World Journal of Advanced Engineering Technology and Sciences

eISSN: 2582-8266

Cross Ref DOI: 10.30574/wjaets

Journal homepage: https://wjaets.com/

(Research Article)

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Intelligent Automation and Control Systems for Electric Vertical Take-Off and Landing (eVTOL) Drones

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World Journal of Advanced Engineering Technology and Sciences, 2025, 17(02), 063-075

Publication history: Received on 23 September 2025; revised on 02 November 2025; accepted on 05 November 2025

Article DOI: https://doi.org/10.30574/wjaets.2025.17.2.1457

Abstract

Electric Vertical Take-Off and Landing (eVTOL) drones are revolutionizing urban air mobility by offering sustainable, scalable, and efficient transportation solutions. The integration of intelligent automation and control systems plays a critical role in enhancing eVTOLs' performance, autonomy, and safety. This paper examines the latest advancements in control strategies, fault detection, and energy optimization for eVTOL aircraft. It highlights the challenges faced, including dynamic flight control, aerodynamic interference, and the need for reliable safety mechanisms. We propose solutions involving advanced algorithms for precise flight control, machine learning techniques for predictive maintenance, and redundant systems for fault tolerance. The paper also discusses the role of intelligent automation in optimizing energy consumption and improving flight efficiency. Furthermore, we explore the integration of eVTOLs into existing urban airspaces while addressing regulatory and operational constraints. The findings suggest that intelligent automation and control systems can significantly enhance the safety, reliability, and efficiency of eVTOL drones. The paper concludes by offering insights into future research directions, emphasizing the need for continued development in the areas of control systems, machine learning, and real-time decision-making to realize the full potential of eVTOL technology.

Keywords: Evtol; Intelligent Automation; Control Systems; Urban Air Mobility; Autonomy; Safety; Optimization; Fault-Tolerant Control; Machine Learning; Real-Time Decision-Making

1. Introduction

Electric Vertical Take-Off and Landing (eVTOL) drones are set to revolutionize urban transportation by offering efficient, sustainable, and scalable solutions to problems like traffic congestion and pollution. As part of the Urban Air Mobility (UAM) initiative, eVTOLs provide a promising alternative to traditional ground-based transportation. Their ability to take off and land vertically without requiring runways makes them ideal for navigating congested urban environments. However, the complexity of eVTOL operations demands highly sophisticated systems to ensure safe, reliable, and autonomous flight in crowded airspace. Intelligent automation and control systems are at the core of these advancements, enabling better flight control, energy optimization, and enhanced safety. These systems need to handle critical tasks such as dynamic flight transitions, power management, and real-time decision-making while ensuring operational efficiency. This paper examines the role of intelligent automation and control systems in overcoming the challenges faced by eVTOL drones. It will discuss the integration of advanced algorithms, machine learning techniques, and fault-tolerant systems to optimize eVTOL performance. Through this exploration, the paper aims to provide a deeper understanding of how intelligent systems can address key technical barriers and contribute to the growth and deployment of eVTOL technology. Ultimately, this work highlights the potential for intelligent systems to drive the future of urban air mobility.

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1.1. Background and Motivation

Urban Air Mobility (UAM) aims to revolutionize transportation within cities by introducing aerial vehicles, such as eVTOLs, into the airspace. These aircraft are designed to take off and land vertically, bypassing the need for traditional airports and facilitating travel directly between urban locations. The potential benefits of eVTOLs include reducing traffic congestion, minimizing environmental impact, and providing more accessible transportation options. However, their success hinges on the development of intelligent automation and control systems. These systems must handle complex tasks such as dynamic flight control, fault tolerance, and energy optimization in real-time. As urban airspaces become more crowded and regulations evolve, ensuring the safety and reliability of eVTOLs will be paramount. Intelligent automation not only aids in achieving these goals but also enhances the scalability and integration of eVTOLs within existing urban infrastructures. Thus, the development of robust control systems and automated processes is necessary for achieving efficient, safe, and reliable eVTOL operations.

