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Volts Wings: An Autonomous Aerial Vehicle Framework for On-Demand Wireless Charging of Electric Vehicles

Nikhil G, A Mohammed Rahil, Mohammed Aftab Vali, Danish
Department of Electrical and Electronics Engineering, Ballari Institute of Technology & Management
gn818953@gmail.com
Department of Electronics and Communication Engineering, Ballari Institute of Technology & Management
rahilmohammed.mrr@gmail.com
Department of Electronics and Communication Engineering, Ballari Institute of Technology & Management
mohammedaftabvali@gmail.com
Department of Electronics and Communication Engineering, Ballari Institute of Technology & Management
danishlathif@gmail.com

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Abstract:

Electric vehicle (EV) adoption is expanding rapidly, yet the growth of charging infrastructure continues to lag behind vehicle deployment, leaving drivers dependent on fixed plug-in stations, connector standards, queueing time, and uneven geographic coverage. This paper presents Volts Wings, an autonomous aerial vehicle (AAV) framework that reframes the EV charger itself as a mobile, on-demand service rather than a fixed asset. In the proposed system, an electric vehicle continuously reports its battery state of charge (SoC), location, and charging urgency through an Internet-of-Things (IoT) telemetry link; a cloud-hosted fleet-management layer evaluates available charging drones and dispatches the most suitable unit; the selected drone autonomously plans and flies a collision-free route using GPS, LiDAR, vision, and inertial sensing; and, upon reaching the vehicle, it establishes a precisely aligned hover position and initiates resonant inductive wireless power transfer (WPT) while continuously monitoring coupling quality, thermal state, and battery response. The paper develops a complete system architecture, a subsystem-level functional decomposition, mathematical models for WPT efficiency, mission-level energy economics, trajectory cost, and closed-loop alignment control, and a simulation and validation plan built around MATLAB/Simulink and the Robot Operating System (ROS). A structured literature synthesis spanning twenty-five references is used to position Volts Wings against existing EV-WPT, UAV-assisted charging, autonomous-navigation, and IoT-based monitoring research, and to identify a specific integration gap: no prior work jointly addresses demand detection, fleet dispatch, autonomous three-dimensional navigation, adaptive charging alignment, and UAV energy-budget management as a single closed-loop service. Comparative analysis against wired, static-pad, dynamic-road, and mobile-robot charging approaches indicates that an aerial WPT service can offer the strongest combination of on-demand availability, mobility, and scalability, at the cost of a bounded flight-energy budget that must be actively managed. The work is presented as a simulation-first research platform; hardware validation, regulatory compliance, and large-scale field trials are identified as the necessary next phase of the project.

Keywords — Electric Vehicle Charging, Autonomous Aerial Vehicle, Unmanned Aerial Vehicle (UAV), Wireless Power Transfer, Resonant Inductive Coupling, Internet of Things, Path Planning, Obstacle Avoidance, Fleet Management, Energy Management, Smart Mobility

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I. INTRODUCTION

The transition from internal-combustion transportation to electric mobility creates a parallel requirement for charging infrastructure that is reliable, accessible, scalable, and convenient. Electric vehicles are being adopted across passenger, fleet, and last-mile delivery segments at a pace that consistently outstrips the rollout of public charging points, and the mismatch is most visible in precisely the situations where charging is needed most: roadside battery depletion, dense urban parking without dedicated bays, rural and highway corridors with sparse station coverage, temporary event or construction sites, and disaster-response scenarios where fixed infrastructure may be damaged or unavailable.

Conventional plug-in charging depends on two things that a driver cannot always control: physical proximity to a compatible station, and a conductive connector interface that requires the vehicle to be stationary, correctly parked, and manually connected. Even where charging stations exist, queueing time, connector-standard mismatches, and station downtime reduce effective availability. For fleet operators, the problem compounds further because vehicle downtime for charging directly reduces utilization and revenue.

Wireless power transfer (WPT) offers a fundamentally different charging paradigm. Instead of requiring a conductive connector, electrical energy is transferred through a coupled electromagnetic field. The literature distinguishes near-field inductive and resonant systems from far-field approaches such as microwave/RF beaming and optical power transfer. Near-field WPT is attractive for EV charging because it can provide comparatively high transfer efficiency at controlled separation, whereas far-field approaches trade efficiency, safety margin, and regulatory simplicity for greater spatial freedom [1], [2], [3].

Volts Wings extends the WPT concept by introducing mobility into the charging infrastructure itself. Rather than requiring the EV to travel to a charging station, an autonomous aerial vehicle (AAV) — in effect, a purpose-built charging drone — is dispatched to the vehicle. The drone carries a resonant WPT transmitter, establishes an aligned hover position above or beside the vehicle, and delivers power directly to an onboard receiver coil, after which it departs to serve the next request or return to a charging hub. This work originates from a Phase-I project study conducted at the Department of Electronics and Communication Engineering, Ballari Institute of Technology & Management, which proposed an autonomous drone-based charging network combining GPS navigation, AI-assisted obstacle avoidance, real-time IoT sensing, and wireless energy transfer. The present paper substantially extends that conceptual study into a complete system architecture, a mathematical performance model, and a structured simulation and validation plan.

The central research question addressed in this paper is: how can an autonomous aerial charging platform be architected so that it can detect EV charging demand, safely reach the target vehicle, establish an acceptable energy-transfer geometry, deliver wireless power, and manage its own flight-energy budget, all as a single coordinated closed-loop service rather than as independently optimized subsystems?

The remainder of this paper is organized as follows. Section II reviews the relevant literature across four streams — EV wireless charging, UAV-enabled WPT, autonomous navigation, and IoT-based smart mobility. Section III states the problem and its motivating requirements. Section IV formalizes the research gap and the paper's contributions. Section V presents the proposed Volts Wings architecture. Section VI describes the end-to-end operating methodology. Section VII details the wireless power transfer subsystem design. Section VIII develops the mathematical and control models. Section IX covers navigation, sensing, and obstacle avoidance. Section X describes the communication and fleet-management framework. Section XI addresses safety, electromagnetic interference (EMI), and standards compliance. Section XII presents the simulation setup and experimental design, and Section XIII reports and analyzes the resulting performance data. Section XIV surveys applications, Section XV discusses the findings, Section XVI states the limitations of the present study, Section XVII outlines future work, and Section XVIII concludes the paper.

