

Intelligent Mid-Air Wireless Charging System for Unmanned Aerial Vehicles Using Hybrid Power Transfer and AI-Based Predictive Alignment

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Abstract

The limited battery capacity of Unmanned Aerial Vehicles (UAVs) significantly restricts their operational efficiency, particularly in long-duration surveillance, agricultural monitoring, and disaster response missions. This paper proposes an advanced mid-air wireless charging system utilizing a mother drone as a mobile power station. Unlike conventional ground-based charging approaches, the proposed system integrates hybrid wireless power transfer combining inductive coupling and microwave beamforming, real-time intelligent alignment using multi-sensor fusion, and AI-based predictive decision-making for optimal charging scheduling. The system architecture incorporates an energy management module with dynamic power control, enabling continuous UAV operation without dependency on fixed infrastructure. Furthermore, the proposed framework supports multi-drone charging through swarm coordination, enhancing scalability for large-scale operations. Mathematical models for power transfer efficiency and alignment error compensation are presented. Simulation results demonstrate significant improvements in flight duration, charging efficiency, and alignment accuracy compared to existing stationary systems. The proposed solution represents a paradigm shift toward fully autonomous and sustainable UAV deployment in dynamic environments.

Keywords-Unmanned Aerial Vehicles; Wireless Power Transfer; Mid-Air Charging; Artificial Intelligence; Swarm Robotics; Energy Management.

Introduction

Unmanned Aerial Vehicles (UAVs) have emerged as transformative platforms for a wide spectrum of applications including aerial surveillance, precision agriculture, disaster response, logistics delivery, and infrastructure inspection. The global UAV market has witnessed exponential growth, with commercial and defense sectors increasingly relying on drone-based solutions for missions that are either too dangerous, expensive, or impractical for human operators. However, the operational capabilities of UAVs remain fundamentally constrained by their limited onboard energy storage capacity. Typical lithium-polymer batteries used in commercial drones provide flight durations ranging from 20 to 45 minutes, depending on payload weight, weather conditions, and flight dynamics. This limitation necessitates frequent landing and battery replacement or recharging, resulting in significant mission downtime and operational inefficiency.

Existing solutions to mitigate battery constraints include ground-based charging stations, automated battery swapping systems, and tethered power supplies. Ground-based charging requires UAVs to interrupt missions and return to fixed infrastructure, thereby compromising mission continuity and coverage area. Battery swapping systems, while reducing downtime compared to conventional charging, involve complex mechanical mechanisms and are limited to predefined locations. Tethered solutions restrict mobility and are unsuitable for dynamic, long-range operations. Consequently, there exists a critical need for mobile, infrastructure-independent charging solutions that can sustain UAV operations in the field without mission interruption.

Wireless Power Transfer (WPT) technologies have gained significant attention as potential solutions for contactless energy delivery. Inductive power transfer (IPT) and capacitive power transfer (CPT) offer high efficiency over short distances but suffer from rapid efficiency degradation with increasing air gap and misalignment. Microwave power

transfer (MPT) and laser power beaming enable longer-range energy transmission but face challenges related to beam divergence, atmospheric absorption, and safety concerns. Recent research has explored hybrid WPT architectures that combine multiple transfer mechanisms to leverage their complementary strengths. However, the integration of hybrid WPT with intelligent alignment and autonomous decision-making for multi-drone mid-air charging remains largely unexplored.

This paper presents a comprehensive framework for an intelligent mid-air wireless charging system utilizing a mother drone as a mobile power transmitter. The primary contributions of this work are: (1) a hybrid WPT architecture combining inductive coupling and microwave beamforming to achieve adaptive efficiency across variable distances; (2) a real-time intelligent alignment system integrating GPS, Inertial Measurement Unit (IMU), and computer vision for precision positioning; (3) an AI-based predictive decision-making module that optimizes charging schedules based on mission profiles, battery states, and environmental conditions; and (4) a scalable multi-drone coordination protocol enabling simultaneous charging of multiple child drones. The proposed system eliminates dependency on ground infrastructure and enables truly continuous UAV operations in dynamic, unstructured environments.

Related Work and Literature Review

The existing body of research on UAV charging can be broadly categorized into three domains: ground-based contactless charging, battery swapping automation, and wireless power transfer systems. Ground-based wireless charging pads utilizing inductive coils have been investigated extensively for automated landing and charging scenarios. Kim et al. [1] demonstrated a resonant inductive coupling system achieving 85% efficiency at 100 mm air gap for small-scale drones. However, such systems require precise landing and are inherently stationary. Zhang and Liu [2] proposed a docking station with mechanical alignment guides, achieving reduced charging times but introducing mechanical complexity and wear.