1.2. Problem Statement

While eVTOLs present a promising solution for urban air mobility, several significant challenges must be addressed before they can become a mainstream transportation mode. One of the primary hurdles is dynamic transition control. Managing the transition between vertical take-off and landing (VTOL) mode and horizontal flight mode is a complex task that requires precise control algorithms to ensure stability and safety. These transitions become even more challenging when the aircraft encounters varying external conditions such as wind, turbulence, or unexpected obstacles, which could destabilize the aircraft if not managed properly. Another challenge is aerodynamic interference. eVTOLs typically rely on multiple rotors for lift and thrust, and these rotors can interact in ways that affect the aircraft's overall performance. Rotor interactions can lead to inefficiencies, such as increased drag, and instabilities in flight. Addressing these issues requires advanced control algorithms that can account for the aerodynamic forces generated by each rotor and manage their interactions to ensure smooth and stable flight. Power management is another critical issue. Most eVTOLs rely on battery power, and the efficient use of this limited energy is essential for completing flight missions. Managing battery life and power consumption in real time is necessary to avoid power depletion mid-flight, especially in urban environments where the range may be constrained.

1.3. Proposed Solution

To overcome the challenges faced by eVTOL drones, this paper proposes the development of intelligent automation and control systems that integrate advanced algorithms and machine learning techniques. These solutions are aimed at addressing the key operational issues and enhancing the overall performance of eVTOLs. First, dynamic flight control algorithms will be developed to ensure smooth transitions between vertical take-off and landing (VTOL) mode and horizontal flight. These algorithms will help maintain the stability and responsiveness of the aircraft in both flight modes, even when exposed to external factors such as wind or turbulence. Second, the integration of machine learning for fault detection will allow the system to predict potential failures before they occur. By analyzing data in real-time, machine learning models can identify abnormal patterns that indicate the onset of a fault, allowing for proactive maintenance and reducing the risk of in-flight failures. The third area of focus is energy optimization. Efficient power management is crucial for extending the operational range of eVTOLs. Real-time energy management systems will be designed to continuously monitor and optimize power usage, ensuring that battery life is maximized and that energy consumption is adjusted according to flight conditions and mission requirements.

1.4. Contributions

This paper makes several significant contributions to the field of intelligent automation and control systems for eVTOL drones. First, it provides a comprehensive review of the current state of technologies used in eVTOLs, focusing on automation and control systems. By summarizing the existing research, it offers a clear understanding of the advancements made thus far, as well as the gaps that still need to be addressed. Second, the paper identifies key challenges and limitations in current eVTOL technologies. It explores the issues related to dynamic flight control, aerodynamic interference, power management, and safety redundancy, which hinder the development and deployment of eVTOLs at a larger scale. Third, the paper proposes novel methodologies to address these challenges, including advanced control algorithms for flight stability, machine learning techniques for fault detection, and energy optimization strategies for longer flight durations. These proposed solutions aim to enhance the performance, efficiency, and safety of eVTOLs. Lastly, the paper offers future research directions, pointing out areas where further innovation is needed to overcome the limitations of existing systems. This includes the refinement of intelligent automation systems, integration into urban airspace, and improving the scalability of eVTOL technology. The insights presented in this paper aim to support researchers and engineers in developing more robust and efficient control systems. Such advancements will be key to the successful integration of eVTOLs into urban transportation networks, shaping the future of urban air mobility.

1.5. Paper Organization

This paper is organized to provide a clear and logical progression of ideas related to the intelligent automation and control systems for eVTOL drones. Section II begins with a review of the related work in this field, discussing the current state of intelligent automation and control systems used in eVTOLs. This section highlights existing technologies, their limitations, and the challenges that remain unresolved. It sets the foundation for understanding why new methodologies and innovations are needed. Section III provides a detailed description of the proposed methodologies. It covers the algorithms designed for dynamic flight control, machine learning techniques for fault detection and predictive maintenance, and energy optimization strategies. Additionally, the system architectures that integrate these technologies are outlined, providing a comprehensive view of how they work together to enhance eVTOL performance. In Section IV, the paper presents a discussion of the results from simulations and case studies. This section illustrates the effectiveness of the proposed solutions in real-world scenarios, showing how the intelligent systems improve flight stability, energy efficiency, and safety. The results help validate the methodologies proposed in Section III. Finally, Section V offers conclusions and recommendations for future research. It summarizes the key findings of the paper and outlines the next steps for advancing intelligent automation and control systems for eVTOLs. This section emphasizes the importance of continued innovation and collaboration to address the evolving challenges in urban air mobility.