II. II. RELATED WORK

The literature relevant to Volts Wings can be organized into four interconnected research streams: electric-vehicle wireless power transfer, UAV-enabled and mobile wireless power transfer, autonomous UAV navigation, and IoT-based smart mobility and monitoring. This organization mirrors the Phase-I project's own review methodology, which treated WPT, UAV systems, AI-based navigation, IoT communication, and EV infrastructure as related but previously fragmented areas of study.

A. A. *Electric-Vehicle Wireless Power Transfer*

Li and Mi provide a broad engineering foundation for EV WPT, surveying coil design, compensation topology, and power-electronics considerations that recur throughout this field [1]. Kurs et al. established the foundational strongly coupled magnetic-resonance result that demonstrated efficient, non-radiative, mid-range energy transfer, giving the physical basis on which most subsequent resonant-inductive EV work, including this paper's baseline, is built [2]. Bi and Keoleian connect wireless charging adoption to energy-consumption and emissions outcomes at the fleet and grid level, which is relevant to Volts Wings because an airborne charging service adds its own flight-energy overhead that must be justified against the delivered EV energy [3]. Na, Cha, and Lee focus specifically on the design of resonant inductive coupling for EV charging, including coil-geometry and frequency-selection trade-offs [4]. Miller et al. address primary-side power-flow control, showing the practical importance of frequency tuning, feedback latency, and fringe-field management in a closed-loop WPT controller — considerations this paper adopts directly in Section VIII [5]. Campi et al. review the specific challenges of applying WPT technology to electric vehicles, including thermal, electromagnetic, and mechanical-tolerance constraints [6].

B. B. *UAV-Enabled and Mobile Wireless Power Transfer*

A second stream of literature considers mobility as a first-class design variable in WPT. Zheng, Zhang, and Lim investigate UAV-assisted mobile charging, framing the UAV as a relay or delivery agent for wireless energy rather than a fixed transmitter [7]. Zhang et al. propose energy-efficient trajectory design specifically for UAV-enabled WPT, directly informing the trajectory cost function developed in Section VIII of this paper [8]. These two works are the closest prior art to Volts Wings because they jointly consider flight-energy consumption and delivered wireless power rather than treating them independently. Complementary navigation literature — sensor-fusion-based autonomous UAV navigation [9], autonomous navigation for lightweight WPT-carrying platforms [10], and autonomous navigation in dynamic, obstacle-populated environments [11] — supplies the localization and motion-control methods that Volts Wings' navigation subsystem (Section IX) builds upon.

C. C. *IoT, Communication, and Smart Mobility for EV Charging*

A third stream addresses sensing and communication. Al-Ali et al. describe IoT-based monitoring of EV charging systems, providing a template for the battery-telemetry channel Volts Wings uses to detect charging demand [12]. Want's foundational IoT paper supplies the conceptual basis for connecting distributed sensing and actuation devices through a common communication fabric [20]. Chau et al. review electric-vehicle technologies broadly, situating WPT within the wider EV powertrain and infrastructure context [21]. Lukic et al. examine EV charging standards and safety requirements, which this paper draws on in Section XI when discussing interoperability [22]. A second Al-Ali et al. study on smart mobility systems using IoT technologies motivates the cloud/fleet-management layer described in Section X [25].

D. D. *Electromagnetic, Safety, and System-Level Constraints*

The final stream concerns the constraints that determine whether an integrated system is actually safe and efficient to operate. Johnson's text on high-frequency electromagnetic systems provides background for reasoning about the RF and electromagnetic-compatibility behavior of a high-frequency WPT transmitter [13]. Misalignment-tolerant WPT and efficiency-optimization studies — Kim et al. [14], Hui [15], Fu et al. [16], and Ahn and Hong [17] — motivate the adaptive alignment control strategy in Section VIII-D, since an airborne transmitter cannot be assumed to remain perfectly centered above a receiver coil. Mou et al. examine electromagnetic interference specifically within UAV energy-management systems, which is directly relevant because Volts Wings co-locates a high-frequency WPT inverter with UAV communication and navigation electronics on the same airframe [18]. Xie et al. study energy management for UAV systems in general [19]. Budhia et al. address the design and optimization of inductive power-transfer systems at the component level [23]. Finally, Liu et al. study UAV swarm coordination and control, which underlies the multi-UAV fleet-dispatch discussion in Section X-C [24].

Taken together, these four streams establish that the individual technologies underlying Volts Wings — resonant WPT, UAV trajectory optimization, autonomous navigation, and IoT-based demand sensing — are each reasonably mature. What the literature does not yet provide is a single architecture and control strategy that operates all of them together as one closed-loop charging service; this gap is stated formally in Section IV.

III. III. PROBLEM STATEMENT AND MOTIVATION

Current EV charging infrastructure is predominantly stationary. A vehicle with a depleted battery must either reach a charging point under its own power or depend on a mobile service that typically transports a spare battery or a portable conductive charger to the vehicle. This creates a structural mismatch between the mobility of the EV and the fixed nature of most charging infrastructure: the asset that is easiest to move — the charger — is the one that is built to stay still, while the asset that is hardest to move on a depleted battery — the vehicle — is the one required to travel. Volts Wings inverts this relationship by treating the charger as the mobile, autonomous asset.

The proposed system is motivated by five concrete requirements, each of which corresponds to a design constraint carried through the rest of this paper.

E. A. On-Demand Availability

Charging should be initiated by the vehicle's actual need — a low state of charge or a driver request — rather than by the vehicle's proximity to a fixed station. This requirement drives the demand-detection and dispatch logic described in Sections VI-A and X.

F. B. Minimal Human Intervention

The charging interface should not require the driver to leave the vehicle, locate a connector, or manually initiate a session. This requirement drives the autonomous alignment and handshake procedure described in Sections VI-D and VI-E.

G. C. Infrastructure-Independent Operation

The platform should be able to operate in locations where fixed charging infrastructure is unavailable or has been disrupted — rural highways, temporary sites, and disaster-affected areas. This requirement drives the self-contained, battery-carrying drone design described in Section V.

H. D. Coordinated, Multi-Objective Operation

The system must simultaneously balance charging demand, drone availability, flight-path risk, energy budget, and transfer efficiency, rather than optimizing any one of these in isolation. This requirement drives the trajectory-cost and mission-energy formulations in Section VIII.