Battery swapping systems represent another approach to minimizing charging downtime. Zhao et al. [3] developed an automated battery exchange station for agricultural UAVs, reducing turnaround time to under 60 seconds. While effective for fleet operations in fixed locations, battery swapping requires substantial infrastructure investment and is impractical for remote or dynamic mission environments. Furthermore, the mechanical precision required for autonomous battery extraction and insertion introduces reliability concerns under field conditions.

Wireless power transfer for aerial applications has been explored through both near-field and far-field techniques. Near-field inductive and capacitive coupling methods offer high efficiency but are severely limited by short effective ranges and stringent alignment requirements. Kurs et al. [4] demonstrated strongly coupled magnetic resonance achieving 60% efficiency at 2 meters, but the system required substantial coil mass unsuitable for aerial platforms. Far-field microwave power transfer has been investigated for longer-range applications. Sample et al. [5] demonstrated microwave power beaming to a micro-UAV at 5 meters with 10% end-to-end efficiency. While this enables greater operational flexibility, the low efficiency and potential safety hazards associated with microwave exposure limit practical deployment.

Recent advances in intelligent alignment and autonomous navigation have opened new possibilities for mobile charging systems. Chen et al. [6] proposed a vision-guided docking system for UAV-to-UAV refueling, utilizing stereo cameras for relative positioning. Their system achieved centimeter-level accuracy under optimal lighting conditions but degraded significantly in adverse weather. Park and Kim [7] investigated GPS-IMU fusion for aerial rendezvous, demonstrating improved robustness but insufficient precision for efficient power transfer coupling.

Problem Statement and System Requirements

Despite significant advances in UAV technology and wireless power transfer, several fundamental challenges persist that prevent the realization of practical mid-air charging systems for sustained autonomous operations. This section formalizes the key limitations of existing approaches and establishes the system requirements for an effective aerial charging solution.

The primary limitation constraining UAV operational envelopes is the energy density of commercially available battery technologies. Lithium-polymer batteries, the dominant energy storage solution for aerial platforms, offer gravimetric energy densities of approximately 200-250 Wh/kg. For a typical commercial hexacopter weighing 15 kg with a 5 kg payload, the available energy translates to 30-40 minutes of hovering flight or 45-60 minutes of forward cruise. Mission profiles requiring extended loiter times, such as border surveillance or disaster area monitoring, inevitably exceed these temporal constraints.

Scalability and multi-drone coordination present additional challenges. Current WPT systems are predominantly designed for single-receiver configurations. Extending to multi-drone scenarios introduces electromagnetic interference between receivers, power allocation optimization problems, and collision avoidance complexity during charging formation. The lack of intelligent scheduling mechanisms results in suboptimal charging sequences, where high-priority drones may experience critical battery depletion while low-priority units occupy charging positions.

Safety and regulatory considerations further constrain system design. Microwave power densities must comply with IEEE C95.1 standards for human exposure limits, restricting transmitted power levels and beam steering freedoms. Thermal management of both transmitter and receiver electronics during high-power transfer is essential to prevent component damage and fire hazards. Additionally, mid-air charging operations must integrate with existing air traffic management frameworks and collision avoidance protocols.

Based on these identified limitations, the following system requirements are established for the proposed intelligent mid-air charging system: (R1) Hybrid power transfer capability adaptable to variable separation distances between 0.1 m and 3.0 m; (R2) Real-time alignment precision within ± 2 cm lateral and ± 3 deg angular tolerance under dynamic flight conditions; (R3) AI-based predictive scheduling optimizing charging sequences for multiple drones based on mission priority, battery state, and estimated time-to-critical; (R4) End-to-end power transfer efficiency exceeding 70% at nominal operating distance; (R5) Compliance with electromagnetic field exposure standards and thermal safety margins; and (R6) Scalable architecture supporting simultaneous charging of up to four child drones without significant performance degradation.

Proposed System Architecture

The proposed intelligent mid-air wireless charging system comprises three primary subsystems: the Mother Drone (Mobile Power Transmitter), the Child Drones (Power Receivers), and the Ground Control Station (GCS) for mission oversight. The architecture integrates hybrid wireless power transfer, multi-sensor fusion-based alignment, and artificial intelligence-driven energy management into a unified operational framework. Figure 1 illustrates the comprehensive system architecture and component interconnections.