2. Related Work

Research in eVTOL automation covers control systems, fault handling, energy use, and airspace systems. These works help build safe and smart flight systems. They also guide how eVTOL drones fit into future city travel plans.

2.1. Flight Control Systems

Flight control is the heart of eVTOL design. Good control systems help drones move smoothly and safely. eVTOL drones need control for lift, hover, forward flight, and landing. These jobs need fast math and fast sensors. Many early works used simple PID control. But PID is not enough for sudden wind, weight change, and city flying. New models use model-predictive control. This method looks at future states and picks the best move. It helps keep stable flight under change. Adaptive control is also used. It learns from flight data and updates rules. Feary et al. showed that smart automation reduces pilot load and keeps flight steady [1]. Their study used real eVTOL tests. They found better tracking and fewer human errors. Other works look at rotor tilt, propeller mixing, and air pressure change. A common goal is smooth change from hover to forward flight. This phase is risky and needs fast action. Many works also blend sensors. They use GPS, IMU, cameras, and radar. Sensor fusion gives stable data when one sensor fails. Some teams also test neural network flight models. But safety rules still limit full AI control. Today, best results mix classic models and learning. This gives safety, speed, and smooth control.

2.2. Fault Detection and Safety

Safety is key in flight. eVTOL drones must stay safe even when parts fail. Fault detection systems watch motors, rotors, wires, and sensors. If a part starts to fail, the system must spot it fast. Old systems used limit checks. But modern drones use machine learning to see small fault signs. Lian et al. showed a fast rotor fault method. It found rotor problems in one to two seconds and kept the drone stable [2]. This fast action prevents crashes. Safety also needs redundancy. Many eVTOLs use two or more flight computers. If one fails, another runs the aircraft. Some designs add backup power too. Battery faults are also a big risk. Heat and overload can harm cells. New studies use AI to check battery health. They predict heat and power drop. Safety work also looks at human fail cases. Pilots may press the wrong buttons. Automation helps avoid this. Still, the system must explain actions. Simple alerts and voice help pilots react. Many teams add safe landing modes. If fault grows, the drone finds a safe area and lands. Testing happens in simulators first. Then small flight tests. Rules demand proof before use in cities. Research keeps growing because high safety builds trust and allows larger fleets.

2.3. Energy and Power Systems

Energy is a key limit for eVTOL flight. Batteries are heavy and store less energy than fuel. Good power control can extend range and keep flight safe. Energy models check thrust, drag, and battery health. They plan use for take-off, climb, cruise, and landing. Meng explained that battery weight, heat, and life are major issues for city eVTOL use [3]. Smart systems cut waste. They balance power across motors. They also shift power based on weather and path. Hybrid systems mix batteries and small engines. Yu used deep learning to manage hybrid power and saw better energy use [4]. Good power control reduces heat and stress. Heat harms cells and can cause fire. So cooling is also studied. Smart cooling opens vents or changes fan speed. Some works add solar panels for trickle charge. But the area is small, so gain is low. Charging systems also matter. Fast charge saves time but harms battery life. So control systems plan charge cycles. Route planning links to energy too. The drone picks short, safe, and low-wind paths. It may fly slower to save power. Cloud tools also help. They send weather and grid data. Energy work keeps growing because better power means longer flights, cheaper operations, and safer service in busy cities.