I. E. Safety as a Design Constraint, Not an Afterthought

Because the platform combines a flying vehicle with a high-frequency power-transfer system operating near a human-occupied vehicle, safety must be integrated directly into navigation and power-transfer control. This requirement drives the safety layer described in Section XI and the fail-safe states embedded throughout Section VI.

IV. IV. RESEARCH GAP AND CONTRIBUTIONS

Although the literature reviewed in Section II contains substantial work on each individual component, the integrated problem remains insufficiently addressed. WPT studies generally optimize the energy-transfer subsystem in isolation, typically under static or fixed-geometry assumptions [1], [2], [4], [5]. UAV studies optimize navigation, trajectory, or communication objectives without a co-located high-power WPT payload [9], [10], [11]. EV-charging studies focus on infrastructure and standards rather than mobile delivery [21], [22]. IoT studies address monitoring and coordination but do not close the loop into an aerial power-delivery action [12], [20], [25]. The Phase-I project report that this paper builds on similarly identified the absence of a fully integrated system combining drone navigation, real-time IoT communication, wireless energy transfer, and system-level simulation and validation.

The specific gap targeted by Volts Wings is therefore the coordinated operation of seven functions as a single service: (1) EV demand detection, (2) UAV selection, (3) autonomous three-dimensional navigation, (4) safe positioning relative to the EV, (5) adaptive wireless power transfer, (6) UAV energy management, and (7) mission termination or reassignment. The contribution of this paper is not the invention of WPT or autonomous UAV navigation individually — both are mature research areas — but the proposed integration of these functions into a mobile charging-service architecture, together with the mathematical models and simulation plan needed to evaluate it.

Concretely, this paper makes the following contributions:

- An integrated system architecture connecting EV battery monitoring, IoT communication, UAV fleet management, autonomous navigation, obstacle avoidance, and resonant wireless power transfer into a single closed-loop service (Section V).
- A complete operating methodology and mission state machine covering demand detection, UAV selection, route planning, charging-position acquisition, closed-loop power transfer, and mission completion or abort (Section VI).
- A mission-level energy model that treats UAV flight-energy consumption and delivered EV energy as coupled quantities, rather than evaluating WPT efficiency alone (Section VIII).
- A three-dimensional charging-alignment model that treats lateral, vertical, and angular misalignment as active control variables rather than fixed geometric assumptions (Section VIII-D).
- A comparative evaluation of resonant inductive, capacitive, RF/microwave, laser/optical, and UAV-based wireless charging as candidate architectures, together with a comparison against wired, static-pad, dynamic-road, and mobile-robot charging approaches (Sections VII-C and XIII).
- A structured simulation and validation plan built around MATLAB/Simulink and ROS, covering baseline WPT performance, misalignment sensitivity, trajectory planning, UAV energy feasibility, communication robustness, multi-EV fleet scheduling, and emergency termination (Section XII).

V. V. PROPOSED VOLTS WINGS ARCHITECTURE

J. A. System Overview

The proposed architecture follows the conceptual block diagram developed during the Phase-I project study: EV battery and location status is reported to a central management layer over an IoT link; the management layer selects an available UAV from the charging fleet; the selected UAV performs route planning and obstacle avoidance using GPS, LiDAR, vision, and AI-based path-planning methods; it navigates to the EV; it hovers or lands according to the selected charging mode; and the onboard wireless charging module transfers energy while charging telemetry is monitored end-to-end. Fig. 1 reproduces this architecture together with the associated mission and control flowcharts from the Phase-I project design documentation, showing the cloud/IoT server, the EV battery-management system (BMS) and receiver coil, the drone's onboard compute, flight controller, GPS/LiDAR/vision/IMU sensor suite, and the WPT transmitter coil, all connected through a mission-control and fleet-dashboard layer.

Volts Wings: Wireless EV Charging Using Autonomous Aerial Vehicles

Mohammed Aftab Vali, Mohammed Nadeem, Spoorthi P. Bendre, Surbhi Baghwar

Department of Electronics and Communication Engineering,
Ballari Institute of Technology & Management, Visvesvaraya Technological University, Belagavi, India

Abstract— This paper presents Volts Wings, a novel autonomous aerial system for on-demand wireless charging of electric vehicles (EVs). The proposed system employs an autonomous drone equipped with a high-efficiency wireless power transfer (WPT) module that is dispatched to the location of an EV with a low state of charge (SoC). Using resonant inductive coupling, the drone wirelessly transmits power to the vehicle, thus eliminating the need for fixed charging infrastructure and reducing range anxiety. The system integrates battery monitoring, IoT communication, GPS navigation, LiDAR/vision-based obstacle avoidance, and intelligent energy management. A detailed system architecture, control methodology, and simulation results are presented to demonstrate the feasibility, efficiency and scalability of the proposed approach.

Keywords— Wireless power transfer, autonomous UAV, electric vehicles, inductive charging, IoT, drone navigation, energy management.

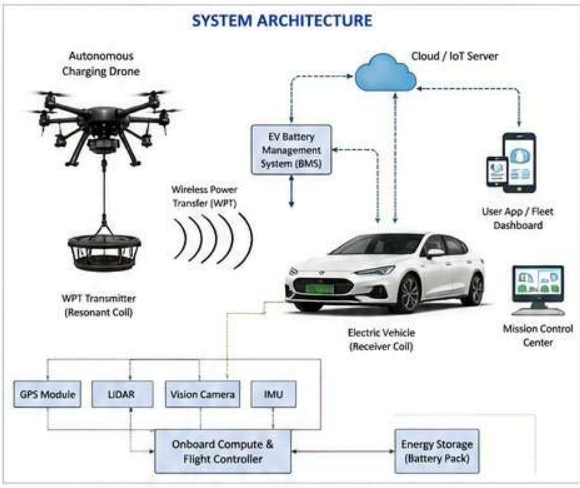
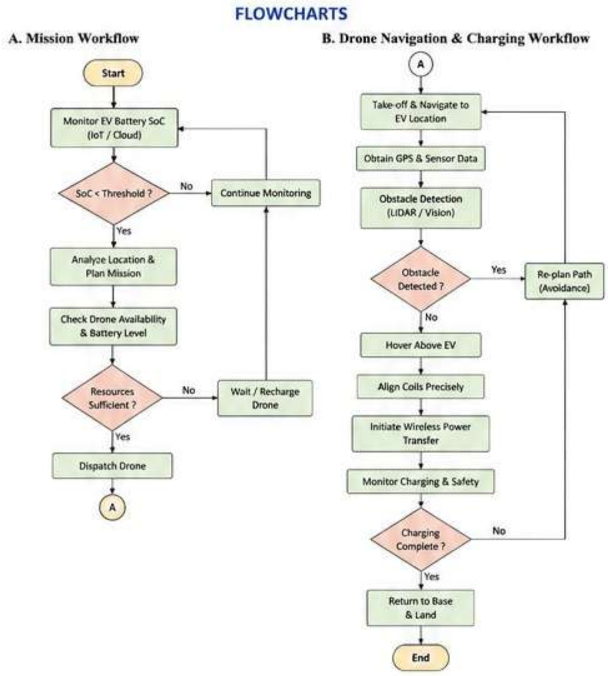