Each Child Drone integrates a complementary hybrid receiver architecture. The inductive receiver comprises a tuned ferrite-core coil with series-series compensation, followed by a full-bridge rectifier and DC-DC buck converter for battery charging regulation. The microwave receiver utilizes a circularly polarized rectenna array with Schottky diode rectification and a power management integrated circuit (PMIC) for voltage regulation. A switching circuit automatically selects the appropriate receiver channel based on received signal strength indicators and separation distance estimates.

The Intelligent Alignment Subsystem fuses data from four sensor modalities: differential GPS (dGPS) providing absolute positioning with 0.5 m accuracy, IMU measuring inertial states at 1000 Hz update rate, a stereo vision system capturing relative pose at 30 frames per second, and a millimeter-wave radar for all-weather range measurement. The sensor fusion algorithm employs an Extended Kalman Filter (EKF) to estimate relative position and orientation between mother and child drones, achieving sub-centimeter accuracy during the final approach phase.

The AI Predictive Module implements a two-tier decision architecture. The Strategic Planner operates at the GCS level, optimizing fleet-wide charging schedules using a mixed-integer linear programming (MILP) formulation considering mission waypoints, predicted energy consumption, and charging station trajectories. The Tactical Controller executes aboard the mother drone, making real-time decisions regarding power mode selection, beam steering angles, and dynamic power adjustment based on instantaneous coupling efficiency measurements and battery state-of-charge (SOC) feedback from child drones.

Hybrid Wireless Power Transfer Design

The hybrid WPT architecture leverages complementary operating regimes of inductive and microwave transfer mechanisms. Inductive coupling dominates at short separations ($d < 0.5$ m) where magnetic field coupling remains strong, offering efficiencies exceeding 85%. Beyond 0.5 m, the system transitions to microwave beamforming, maintaining functional power delivery up to 3.0 m albeit with reduced efficiency (35-50%). The transition threshold is dynamically adjusted based on real-time efficiency monitoring and atmospheric conditions.

The inductive transmitter coil features a planar spiral design with outer diameter 300 mm, implemented using Litz wire to minimize skin effect losses at 85 kHz. Series compensation capacitance is selected to achieve unity power factor at the resonant frequency, reducing reactive power circulation and inverter switching losses. The microwave transmitter

array utilizes 16 circularly polarized patch elements arranged in a 4x4 grid, providing 18 dBi gain and +/-30 deg electronic beam steering in both azimuth and elevation planes. A retro-reflective beam tracking mechanism ensures microwave alignment by analyzing pilot tone reflections from the child drone rectenna.

Multi-Drone Coordination Protocol

The proposed system supports concurrent charging of up to four child drones through a time-division and spatial-division multiplexing scheme. For inductive charging, child drones arrange in a vertical stack formation beneath the mother drone, each separated by 200 mm to minimize inter-coil coupling interference. The mother drone sequentially energizes individual coils using solid-state relays, dedicating 30-second charging slots to each child in a round-robin fashion. Priority weighting modifies slot allocation, granting extended charging periods to drones with critically low battery levels.

For microwave charging, spatial separation is achieved through beam steering, directing independent beams to each child drone based on their relative positions. The phased array controller implements an orthogonal beamforming algorithm that minimizes sidelobe interference between concurrent beams. Power allocation follows a water-filling optimization, maximizing total received power across all child drones while respecting per-drone safety limits and total transmitter power constraints.

Mathematical Modeling and Analysis

This section presents the mathematical foundations governing the hybrid wireless power transfer system, alignment error compensation, and predictive energy management. The models establish design parameters and performance boundaries for the proposed architecture.

Inductive Power Transfer Efficiency

The efficiency of resonant inductive coupling between transmitter and receiver coils is modeled using coupled-mode theory. The power transfer efficiency for a two-coil system with series compensation is given by:

where k represents the magnetic coupling coefficient, and Q_1 and Q_2 denote the quality factors of the transmitter and receiver coils, respectively. The coupling coefficient depends on coil geometry and separation distance according to:

$$\eta_{ind} = \frac{k^2 Q_1 Q_2}{(1 + \sqrt{1 + k^2 Q_1 Q_2})^2}$$

$$k(d) = \frac{r_1^2 r_2^2}{2\sqrt{r_1 r_2} (d^2 + r_1^2)^{3/2} (d^2 + r_2^2)^{3/2}}$$

where r_1 and r_2 are the coil radii, and d is the axial separation distance. For the proposed system with $r_1 = r_2 = 150$ mm and operating distance $d = 300$ mm, the coupling coefficient k is approximately 0.15. With quality factors $Q_1 = Q_2 = 250$, the theoretical efficiency calculates to approximately 0.82, validating the high-efficiency short-range operating regime.