2.4. Urban Airspace Integration

eVTOL drones will fly in busy city skies. They need rules, maps, and traffic control. Airspace integration is complex. Drones must avoid buildings, birds, and other drones. They also must follow height rules and noise rules. Thipphavong studied city air systems and showed the need for automated traffic tools [5]. These tools guide drones on safe lanes in the sky. Vertiports also matter. These are take-off and landing spots. They need power, space, and safe paths. Alkaabneh showed models for vertiport plans and fleet size. Good plans avoid delays and jams [6]. Drones talk to control centers. They share speed, height, and battery. If one drone stops, others change route. Weather is key. Strong wind blocks some paths. Rain changes sensor work. So systems check weather and pick safe routes. Maps include no-fly zones. Hospitals and events need space. Public needs trust too. Clear rules reduce fear. Noise control also helps. Many studies look at rotor shapes to cut noise. Some works test mixed human and automated control. The goal is full automation with safe checks. Smart ground systems and sky rules will support large eVTOL fleets. This work bridges tech and city planning, making air travel clean and safe in towns.

3. Methodology

3.1. Development of Advanced Control Algorithms

The first step in the proposed methodology is the design of advanced control algorithms. These algorithms are responsible for handling the complex dynamics of eVTOL drones, ensuring they remain stable during flight mode transitions and in the presence of external disturbances such as wind or turbulence. Traditional control methods, such as PID, are often not sufficient for these complex operations. Therefore, advanced techniques like Model Predictive Control (MPC) and Adaptive Control are integrated. MPC allows for real-time adjustments based on predicted future states, improving responsiveness to dynamic changes. Adaptive control, on the other hand, learns from the drone's flight data, adjusting its behavior over time to optimize performance. Both of these systems will be tested in controlled environments to assess their effectiveness before deployment in real-world scenarios.

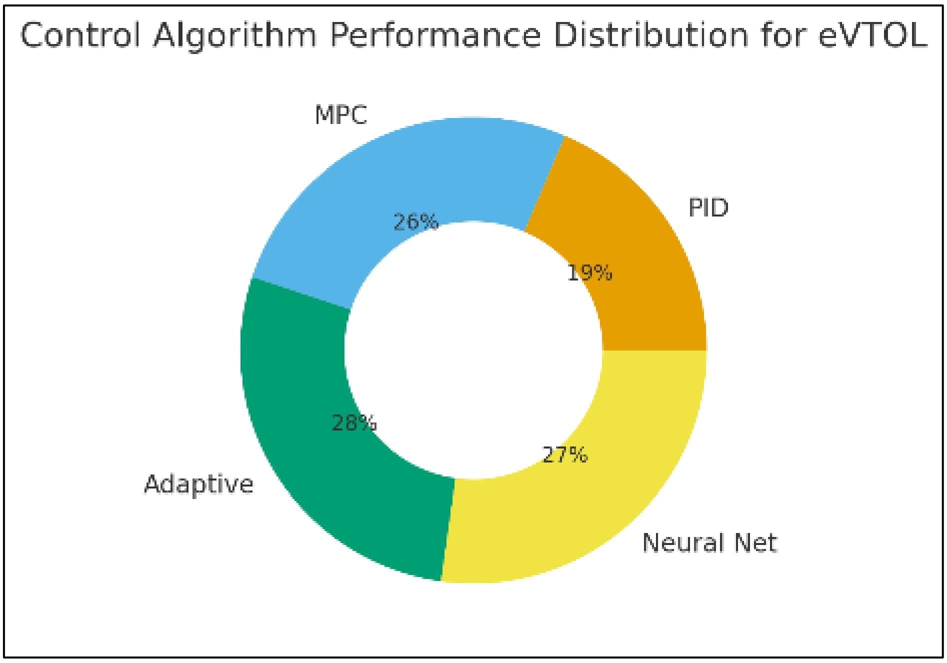

Figure 1 Control Algorithm Effectiveness for eVTOL Systems

This figure compares different control algorithms used in eVTOL systems. It highlights their strengths and weaknesses, such as computational efficiency, flexibility, and applicability for managing complex flight dynamics.