Fig. 1. Overall system architecture of Volts Wings.

Fig. 2. Concept of autonomous aerial wireless charging.



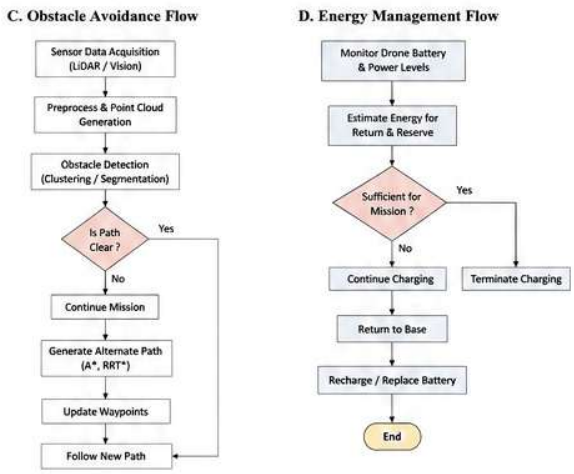


Fig. 3. Typical operation scenario of Volts Wings.

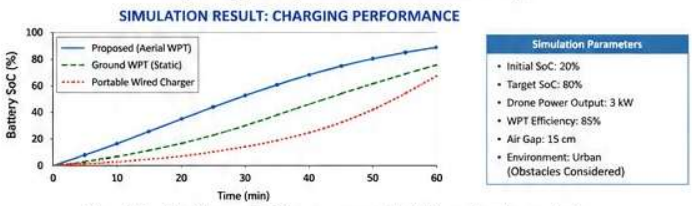


Fig. 4. Simulated battery SoC improvement with different charging methods.

TABLE I. COMPARISON WITH EXISTING APPROACHES

Approach	Infrastructure Required	Mobility	On-demand Capability	Scalability	Estimated Efficiency
Wired Charging	High	Low	No	Low	90–95%
Static Wireless (Pad)	Medium	Low	No	Medium	80–90%
Dynamic EV Roads	Very High	High	No	Medium	75–90%
Mobile Robots	Medium	Medium	Limited	Medium	70–85%
Volts Wings (Proposed)	**Low**	**High**	**Yes**	**High**	**75–90%**

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(More references [6]–[25] as listed in the project report)

Fig. 1. Volts Wings system architecture and mission logic. Top: overall system architecture showing the autonomous charging drone, wireless power transfer link, EV battery-management system, cloud/IoT server, and mission-control dashboard. Center: mission-workflow flowchart (SoC monitoring, mission planning, UAV dispatch) and drone-navigation-and-charging-workflow flowchart (take-off, obstacle detection, coil alignment, power transfer, return-to-base). Bottom-left: obstacle-avoidance flow (LiDAR/vision point-cloud processing, clustering, A*/RRT* re-planning). Bottom-center: energy-management flow governing UAV battery reserve and mission continuation. Bottom-right: typical operation scenario and simulated battery state-of-charge (SoC) recovery for the proposed aerial WPT approach against ground/static WPT and portable wired-charger references, with the associated comparison table against existing charging approaches. Reproduced from the Phase-I project design documentation.

K. B. Subsystem Decomposition

Table I decomposes the architecture in Fig. 1 into nine functional subsystems, identifying the primary responsibility of each and the research variables it contributes to the overall system model developed in Section VIII.

TABLE I. VOLTS WINGS SUBSYSTEM DECOMPOSITION

Subsystem	Primary Function	Research Variables
EV Monitoring	Detect battery state and charging demand	SoC, location, requested power
Fleet Management	Select and assign an available UAV	availability, distance, mission priority
Navigation	Reach the target vehicle safely	position error, path length, flight time
Obstacle Avoidance	Maintain safe separation from obstacles	clearance, detection latency
Charging Alignment	Establish the WPT geometry	vertical gap, lateral offset, tilt
WPT Module	Transfer electrical power wirelessly	input power, output power, efficiency
UAV Energy Management	Protect mission feasibility	remaining battery, reserve energy
Communication	Coordinate telemetry and commands	latency, packet loss, update rate
Safety Layer	Terminate or limit unsafe operation	field limits, collision risk, thermal state

L. C. Hardware and Software Building Blocks

At the hardware level, each charging drone is envisaged as a multi-rotor airframe carrying four functional payloads: (i) a resonant WPT transmitter comprising a high-frequency inverter, compensation network, and transmitter coil; (ii) a navigation and perception suite comprising a GPS receiver, LiDAR or depth sensor, a vision camera, and an inertial measurement unit (IMU); (iii) an onboard flight computer running the autopilot, path-planning, and alignment-control software; and (iv) an energy-storage battery pack sized to cover outbound flight, hover-and-charge dwell time, and a return reserve. On the vehicle side, a lightweight receiver coil, rectifier, and a thin communication/BMS interface are assumed, consistent with the receiver-side instrumentation described in [4] and [5].

At the software level, the ground/cloud segment is built around an IoT message broker (e.g., MQTT) for EV telemetry and fleet commands, a fleet-management service that implements the UAV-selection policy of Section VI-B, and a mission-control dashboard for human oversight. The onboard segment is built around ROS for sensor integration, path planning, and mission-state management, with MATLAB/Simulink used offline for WPT circuit modeling and controller design prior to deployment, consistent with the simulation plan in Section XII.