Microwave Power Transfer Analysis

The received power in microwave power transfer follows the Friis transmission equation modified for atmospheric attenuation. The received power density S_r at the child drone rectenna is:

$$S_r = \frac{P_t G_t A_{eff}}{4\pi d^2} e^{-\alpha d}$$

where P_t is the transmitted power, G_t is the transmitter antenna gain, A_{eff} is the effective aperture area of the rectenna, d is the separation distance, and α is the atmospheric attenuation coefficient. For clear atmospheric conditions at 5.8 GHz, α is approximately 0.01 dB/km, which is negligible for the operational range considered. The rectenna conversion efficiency depends on incident power density and load matching:

$$\eta_{rect} = \eta_{diode} \cdot \eta_{match} \cdot [1 - e^{-S_r/S_{sat}}]$$

where η_{diode} is approximately 0.75 representing the Schottky diode rectification efficiency, η_{match} is approximately 0.90 accounting for impedance matching network losses, and S_{sat} denotes the diode saturation power density. The overall microwave transfer efficiency is the product of path efficiency, rectenna conversion, and DC regulation efficiency.

Alignment Error Model

Alignment errors in the lateral (Δx , Δy) and angular (θ , ϕ) dimensions degrade inductive coupling efficiency. The modified coupling coefficient accounting for misalignment is approximated by:

$$k_{\text{mis}} = k_{\text{ideal}} \cdot e^{-(\Delta x^2 + \Delta y^2)/(2\sigma^2)} \cdot \cos \theta \cdot \cos \phi$$

where σ represents the coil characteristic length scale, and θ , ϕ are pitch and roll angular deviations. The alignment control objective minimizes the cost function $J = w_1(\Delta x^2 + \Delta y^2) + w_2(\theta^2 + \phi^2)$, where w_1 and w_2 are weighting coefficients prioritizing lateral versus angular correction during the docking phase.

Battery State Estimation and Predictive Control

The battery state-of-charge (SOC) is estimated using an Extended Kalman Filter integrating coulomb counting with open-circuit voltage (OCV) correction. The discrete-time SOC dynamics follow:

$$\text{SOC}(k+1) = \text{SOC}(k) - \frac{\eta_c \Delta t}{Q_{\text{nom}}} I_{\text{batt}}(k) + w_k$$

where η_c is the coulombic efficiency, Δt is the sampling interval, Q_{nom} is the nominal battery capacity, I_{batt} is the discharge current, and w_k represents process noise. The AI predictive module forecasts future SOC trajectories using a Long Short-Term Memory (LSTM) network trained on mission profiles, weather conditions, and historical consumption patterns. The predicted time-to-critical (TTC) for each child drone is computed as:

where SOC_{min} denotes the minimum safe charge threshold (typically 20%). The scheduling algorithm prioritizes drones with smallest TTC values while optimizing mother drone trajectory to minimize total fleet energy consumption.

$$\text{TTC}_i = \frac{\text{SOC}_i(t) - \text{SOC}_{\text{min}}}{|d\text{SOC}_i/dt|_{\text{predicted}}}$$

Methodology and Operational Workflow

The operational workflow of the proposed intelligent charging system consists of seven sequential phases, executed autonomously with minimal human oversight. The methodology integrates continuous monitoring, predictive analytics, precision navigation, and adaptive power control to achieve seamless mid-air energy replenishment.

Phase 1: Battery Monitoring and Anomaly Detection. Each child drone continuously monitors its battery SOC, cell voltage balance, and temperature using the onboard Battery Management System (BMS). Telemetry data is transmitted to the mother drone and GCS at 10 Hz via the mesh network. Anomaly detection algorithms identify abnormal discharge patterns, thermal runaway precursors, or sensor faults that may compromise charging safety.

Phase 2: Charging Request Generation and Priority Assignment. When a child drone SOC falls below the mission-critical threshold (typically 30%), it issues a charging request containing its current position, SOC, mission priority level, and estimated remaining mission duration. The GCS Strategic Planner collects all active requests and solves the MILP scheduling problem to generate an optimal charging sequence. Priority weights are assigned based on mission criticality (surveillance > mapping > transport), TTC values, and geographical clustering to minimize mother drone transit overhead.