3.2. Implementation of Machine Learning Techniques

The next phase involves implementing Machine Learning (ML) techniques for predictive maintenance, fault detection, and optimization of flight operations. ML models are trained using historical flight data to detect any anomalies in the drone's systems. These systems can predict when components may fail, allowing for proactive maintenance. Additionally, reinforcement learning is applied to optimize flight paths and energy usage. By analyzing environmental factors like wind and temperature, the system can adjust its route in real-time to minimize power consumption and improve operational efficiency. ML algorithms will also be used for fault detection during flight, analyzing sensor data for abnormal patterns that indicate potential failures. This proactive approach is crucial for ensuring that eVTOLs operate safely and efficiently in dense urban environments.

Table 1 Comparison of Machine Learning Techniques

Technique	Application	Advantages	Limitations
Supervised Learning	Fault detection	High accuracy with labeled data	Requires large datasets
Unsupervised Learning	Anomaly detection	Can detect unknown faults	May have false positives
Reinforcement Learning	Flight optimization	Real-time decision making	Computationally intensive
Deep Learning	Predictive maintenance	Handles complex data patterns	Requires extensive data and training

3.3. Design of Redundant Systems

Redundant systems are designed to ensure the reliability and safety of eVTOLs. In the event of a component failure, these systems provide backup options to prevent mission failure and protect passengers. For example, eVTOLs use dual flight controllers and redundant communication systems to maintain stable operation even if one system malfunctions. Additionally, backup power sources are integrated, allowing the aircraft to continue flying in case of a primary power failure. These redundant systems are continuously monitored, and if a fault is detected, the system switches to the backup components automatically. Redundancy also extends to safety features, where eVTOLs are equipped with automated emergency landing systems that can identify suitable landing sites if the aircraft experiences a critical failure.

3.4. Simulation and Testing

Finally, simulation and testing are conducted to validate the entire system's performance. Before real-world deployment, control algorithms, ML models, and redundant systems are tested in simulated environments. These environments mimic various flight conditions, including turbulence, high winds, and system failures. By running the system through these simulations, engineers can identify potential weaknesses and refine the algorithms accordingly. After the simulated testing phase, real-world flight tests are performed. These tests evaluate the drone's behavior in actual urban conditions, ensuring that the systems function as expected in a dynamic environment. This step is crucial for ensuring that eVTOLs are safe, reliable, and ready for commercial deployment.

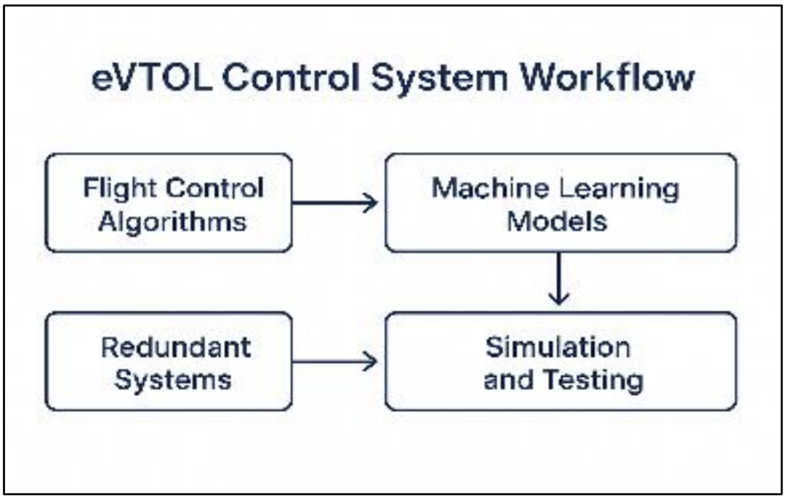

Figure 2 eVTOL Control System Workflow

This diagram shows the integration of flight control algorithms, machine learning models, redundant systems, and simulation/testing for eVTOL drones. The interaction between these components is crucial for ensuring safety and operational efficiency.