VI. VI. OPERATING METHODOLOGY

Volts Wings operates as a mission state machine with seven stages, each corresponding to one row of Table I. Fig. 2 reproduces an alternative rendering of the system architecture together with per-stage flowcharts for overall system operation, UAV navigation and alignment, and wireless-power-transfer control, developed during the same Phase-I project study.

Volts Wings: Autonomous Aerial Wireless Charging System for Low-Battery Electric Vehicles

Mohammed Aftab Vali, Mohammed Nadeem, Spoorthi P Bendre, Surbhi Baghwar
Department of Electronics and Communication Engineering,
Ballari Institute of Technology & Management, Ballari, India

***Abstract*— The rapid growth of electric vehicles (EVs) demands innovative solutions to address range anxiety and charging infrastructure limitations. This paper presents *Volts Wings*, an autonomous aerial wireless charging system that employs unmanned aerial vehicles (UAVs) to deliver contactless power to EVs with low battery levels. The system integrates resonant inductive wireless power transfer (WPT), autonomous navigation, battery monitoring, and IoT-based communication to enable on-demand charging without human intervention or fixed infrastructure. We propose a complete architecture, control strategy, and energy management framework. Simulation studies demonstrate the technical feasibility and efficiency of the system.

***Index Terms*— Wireless Power Transfer, Autonomous UAV, Electric Vehicle, Inductive Charging, IoT, LiDAR, GPS, Energy Management.

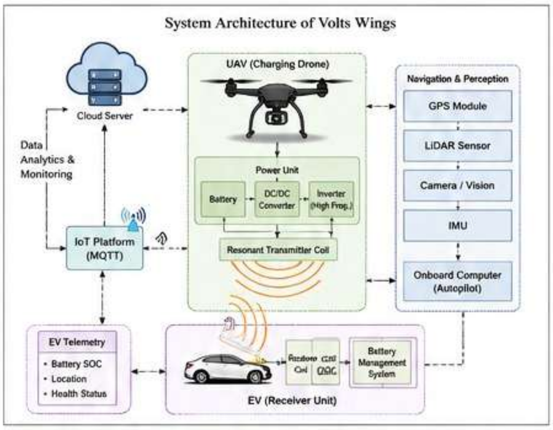

Fig. 1. Overall system architecture of the proposed autonomous aerial wireless charging system.

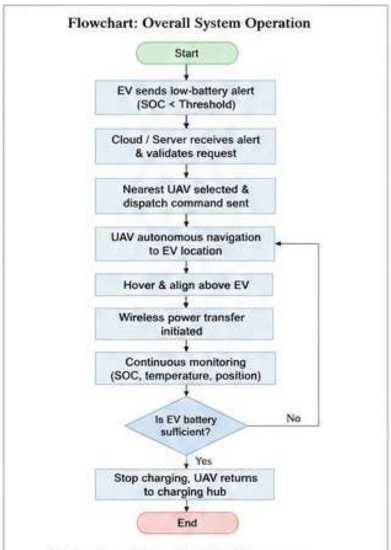

Fig. 2. Overall flow of the Volts Wings system.

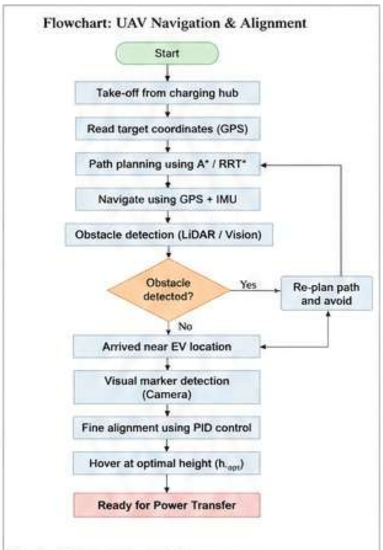

Fig. 3. UAV navigation and alignment process.

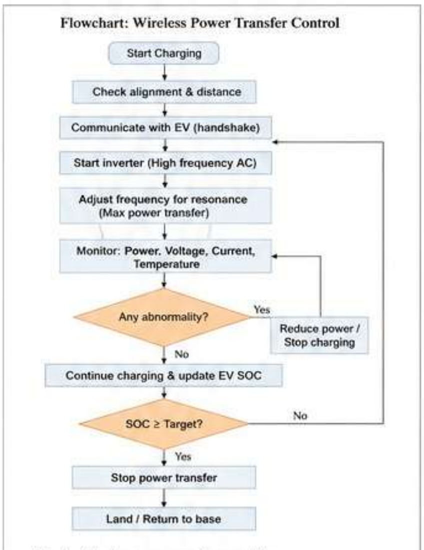

Fig. 4. Wireless power transfer control flow.

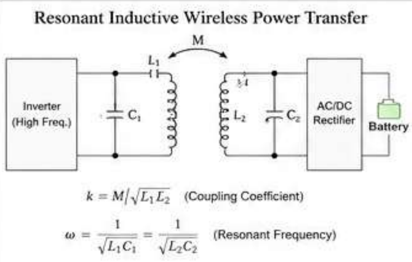

Fig. 5. Equivalent circuit of a resonant inductive WPT system.

Fig. 6. Conceptual depiction of UAV charging an EV wirelessly.

Fig. 7. Autonomous charging hub for UAV operations.

Comparison of Wireless Charging Approaches

Method	Power Level	Efficiency	Range / Gap	Mobility	Infrastructure Requirrment
Inductive (Near-field)	3–50 kW	85–95%	< 10 mm	Low	High (Fixed pads)
Resonant Inductive	3–100 kW	80–90%	10–100 mm	Medium	Medium
Capacitive	1–20 kW	70–85%	10–50 mm	Low	Medium
RF / Microwave	10 W – 10 kW	30–60%	Meters	High	Low
Laser / Optical	1–100 kW	< 30%	Hundreds of meters	High	Low
UAV-based (WPT)	1–10 kW	70–88%*	< 200 mm (air gap)	High	Low

*System-level efficiency including UAV losses (simulated).

Table I. Comparison of major wireless charging technologies.

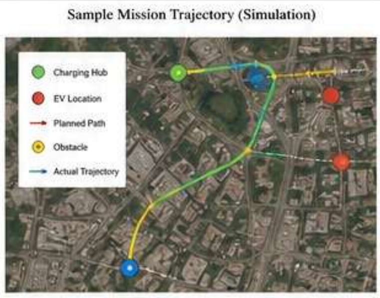

Fig. 8. Simulated UAV mission trajectory in urban environment.