Phase 3: Mother Drone Navigation and Rendezvous. Upon receiving the charging assignment, the mother drone computes an optimal approach trajectory using rapidly-exploring random trees (RRT*) algorithm, considering obstacle avoidance, wind field estimation, and energy-optimal routing. The approach is executed in three stages: coarse approach ($d > 5$ m, GPS-guided), intermediate approach ($5 \text{ m} > d > 1$ m, GPS-IMU fusion), and fine approach ($d < 1$ m, vision-radar fusion). Maximum approach velocity is constrained to 2 m/s during the fine phase to ensure docking safety.

Phase 4: Precision Alignment and Coupling Establishment. During the fine approach, the Extended Kalman Filter fuses stereo vision disparity maps, millimeter-wave radar range measurements, and IMU attitude data to estimate relative pose at 50 Hz update rate. A proportional-integral-derivative (PID) controller with adaptive gains adjusts the child drone position to minimize lateral and angular misalignment. Once alignment errors satisfy the tolerance criteria ($\Delta_x, \Delta_y < 2$ cm; $\theta, \phi < 3$ deg), the system initiates power transfer handshake protocols.

Phase 5: Hybrid Power Transfer Initiation. Based on measured separation distance, the mother drone selects the optimal power transfer mode. For $d < 0.5$ m, the inductive coil is energized at 85 kHz with frequency tracking to maintain resonance despite coil impedance variations. For $d > 0.5$ m, the microwave array transmits a low-power pilot tone to establish beam alignment, followed by gradual power ramp-up to the operational level. The child drone activates the corresponding receiver channel and confirms power reception via telemetry acknowledgment.

Phase 6: Adaptive Power Control and Efficiency Optimization. During charging, the system continuously monitors coupling efficiency, received power, battery temperature, and alignment stability. If efficiency drops below the threshold due to relative motion or atmospheric disturbances, the Tactical Controller adjusts transmitter power, re-optimizes beam steering angles, or commands minor position corrections. The power transfer rate is modulated based on child drone SOC: high-rate charging (2C) for SOC $< 50\%$, tapering to trickle charge (0.2C) as SOC approaches 90% to preserve battery longevity.

Phase 7: Charging Termination and Mission Resumption. Charging terminates when the child drone reaches the target SOC (typically 85-90%, reserving margin for emergency reserve) or when the mother drone must service a higher-priority request. A graceful disconnection sequence ensures electrical isolation before physical separation. The child drone resumes its pre-interrupted mission waypoint sequence, while the mother drone proceeds to the next charging assignment or returns to a solar harvesting loiter pattern if no requests are pending.

Algorithm Design

The intelligent charging system relies on three core algorithms: the Predictive Charging Scheduler, the Multi-Drone Coordination Protocol, and the Adaptive Power Controller. These algorithms operate across hierarchical time scales, from fleet-level mission planning to millisecond-scale power regulation.

Predictive Charging Scheduler

The Predictive Charging Scheduler addresses the NP-hard problem of optimally sequencing charging events for N child drones subject to temporal and spatial constraints. The algorithm formulates the problem as a mixed-integer linear program with the objective of minimizing total fleet mission interruption time.

Decision variables include binary assignment variables x_{ij} in $\{0,1\}$ indicating whether child drone i is assigned to charging slot j , and continuous variables t_j representing the start time of slot j . Constraints enforce: (C1) each drone receives at most one charging slot per scheduling horizon; (C2) charging slots do not overlap for inductive charging (though microwave slots may overlap spatially if angular separation exceeds 30 deg); (C3) mother drone transit time between consecutive assignments must not exceed inter-slot gaps; and (C4) each drone must complete charging before its predicted critical depletion time.

The objective function combines charging completion time, total transit distance, and priority penalties for delayed critical missions. Due to the computational complexity of exact MILP solutions for large fleets, a rolling-horizon heuristic is employed: the scheduler re-optimizes every 60 seconds over a 10-minute lookahead window, accommodating dynamic mission changes and emergency insertions. For real-time execution, a greedy approximation with 2-opt local search provides solutions within 15% of optimal in under 100 milliseconds.

Multi-Drone Coordination Algorithm

The Multi-Drone Coordination Algorithm manages formation geometry and collision avoidance during simultaneous charging operations. For inductive multi-drone charging, child drones execute a vertical stacking formation beneath the mother drone, each separated by 200 mm to minimize inter-coil coupling interference. The formation controller uses a virtual leader approach, where the first child drone aligns directly beneath the mother drone, and subsequent drones position relative to the leader rather than the transmitter, reducing cumulative alignment error.

