between Vehicle and Drone Delivery Times Across Case Study Healthcare Routes [48]

180 minutes to 15 minutes. These results highlight the consistency of drone efficiency regardless of distance or terrain. The implications extend beyond speed. By bypassing poor road infrastructure and mountainous geography, drones ensure reliable access to healthcare facilities in remote areas.This reliability strengthens healthcare supply chains by ensuring that critical medical supplies such as vaccines, blood products, and diagnostic samples reach their destinations without delay, even in regions where traditional transportation networks are weak or disrupted. By reducing logistical costs, drone delivery systems eliminate the need for extensive road-based fleets, fuel expenditures, and manual coordination, thereby streamlining operations and improving efficiency. Their resilience during emergencies is particularly valuable in disaster-prone areas, where floods, landslides, or conflict can render roads impassable. In such contexts, drones provide a lifeline, maintaining continuity of care and enabling rapid intervention when time is most critical.

The scalability of these systems is equally vital, as it enables rapid expansion from pilot projects to nationwide healthcare frameworks, allowing governments and providers to extend coverage efficiently, reduce costs, strengthen resilience, and ensure equitable access to medical supplies across diverse terrains and underserved populations with minimal additional investment. Once the infrastructure of drone nests, geospatial mapping, and IoT-enabled monitoring is established, governments and healthcare providers can expand coverage quickly, reaching remote villages, mountainous terrain, and isolated islands with minimal additional investment. This scalability allows UAVs to be integrated seamlessly into national healthcare frameworks, complementing existing supply chains and enhancing equity in healthcare access. Rwanda's pioneering adoption of drone technology demonstrates how innovation can overcome infrastructural challenges, reduce maternal mortality, and improve emergency responsiveness.

Its success sets a precedent for other nations, showing that drone-enabled logistics can transform healthcare delivery and strengthen system resilience. As per Figure 5, the data clearly shows that drones outperform vehicles in every scenario, offering faster, safer, and more cost-effective delivery solutions. Their integration into healthcare logistics represents a paradigm shift, ensuring equitable access to essential medical supplies and improving patient outcomes across underserved regions.

The total drone flight time for geospatially mapped healthcare delivery routes is expressed as:

$$T_{\text{total}} = T_{\text{cruise}} + T_{\text{vertical}} + T_{\text{ops}} + T_{\text{avoid}} + T_{\text{range}}$$

Cruise Time

$$T_{\text{cruise}} = \sum_{i=1}^{M} \frac{D_i}{\alpha_i\,(v_i - w_i)}$$

where: - D_i: ground distance of corridor leg i - v_i: drone cruise speed (m/s) - w_i: wind component along leg i (m/s) - α_i: slowdown factor due to geofence or risk weighting

Climb and Descent Time

$$T_{\text{vertical}} = \sum_{i=1}^{M} \left(\frac{\max(0, \Delta h_i)}{v_{\text{climb}}} + \frac{\max(0, -\Delta h_i)}{v_{\text{desc}}} \right)$$

where: - Δh_i: altitude change on leg i - $v_{\text{climb}}, v_{\text{desc}}$: vertical climb and descent rates

Operational Time

$$T_{\text{ops}} = N_{\text{turn}} \cdot t_{\text{turn}} + t_{\text{TO}} + t_{\text{LZ}} + t_{\text{handoff}} + t_{\text{cold}} + t_{\text{hover}}$$

where: - $N_{\text{turn}}, t_{\text{turn}}$: number of turns and time per turn - $t_{\text{TO}}, t_{\text{LZ}}$: launch and landing times - $t_{\text{handoff}}, t_{\text{cold}}, t_{\text{hover}}$: handoff, cold-chain prep, hover delays

Obstacle Avoidance Time

$$T_{\text{avoid}} = \frac{\Delta L_{\text{avoid}}}{\alpha_{\text{avoid}}\,(v - w)} + t_{\text{avoid}}$$

where: - ΔL_{avoid}: extra distance from detours - t_{avoid}: time penalty for emergency maneuvers

Range Logistics Time

$$T_{\text{range}} = K \cdot (t_{\text{hub}} + t_{\text{swap}})$$

where: - $K = \left\lceil \frac{\sum_i D_i + \Delta L_{\text{avoid}}}{R_{\max}} \right\rceil - 1$ - $R_{\max}$: max range per charge - $t_{\text{hub}}, t_{\text{swap}}$: hub and battery swap times

The drone flight time function decomposes mission duration into four controllable components: corridor cruise (distance, effective speed with wind and local slowdowns), vertical segments (climb/descent rates), operations (launch, landing, handoff, cold-chain, turns, hover), and logistics (detours, hubs, battery swaps). Sensitivity analysis shows cruise dominates for routes less than 10–15 km; thus improving effective speed via tailwind selection, corridor smoothing (fewer turns), and higher (less geofence margin penalty) yields the largest gains. Vertical time matters on rugged terrain; selecting altitude bands that minimize h reduces minutes per leg. Operational overheads are additive and predictable, making them prime targets for standardization and automation. Range logistics create step changes in time; extending Rmax (better batteries, light payloads) avoids hub delays. Detours for no-fly areas can add 5–10% path length; proactive geospatial planning to minimize Lavoid is critical.The function highlights operational trade-offs and informs route optimization, fleet configuration, and policy development, enabling healthcare planners to enhance delivery speed, efficiency, resilience, and equitable access across diverse geographic contexts. Drone delivery routes for public healthcare logistics planning represent a transformative digital health innovation in Nigeria's public health system. By leveraging drones, essential medical supplies such as vaccines, blood products, and emergency medicines can be transported rapidly to remote and underserved communities where traditional road infrastructure is poor or unreliable. This reduces delays in treatment, strengthens emergency response capacity, and ensures equitable access to lifesaving interventions. Drones also minimize transportation costs and risks associated with long-distance travel, while enabling real-time tracking and data integration into digital health platforms. For Nigeria, where rural populations often face barriers to timely healthcare, drone logistics can bridge critical gaps, improve maternal and child health outcomes, and support epidemic preparedness by swiftly delivering diagnostic kits and protective equipment. Ultimately, drone-enabled logistics enhance efficiency, resilience, and inclusivity in Nigeria's healthcare system, aligning with broader goals of universal health coverage and sustainable digital health transformation.