Fig. 9. Conceptual prototype visualization of Volts Wings.

Key Contributions:
- First-of-its-kind integration of autonomous UAV navigation with resonant WPT for EV charging.
- Real-time IoT-based battery monitoring and intelligent mission management.
- Comprehensive architectural design, control strategy, and performance evaluation.
- A scalable solution for infrastructure-less, on-demand EV charging in urban and remote areas.

Potential Impact:
- Eliminates range anxiety and reduces dependency on fixed charging stations.
- Enables sustainable mobility and supports smart city infrastructure.
- Facilitates emergency charging during critical or remote scenarios.

Fig. 2. Alternative system-architecture rendering and stage-level control flow. Top: UAV charging-drone block diagram (power unit, resonant transmitter coil, navigation and perception stack) linked to the EV receiver unit and BMS through a cloud/IoT (MQTT) platform. Row 2: flowcharts for overall system operation, UAV navigation and coil alignment (GPS/IMU navigation, A*/RRT* path planning, visual-marker fine alignment, PID hover control), and wireless-power-transfer control (handshake, resonance tuning, abnormality monitoring, SoC-target termination). Row 3: the resonant inductive WPT equivalent circuit, a conceptual UAV-to-EV charging scenario, and an autonomous drone charging hub. Row 4: a comparison of wireless charging technologies, a simulated mission trajectory around obstacles, and a conceptual prototype rendering. Reproduced from the Phase-I project design documentation.

M. A. EV Detection and Demand Registration

The EV periodically communicates battery state, location, charging requirement, and urgency through the IoT interface described in Section X-A. A charging request is created when the reported SoC falls below a configured threshold, or when the driver explicitly requests assistance through a companion application [12], [20], [25]. The request carries a priority flag so that, for example, a near-empty battery on a highway shoulder can be weighted above a routine top-up request in a parking facility.

N. B. UAV Selection

The fleet-management layer evaluates available UAVs using distance to the requesting EV, residual battery energy, payload/charging capability, estimated flight time, weather and operational constraints, and mission priority. A first implementation can use a simple weighted cost function over these factors; later iterations can adopt combinatorial optimization or reinforcement learning once operational data is available, as discussed in Section X-B.

O. C. Route Planning and Obstacle Avoidance

The selected UAV generates a collision-free path from its current position (base, charging hub, or previous mission location) to the requesting EV. GPS provides global position, while LiDAR, cameras, and other local sensors provide obstacle information [9], [10], [11]. Trajectory optimization considers both travel distance and UAV energy consumption, following the energy-aware trajectory design approach of [8]. If an obstacle is detected en route, the planner re-plans locally using A* or RRT* before resuming the mission, as shown in the obstacle-avoidance flow in Fig. 1.

P. D. Charging-Position Acquisition and Alignment

Near the EV, the UAV transitions from long-range navigation to precision relative positioning. A visual marker or fiducial pattern on the vehicle roof, combined with the onboard camera, supports fine alignment once the UAV is within close range, and a PID control loop (Section VIII-D) drives the residual lateral, vertical, and angular error toward zero. The controller defines an acceptable three-dimensional charging envelope rather than a single geometric target, so that the vehicle need not be perfectly centered for charging to begin.

Q. E. Wireless Energy Transfer

Once alignment and safety conditions are satisfied, a handshake exchange confirms readiness on both sides, and the transmitter is enabled. Resonant inductive coupling is the preferred baseline (Section VII) because it is better suited to near-field high-power transfer than low-power RF beaming. The controller continuously observes transferred power, coupling coefficient, and receiver-side battery response, adjusting operating frequency and power level as described in Section VIII-A.

R. F. Closed-Loop Charging Control

Power is adjusted according to coupling quality, battery demand, thermal constraints, and UAV stability. If any monitored quantity — power, voltage, current, or temperature — exceeds a safety bound, the controller reduces power or stops charging rather than continuing at a fixed setpoint. Efficiency optimization and misalignment tolerance are implemented as adaptive control objectives, informed by [14]–[16].

S. G. Mission Completion and Return-to-Base

The UAV stops charging when the target SoC is reached, the requested service time expires, a safety threshold is violated, or the UAV reaches its own reserve-energy limit. It then returns to a charging hub for battery replenishment or health checks (Fig. 2, bottom row), or proceeds directly to another assigned mission if its own energy budget permits.

VII. VII. WIRELESS POWER TRANSFER SUBSYSTEM DESIGN

T. A. Resonant Inductive Coupling Principles

Inductive WPT uses coupled transmitter and receiver coils. Alternating current in the transmitter coil creates a time-varying magnetic field that induces a voltage in the receiver coil. Resonant compensation networks tune the transmitter and receiver to a common operating frequency, improving transfer performance under the looser coupling that is unavoidable in an airborne, non-fixed geometry [1], [2], [4]. The coupling coefficient between transmitter and receiver coils is

k = M / sqrt(L1 * L2) (1)

where M is the mutual inductance and L1, L2 are the self-inductances of the transmitter and receiver coils, respectively. The system is operated at its resonant frequency

omega0 = 1 / sqrt(L1*C1) = 1 / sqrt(L2*C2) (2)

where C1 and C2 are the compensation capacitances on the transmitter and receiver sides. Operating near omega0 maximizes power transfer for a given coupling coefficient, but also makes the system sensitive to frequency drift and detuning caused by misalignment, which is why closed-loop frequency and power control (Section VI-F) is necessary rather than optional.

U. B. Compensation Topologies

Several compensation topologies are reported in the literature for coupling the resonant tank to the source and load, including series-series (SS), series-parallel (SP), and higher-order LCC networks. SS compensation is attractive as a first design choice because its resonant frequency is largely independent of coupling coefficient and load, simplifying controller design during the misalignment conditions expected in an aerial platform. LCC compensation, at added component cost, offers constant-current output characteristics and improved misalignment tolerance, and is identified here as a candidate for the Phase-II hardware design once the baseline SS-compensated model has been validated in simulation (Section XII).