For microwave multi-drone charging, the Spatial Division Multiple Access (SDMA) controller computes beamforming weights using a zero-forcing precoding matrix to minimize inter-beam interference. The algorithm periodically re-evaluates drone positions and recalculates beam directions every 100 ms. If angular separation between two child drones falls below 15 deg, the system either temporally multiplexes their charging slots or commands one drone to adjust its

holding position. A potential field method provides collision avoidance, generating repulsive forces when inter-drone distances approach the 1.5 m safety envelope.

Adaptive Power Control Algorithm

The Adaptive Power Control Algorithm maintains optimal charging efficiency despite dynamic environmental and positional variations. The controller implements a dual-loop structure: an outer loop adjusts transmitter power setpoints based on child drone SOC and thermal state, while an inner loop performs real-time impedance matching and frequency tracking for the inductive subsystem.

For the inductive channel, a perturb-and-observe method tracks the resonant frequency by modulating the inverter switching frequency and monitoring coil current phase. When the phase difference between voltage and current exceeds 5 deg, indicating detuning due to coil displacement or temperature drift, the controller adjusts compensation capacitance through switched capacitor arrays. For the microwave channel, a maximum power point tracking algorithm adjusts beam steering angles based on rectenna feedback power measurements, implementing gradient ascent in the angular domain with adaptive step sizes to balance convergence speed and stability.

Performance Analysis and Simulation Results

The proposed system was evaluated through comprehensive simulations in MATLAB/Simulink and validated using a hardware-in-the-loop (HIL) testbed. The simulation environment models aerial dynamics, electromagnetic coupling, battery electrochemistry, and atmospheric conditions to assess system performance across diverse operational scenarios.

Power Transfer Efficiency Characterization

Figure 2 presents the measured power transfer efficiency as a function of separation distance for both inductive and microwave channels, as well as the composite hybrid system. The inductive channel maintains efficiency above 80% for separations below 400 mm, with peak efficiency of 88% at 150 mm. Beyond 500 mm, inductive efficiency drops below 50%, rendering it unsuitable for longer ranges. The microwave channel achieves 42% efficiency at 1000 mm, decreasing gradually to 28% at 3000 mm. The hybrid system automatically selects the optimal channel, maintaining composite efficiency above 75% across the entire operational envelope from 100 mm to 3000 mm.

At the nominal operating distance of 300 mm, the hybrid system achieves 82% end-to-end efficiency, comprising 85% inductive coupling efficiency, 97% rectification and regulation efficiency, and 99% DC-DC conversion efficiency. This represents a 35% improvement over pure microwave systems at equivalent distance and a 400% range extension over pure inductive systems while maintaining comparable efficiency.

Alignment Accuracy and Stability

The intelligent alignment subsystem was evaluated under varying environmental conditions including clear sky, moderate turbulence (wind gusts up to 8 m/s), and low visibility (fog with visibility < 100 m). Table 1 summarizes the alignment accuracy metrics across these scenarios.

Under clear conditions, the sensor fusion achieves lateral alignment precision of 4.2 mm RMS and angular precision of 1.1 deg RMS, well within the required tolerances. Moderate turbulence increases lateral error to 8.7 mm RMS due to wind-induced position disturbances, but the adaptive PID controller with gain scheduling maintains stable convergence within 3 seconds of disturbance onset. Low visibility degrades vision system contribution, forcing reliance on radar and IMU fusion; lateral error increases to 12.3 mm RMS, still acceptable for microwave charging but necessitating tighter approach for inductive coupling. The system automatically extends fine approach duration under degraded conditions to ensure safe coupling establishment.

Table 1: Alignment Accuracy Under Different Environmental Conditions

Environmental Condition	Lateral Error (mm)	Angular Error (deg)	Convergence Time (s)
Clear Sky, Calm	4.2 +/- 1.1	1.1 +/- 0.3	2.1
Moderate Turbulence	8.7 +/- 2.4	2.3 +/- 0.8	3.0
Low Visibility (Fog)	12.3 +/- 3.6	3.1 +/- 1.2	4.5
Night Operation	6.8 +/- 1.9	1.8 +/- 0.5	2.8

Flight Duration and Mission Continuity

To quantify the operational impact of mid-air charging, mission simulations were conducted for a surveillance scenario requiring 8 hours of continuous area coverage. A fleet of six child drones with baseline battery capacity of 22,000 mAh (providing 35 minutes flight time) was compared against the same fleet equipped with the proposed charging system and a single mother drone with 100,000 mAh capacity and 500 W solar charging capability.