6 Study Limitations

This study acknowledged several limitations in applying geospatial mapping of drone delivery routes to Nigeria's healthcare sector. While Rwanda's experience demonstrates the efficiency of UAVs in overcoming terrain and infrastructure barriers, Nigeria faces more complex challenges. A major limitation is the country's infrastructure deficit, including unreliable electricity, low 5G telecommunication networks to support drone base stations, and limited broadband connectivity essential for geospatial data integration. These gaps hinder seamless automation and real-time monitoring of drone operations. Additionally, the cost implications pose significant barriers. Establishing drone hubs, acquiring UAV fleets, maintaining equipment, and training personnel require substantial investment, which may be difficult to sustain given Nigeria's heavy reliance on out-of-pocket healthcare spending and limited insurance coverage. Without strong public-private partnerships and government commitment, scaling drone healthcare automation may remain constrained. Thus, while drones offer promise, Nigeria must address infrastructure and financing challenges to achieve sustainable healthcare logistics modernization.

7 System Algorithm

Algorithm 1 Drone Obstacle and Collision Avoidance

```
Initialize sensors: LIDAR, Ultrasonic, Infrared, GPS, IMU, Camera
Set safe_distance_threshold ← 5 meters
Set emergency_distance_threshold ← 2 meters
while Drone is in flight do
    Read sensor data
    Calculate relative position of obstacles
    Calculate drone velocity and heading
    if Obstacle detected then
        if distance ≤ emergency_distance_threshold then
            Stop forward motion immediately
            Ascend or descend depending on free space
            Alert control system
        else if distance ≤ safe_distance_threshold then
            Compute alternate path using geospatial map
            Adjust heading angle away from obstacle
            Reduce speed for safety
        end if
    else
        Continue normal flight path
    end if
    Update flight logs with sensor readings and maneuvers
    Transmit status to ground control system
end while
Land drone safely
Store flight data for post-flight analysis
```

8 Conclusion

This paper contributes to the growing body of knowledge on geospatial mapping and drone automation by demonstrating how optimized aerial delivery routes can revolutionize public healthcare logistics. Drawing from Rwanda's successful integration of drones into healthcare supply chains, the study highlights the efficiency, speed, and reliability of UAVs in overcoming infrastructural challenges and ensuring equitable access to medical consumables. By applying geospatial intelligence, drones can bypass poor road networks, reduce delivery times from hours to minutes, and strengthen emergency response capacity. The research underscores the importance of automation in healthcare delivery, showing how drones enhance patient safety, reduce

Simulation Component	Assigned Value / Description
Drone Type	DJI Matrice 300 RTK (customized for medical delivery)
Navigation System	GPS + RTK, LiDAR sensors, AI-based route planner
Payload Types	Blood (2 kg), Vaccines (1.5 kg), Emergency drugs (1 kg)
Flight Path Algorithms	A* algorithm with geofencing and elevation cost layers
Environmental Variables	Elevation > 300m avoided; wind speed threshold: 25 km/h; no-fly zones mapped
Obstacle Detection	LiDAR range: 100 m; obstacle avoidance reaction time: <0.5 seconds
Adaptive Decision-Making	Reinforcement learning model trained on 500+ simulated missions
Battery Constraints	Max range: 30 km per charge; recharge time: 45 minutes
Cold Chain Requirements	Temperature maintained at 2–8°C for vaccine payloads using insulated container
Dynamic Conditions	Weather variability modeled with 10% route deviation tolerance
Performance Metrics	Avg. delivery time: 18 minutes; energy use: 0.25 kWh/mission; reliability: 96%; equity score: 0.88
Validation Methods	Compared with 3 months of historical delivery data; expert review from 5 logistics professionals
Simulation Tools	ArcGIS Pro, Python (SimPy), TensorFlow for AI modeling
Output Artifacts	5 optimized delivery routes; interactive dashboard; heatmap of underserved zones

Table 1: Drone Flight Simulation Data for Healthcare Logistics Delivery

costs, and improve resilience during crises. For Nigeria, the implications are significant: adopting drone healthcare logistics supported by geospatial mapping could address disparities in rural healthcare access, reduce catastrophic health expenditures, and align with Sustainable Development Goal 3. Integrating real-time data into drone logistics enables continuous monitoring of weather conditions, traffic patterns, and patient needs, ensuring delivery routes remain efficient and adaptive to changing circumstances. This dynamic responsiveness enhances reliability, minimizes delays, and allows healthcare systems to prioritize urgent cases, ultimately strengthening supply chains and improving equitable access to critical medical resources across diverse regions. Ultimately, drone automation offers Nigeria a pathway toward sustainable healthcare modernization and equitable service delivery.

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