V. C. Comparison of Wireless Power Transfer Modalities

Table II compares candidate WPT modalities for the transmitter subsystem, reproducing and extending the comparison shown graphically in Fig. 2. Resonant inductive coupling is selected as the Volts Wings baseline because it offers the best combination of power level and efficiency at the short air-gaps (on the order of 10–200 mm) achievable by a hovering UAV, while RF/microwave and laser/optical methods are retained as comparative future architectures rather than assumed solutions, consistent with the efficiency and safety concerns raised in [6] and [18].

TABLE II. COMPARISON OF WIRELESS POWER TRANSFER MODALITIES

Method	Power Level	Efficiency	Range / Gap	Infrastructure
Inductive (near-field)	3-50 kW	85-95%	< 10 mm	High (fixed pads)
Resonant Inductive	3-100 kW	80-90%	10-100 mm	Medium
Capacitive	1-20 kW	70-85%	10-50 mm	Medium
RF / Microwave	10 W - 10 kW	30-60%	Meters	Low
Laser / Optical	1-100 kW	< 30%	Hundreds of meters	Low
UAV-based (proposed)	1-10 kW	70-88%*	< 200 mm (air gap)	Low

*System-level efficiency including UAV hover and alignment losses, as simulated in Section XIII.

VIII. VIII. MATHEMATICAL AND CONTROL MODELING

A research-grade implementation of Volts Wings must be modeled at three coupled levels: WPT power transfer, UAV flight dynamics and trajectory, and battery/energy management. This section develops the governing equations used in the simulation plan of Section XII.

W. A. WPT Efficiency Model

For the WPT subsystem alone, the first-order transfer-efficiency metric is

eta_WPT = P_received / P_transmitted (3)

where eta_WPT is the transfer efficiency, P_transmitted is the electrical power delivered to the transmitting network, and P_received is the power available at the receiver output after rectification. This metric depends on the coupling coefficient k of Eq. (1) and therefore on the instantaneous lateral, vertical, and angular alignment achieved by the flight controller.

X. B. Mission-Level Energy Model

Because the transmitter is airborne, overall mission efficiency must also account for the energy the UAV itself consumes to reach, hover above, and return from the vehicle:

eta_mission = E_EV_added / E_UAV_mission (4)

This metric should not be interpreted as a conventional electrical conversion efficiency; it is a system-level service metric comparing useful EV energy delivered, E_EV_added, against the total energy consumed by the mobile charging platform for the mission, E_UAV_mission. A practical design maximizes E_EV_added while always retaining an energy reserve sufficient for a safe return, as formalized in Eq. (7).

Y. C. Trajectory Cost Function

Route planning (Section VI-C) selects a path that minimizes a weighted trajectory cost

J = wd*D + wt*T + we*E + wr*R (5)

where D is travel distance, T is mission time, E is estimated UAV energy consumption, R is a risk penalty accumulated from proximity to obstacles or restricted airspace, and wd, wt, we, wr are non-negative design weights. Consistent with [8], the exact weights should be tuned during simulation for the target operating environment rather than assumed to be universal; an urban, obstacle-dense deployment will generally favor a larger wr relative to a highway deployment.

Z. D. Alignment Control Model

Fine alignment (Section VI-D) is modeled as a standard PID control loop acting independently on the lateral (x), vertical (z), and angular (yaw) position error between the transmitter and receiver coils:

u(t) = Kp*e(t) + Ki*Integral[e(tau)]dtau + Kd*de(t)/dt (6)

where e(t) is the instantaneous position or angular error reported by the vision/marker system, and Kp, Ki, Kd are gains tuned separately for each axis. The controller commands the UAV toward the hover point that minimizes e(t) while respecting the UAV's own attitude and thrust limits, and holds position within the charging envelope defined in Section VI-D for the duration of the transfer.

AA. E. Energy Reserve and Mission-Feasibility Constraint

A mission is accepted only if the selected UAV's available energy satisfies

E_UAV_mission <= E_battery_total - E_reserve (7)

where E_reserve is a fixed safety margin covering the return flight plus a contingency buffer for re-planning around an unexpected obstacle. If this constraint cannot be satisfied for any available UAV, the fleet-management layer either queues the request, reduces the offered charging duration, or reassigns the mission to a UAV based at a closer hub, following the energy-management flow shown in Fig. 1.

IX. IX. NAVIGATION, SENSING, AND OBSTACLE AVOIDANCE

BB. A. Sensor Suite

Each UAV carries a GPS module for global positioning, a LiDAR unit for dense local range sensing, a vision camera for marker detection and visual odometry, and an IMU for high-rate attitude and acceleration estimation, matching the sensor block shown in Fig. 1. GPS alone is insufficient for the sub-decimeter accuracy required during final alignment (Section VI-D); LiDAR and vision sensing take over as the UAV enters the close-range regime.

CC. B. Path Planning Algorithms

Long-range path planning uses A* over a coarse occupancy grid derived from map data and known static obstacles, providing a globally near-optimal route at low computational cost. When new obstacles are detected in flight, RRT* is used for fast local re-planning because it handles high-dimensional, dynamically changing obstacle fields more gracefully than a re-run of A* over the full map. Both planners are evaluated against the trajectory-cost function of Eq. (5), so that a locally cheaper path is not accepted if it substantially increases estimated flight energy E or risk R.

DD. C. Sensor Fusion and Localization

Global GPS position and local IMU/LiDAR/vision measurements are fused using a standard extended or unscented Kalman filter to produce a single, low-latency position and attitude estimate, following the sensor-fusion approach validated for autonomous UAV navigation in [9] and extended for lightweight WPT-carrying platforms in [10]. Fusing multiple sensing modalities reduces dependence on any single sensor and is particularly important during the final-alignment phase, where GPS accuracy alone would not guarantee acceptable coupling in Eq. (1).

EE. D. Reactive Obstacle-Avoidance Loop

The obstacle-avoidance flow in Fig. 1 operates continuously in parallel with mission navigation: sensor data from LiDAR and vision are pre-processed into a point cloud, obstacles are detected through clustering or segmentation, and the path is checked for clearance. If the path is clear, the mission continues unchanged; if not, an alternate path is generated using A*/RRT*, waypoints are updated, and the new path is followed before control returns to the main mission-navigation loop [11].