Without mid-air charging, the fleet required 92 battery swap events at ground stations, accumulating 4.6 hours of mission downtime (accounting for return transit, swap time, and redispach). Coverage continuity was interrupted every 35 minutes, with maximum gap duration of 12 minutes during concurrent battery depletion events.

With the proposed system, child drones executed 34 charging events at altitudes between 50-100 m, with average charging duration of 8 minutes per event. Total mission downtime reduced to 0.9 hours (80% reduction), and coverage gaps were limited to 45 seconds during mother drone transition between charging positions. The mother drone solar harvesting replenished approximately 35% of its daily energy expenditure, extending its own operational endurance to 14 hours before requiring ground replenishment. Figure 3 illustrates the SOC trajectories of representative child drones, demonstrating sustained operation above 25% SOC throughout the mission.

Multi-Drone Charging Scalability

Scalability was evaluated by varying the number of child drones from 1 to 6 while maintaining a single mother drone. For inductive charging, throughput saturated at 4 drones due to time-slot allocation constraints, achieving average per-drone charging intervals of 6 minutes. Adding a fifth drone increased interval to 9 minutes, causing some drones to reach critical SOC before receiving service.

Microwave charging demonstrated superior scalability, supporting 6 drones with average beam allocation of 85% per drone due to spatial multiplexing. However, total power demand approached the mother drone 2 kW transmission limit, reducing per-drone power share and extending individual charging times by 40%. The hybrid scheduling algorithm dynamically switches between modes based on fleet size: pure inductive for 1-2 drones, hybrid for 3-4 drones, and pure microwave with temporal multiplexing for 5-6 drones. This adaptive strategy maintains fleet availability above 90% for all tested configurations.

Comparative Analysis

Table 2 presents a comprehensive comparison between the proposed intelligent mid-air charging system and existing charging methodologies across key performance metrics. The comparison encompasses ground-based inductive charging, automated battery swapping, tethered power supply, and existing wireless power transfer systems reported in literature.

Table 2: Comparative Analysis of UAV Charging Systems

Feature	Ground IPT [1]	Battery Swap [3]	Tethered [11]	Microwave [5]	Proposed System
Charging Mode	Ground/static	Ground/static	Ground/static	Airborne	Mid-air dynamic
Flight Continuity	Interrupted	Interrupted	Continuous	Continuous	Continuous
Mobility	None	Limited	None	High	Fully mobile
Max Efficiency	85%	N/A	95%	35%	82% (hybrid)
Alignment	Manual/basic	Mechanical	Fixed	Basic pointing	Real-time AI
Multi-drone	Sequential	Sequential	Single	Limited	Up to 6 drones
Autonomy	Low	Medium	Low	Medium	High (AI-based)
Infrastructure	Required	Required	Required	Minimal	Not required
Scalability	Poor	Moderate	Poor	Moderate	High
Weather Robust	Moderate	Moderate	High	Low	High

The proposed system demonstrates distinct advantages across all evaluated dimensions. Unlike ground-based solutions, it eliminates infrastructure dependency and mission interruption. Compared to pure microwave systems, the hybrid architecture achieves 2.3x higher efficiency at nominal range while maintaining comparable mobility. The AI-based alignment and scheduling capabilities represent a significant advancement over existing autonomous charging approaches, enabling true self-sustaining UAV fleet operations.

Safety Analysis and Regulatory Compliance

The deployment of high-power wireless energy transmission in aerial environments necessitates rigorous safety analysis encompassing electromagnetic field exposure, thermal management, and collision avoidance. This section evaluates the proposed system against established safety standards and identifies mitigation strategies for identified risks.

Electromagnetic field exposure limits are governed by IEEE C95.1-2019 and ICNIRP guidelines. For the general public, the maximum permissible power density at 5.8 GHz is 10 W/m^2 (1 mW/cm^2) for continuous exposure. The proposed microwave transmitter operates at maximum equivalent isotropically radiated power (EIRP) of 4 kW, yielding a power density of 8.5 W/m^2 at 3 m distance and 31.8 W/m^2 at 1 m distance in the main beam direction. To comply with exposure limits, the system implements three protective measures: (1) beam power is reduced to 500 W EIRP when separation falls below 2 m, maintaining power density below 4 W/m^2 ; (2) a radar-based intrusion detection system immediately terminates transmission if human presence is detected within the 30 deg beam cone; and (3) charging operations are restricted to altitudes above 50 m in populated areas, ensuring ground-level power density attenuation below 0.1 W/m^2 due to free-space spreading.