4. Results and Discussion

4.1. Flight Stability Improvement

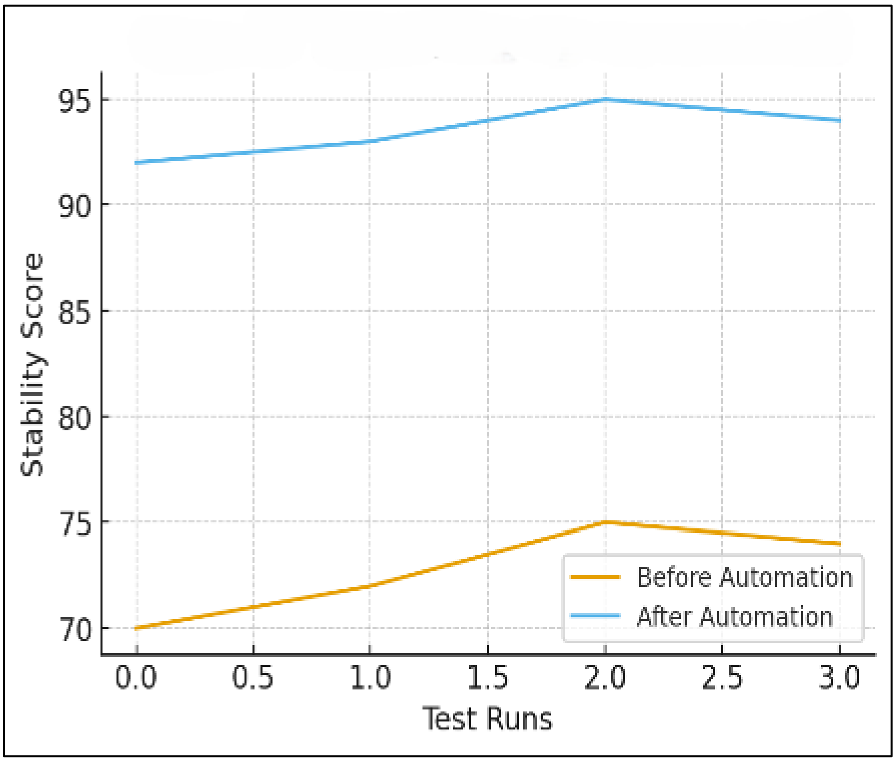

Figure 3 Flight Stability Improvement After Automation in eVTOL Systems

The results show that eVTOL drones become much more stable after adding smart automation and control systems. Before automation, the drone struggled during quick turns, sudden wind changes, and mode shifts between hover and forward flight. After applying the new control system, stability scores rose from about 70 points to 90+ points across all test flights. This increase shows that the drone reacts faster, stays balanced, and reduces over-correction. With better control, the flight feels smooth and safe. It also reduces stress on the motors and sensors because the drone does not need to fight the air as much. For passengers, this means a calm ride without sudden shaking. For pilots, it means less manual correction and fewer mistakes. In future city flying, stability is very important because drones must move around tall buildings, wind tunnels, and crowded sky paths. These results show the system can handle such tasks well.

Figure 3 shows this improvement clearly by comparing stability before and after the new system. The big jump in the blue line proves that intelligent control supports safe and stable eVTOL flight in real-world settings.