Thermal safety considerations address both transmitter and receiver electronics. During inductive charging at 500 W transfer power, coil resistive losses generate approximately 75 W of waste heat in the transmitter and 60 W in the receiver. The mother drone employs forced air cooling through ducted fans integrated into the coil housing, maintaining coil temperature below 65 degC under continuous operation. Child drones utilize phase-change material thermal interfaces between the receiver coil and airframe, absorbing transient heat spikes during high-rate charging. Battery thermal management maintains cell temperature within 15-45 degC operating window through active cooling loops and charge rate throttling when thermal limits are approached.

Collision avoidance during charging formation is critical given the close proximity of multiple aerial vehicles. The system implements a layered safety architecture: Layer 1 utilizes ADS-B (Automatic Dependent Surveillance-Broadcast) transponders for cooperative traffic awareness within 10 km radius; Layer 2 employs onboard LiDAR and optical flow sensors for non-cooperative obstacle detection within 50 m; Layer 3 implements a virtual ellipsoidal safety envelope (major axis 3 m, minor axis 1.5 m) around each drone, with automatic emergency separation maneuvers triggered if any envelope intersection is predicted within 2 seconds. The emergency maneuver commands vertical divergence at 3 m/s^2 , ensuring rapid deconfliction while minimizing power transfer disruption.

Future Work

While the proposed system represents a significant advancement in autonomous aerial charging, several avenues for future research and development are identified to further enhance capabilities and operational scope.

Reinforcement Learning for Dynamic Scheduling. The current MILP-based scheduler, while effective for static mission profiles, may not optimally adapt to highly dynamic environments with emergent threats, weather fronts, or pop-up targets. Future work will investigate deep reinforcement learning (DRL) approaches, specifically Proximal Policy Optimization (PPO) and Soft Actor-Critic (SAC) algorithms, trained in high-fidelity simulators to learn adaptive scheduling policies that generalize across diverse mission scenarios without explicit programming of heuristics.

All-Weather Operation. Current alignment accuracy degrades under fog and heavy precipitation. Future sensor suites will incorporate ultra-wideband (UWB) ranging modules providing centimeter-level accuracy regardless of visibility, and millimeter-wave radar with synthetic aperture processing for high-resolution imaging in adverse weather. Machine learning-based sensor dropout compensation will maintain alignment estimates when individual sensor modalities become unreliable.

Integration with Urban Air Mobility (UAM). As urban drone delivery and passenger aerial vehicle ecosystems mature, mid-air charging infrastructure will become essential for continuous operations in dense urban corridors. Future work will address regulatory frameworks for aerial charging zones, integration with unmanned traffic management (UTM) systems, and multi-vendor interoperability standards enabling charging-as-a-service business models.

Conclusion

This paper has presented a comprehensive intelligent mid-air wireless charging system for Unmanned Aerial Vehicles, addressing the fundamental limitation of restricted battery capacity that constrains operational endurance and mission effectiveness. The proposed architecture integrates three key innovations: a hybrid wireless power transfer mechanism combining inductive coupling and microwave beam forming to achieve adaptive efficiency across variable separation distances; a multi-sensor fusion alignment system utilizing GPS, IMU, vision, and radar for precision positioning under diverse environmental conditions; and an AI-based predictive decision-making framework optimizing charging schedules and power allocation for scalable multi-drone operations.

The mathematical models developed for power transfer efficiency, alignment error compensation, and battery state estimation provide rigorous design foundations and performance boundaries. Simulation results demonstrate that the hybrid system maintains end-to-end efficiency above 75% across the operational range of 0.1-3.0 m, with peak efficiency of 88% at short range. The intelligent alignment subsystem achieves sub-centimeter precision under clear conditions and maintains acceptable accuracy under turbulence and reduced visibility. Mission continuity simulations for an 8-hour surveillance scenario demonstrate 80% reduction in mission downtime compared to ground-based charging, with fleet availability maintained above 90% for configurations up to six child drones.

The intelligent mid-air wireless charging system presented herein constitutes a significant step toward fully autonomous, self-sustaining UAV ecosystems capable of indefinite operational endurance in dynamic, unstructured environments.

ACKNOWLEDGMENT

The authors gratefully acknowledge the guidance and support of their faculty advisors, Ramya Dorai and Dr. Meena YR, from the Department of Engineering at JAIN (Deemed-to-be-University), Bengaluru. The authors also extend their sincere gratitude to the university administration for providing access to computational resources and laboratory facilities essential for this research. The constructive feedback from peers and anonymous reviewers significantly improved the quality of this manuscript.

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