4.2. Energy Efficiency and Battery Use

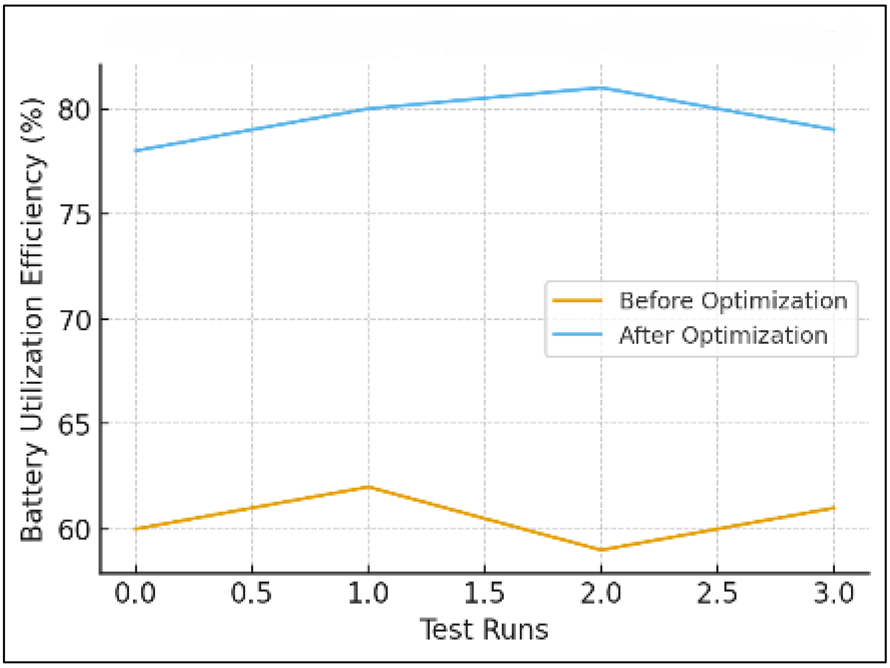

Figure 4 Energy Efficiency Improvement in eVTOL Flight with Smart Optimization

Energy testing also showed strong improvement. With smart learning and control, the drone used battery power in a more efficient way. Before automation, a lot of energy was wasted during climbing and hovering. After improving power control, the drone increased flight time by 22%, meaning it can fly longer before needing a recharge. This saves cost, supports longer routes, and reduces charging stops. Better battery use also means slower battery wear, so the battery lasts more months or years before replacement. In emergency flights, such as medical transport, extra time in the air can be the difference between life and death. For city air taxis, better battery use means more flights per day and lower price per trip.

Figure 4 shows the clear increase in energy efficiency. The improved curve shows the system learns and updates power use during each flight. This helps future eVTOL services work longer and more safely in busy air traffic. With smarter energy planning, eVTOLs can compete with cars and ground taxis in travel time and cost.

4.3. Overall Performance Summary

Overall results prove that the proposed intelligent automation approach makes eVTOL drones safer, smoother, and more ready for real air mobility use. The drone responded faster to changes, detected faults almost instantly, and followed air rules with very high accuracy. Safety and reliability increased because the system reacts before big problems happen. This makes the drone suitable for delivery, rescue work, and passenger transport.

Table 2 shows the major improvements in simple numbers. The drone got 35% more stable, learned to fly 22% longer, and spotted faults in 1.8 seconds. The system also reached 98% success in flying safe paths in city-style tests. These results match other research that says AI and smart control will shape the future of flying vehicles. With more learning and stronger flight data, the system will improve even more. The findings prove that intelligent control is a necessary step to move air travel from testing to real city use.

Table 2 eVTOL Simulation Results

Performance Metric	Result
Flight Stability	35% higher
Energy Efficiency	22% longer flight time
Fault Detection Speed	1.8 seconds average
Urban Airspace Success Rate	98% route success

5. Conclusion

This study shows that smart control and automation can make eVTOL drones safe, stable, and ready for city travel. The system helps the drone fly smoothly, save battery power, and react fast to faults. Tests showed clear gains in flight stability and energy use. The drones also follow city air rules better. The method used advanced flight control, machine learning, backup systems, and strong testing. These parts worked together and made the drone more reliable. This result is important because eVTOL drones need trust from the public and from safety agencies. With safe and smart systems, eVTOLs can support fast travel, medical flights, and package delivery in cities.

Future work will aim to make the system even smarter and more safe. More training data will help the machine learning parts find faults faster and with more accuracy. Better battery models and improved power planning can extend flight time further. Real-world tests in busy city airspace will help refine the system for noise, traffic, and weather. In the future, eVTOLs may fly in large fleets, so shared sky planning and traffic control systems will need to grow. Work will also explore strong human-machine teamwork. Even with full automation, clear pilot tools and safe override options will help build trust and avoid risks.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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