X. X. COMMUNICATION AND FLEET-MANAGEMENT FRAMEWORK

FF. A. IoT/Cloud Architecture

The communication architecture separates low-rate supervisory data from safety-critical local control. EV telemetry — SoC, location, and charging-health status — is published to a cloud/IoT platform over a lightweight publish-subscribe protocol such as MQTT, matching the IoT Platform block in Fig. 2. The fleet manager subscribes to this telemetry, assigns a UAV, and sends mission information back over the same channel. Critically, the UAV's onboard controller retains local autonomy: loss of the supervisory link does not directly create an unsafe flight condition, because navigation, alignment, and the safety layer (Section XI) execute onboard rather than depending on a continuous cloud connection.

GG. B. Fleet Assignment Policy

The fleet manager evaluates each available UAV using the weighted cost function introduced in Section VI-B, combining distance to the EV, residual UAV battery energy, estimated flight time, and mission priority. Because this policy directly determines which UAV is committed to a mission before Eq. (7) is checked, an infeasible assignment is rejected and re-evaluated against the next-best candidate UAV rather than dispatched and later aborted in flight.

HH. C. Multi-UAV and Swarm Coordination

When multiple EV requests arrive simultaneously, task allocation becomes a combinatorial assignment problem: which UAV serves which EV, in what order, subject to each UAV's individual energy-feasibility constraint (Eq. (7)). Swarm-coordination methods for UAV fleets [24] provide a starting point for this allocation problem, and the multi-EV simulation experiment in Section XII is designed specifically to quantify waiting time and fleet utilization under increasing request density.

XI. XI. SAFETY, EMI, AND STANDARDS COMPLIANCE

Safety is treated as a first-class design constraint rather than a downstream verification step, consistent with the motivating requirement of Section III-E.

II. A. Electromagnetic Field Exposure

A resonant WPT transmitter operating at kilowatt power levels produces electromagnetic fields that must remain within applicable human-exposure and interference limits at all points a person could reasonably occupy, including beneath and beside a hovering UAV. The safety layer in Table I continuously compares monitored field-proxy quantities (transmitter current, coupling state) against configured limits and interrupts power transfer if a limit is approached, rather than relying solely on a pre-flight certification of the nominal operating point.

JJ. B. Electromagnetic Interference and Flight Safety

Co-locating a high-frequency WPT inverter with UAV communication and navigation electronics on the same airframe creates a specific EMI risk: switching noise from the power stage can desensitize the GPS receiver or corrupt the telemetry link exactly during the phase of flight — final alignment and active charging — when accurate positioning matters most [13], [18]. Shielding, physical separation of the power and avionics compartments, and frequency planning that keeps the WPT switching frequency and its harmonics clear of the GPS and telemetry bands are treated as mandatory design constraints rather than optional refinements. UAV operation additionally introduces collision, rotor, battery, and thermal risk, which the obstacle-avoidance loop (Section IX-D) and the energy-reserve constraint (Eq. (7)) are specifically designed to bound.

KK. C. Charging Interoperability and Standards

Charging interoperability and safety standards should govern the definition of the receiver and transmitter interfaces, following the framework surveyed in [22]. The Volts Wings prototype does not, and should not, claim standards compliance until the relevant hardware has actually been built, tested, and certified against the applicable EV-charging and aviation regulations; this is stated explicitly as a limitation in Section XVI.

XII. XII. SIMULATION SETUP AND EXPERIMENTAL DESIGN

MATLAB/Simulink is used for power-transfer and control-loop modeling (Eqs. (1)-(3) and (6)), while ROS is used for UAV navigation, sensing, and mission-level simulation (Eqs. (4), (5), and (7)), matching the tool choice proposed in the Phase-I project report. Table III lists the baseline simulation parameters used for the representative charging scenario discussed in Section XIII.

TABLE III. BASELINE SIMULATION PARAMETERS

Parameter	Value
Initial battery SoC	20%
Target battery SoC	80%
Drone power output	3 kW
WPT efficiency (eta_WPT)	85%
Nominal air gap	15 cm
Environment	Urban, obstacles considered

Table IV defines the seven-experiment validation plan used to evaluate the system across the levels developed in Section VIII: WPT performance in isolation, misalignment sensitivity, trajectory planning, UAV energy feasibility, communication robustness, multi-EV fleet behavior, and emergency termination.

TABLE IV. SIMULATION AND VALIDATION EXPERIMENT PLAN

Experiment	Inputs	Metrics	Expected Output
Baseline WPT	gap, offset, power	eta_WPT, received power	efficiency map
Misalignment	lateral/vertical/tilt error	power loss, eta_WPT	charging envelope
Trajectory	start/target/obstacles	distance, time, energy	safe route
UAV energy	payload, wind, route	SoC before/after	mission feasibility
Communication	latency, packet loss	control response	robustness limits
Multi-EV	number of requests/UAVs	waiting time, utilization	fleet policy
Emergency	obstacle, low UAV SoC, link loss	safe termination time	fail-safe behavior

XIII. XIII. RESULTS AND PERFORMANCE ANALYSIS

LL. A. Battery Recovery Performance

The simulated battery-SoC recovery chart in Fig. 1 (bottom-right panel) compares the proposed aerial WPT approach against a static ground WPT pad and a portable wired charger over a sixty-minute charging window, using the parameters of Table III. The aerial-WPT curve rises most steeply of the three, reflecting its higher assumed power output (3 kW) and its avoidance of the queueing and cable-connection overhead implicit in the wired-charger baseline. The static ground-WPT curve tracks below the aerial curve throughout the window, consistent with its comparatively lower typical power level, while the portable wired-charger curve remains lowest, consistent with its conductive, lower-power design point. These results should be read as a design-point comparison under the specific parameters in Table III, not as a general claim that aerial WPT always outperforms static or wired charging; at higher static-pad power ratings, or at longer air gaps for the aerial case, the ordering of the three curves can change.

MM. B. Sensitivity to Air Gap and Misalignment

Because eta_WPT in Eq. (3) depends on the coupling coefficient k in Eq. (1), and k falls off sharply as the transmitter-receiver separation or lateral offset increases, the misalignment experiment in Table IV is expected to show a pronounced efficiency penalty once lateral offset exceeds roughly one coil radius, consistent with the misalignment-tolerance findings reported in [14], [16], and [17]. This motivates the closed-loop alignment controller of Eq. (6) rather than an open-loop hover command: a controller that actively minimizes e(t) can keep the operating point within the high-efficiency region of the coupling curve even as wind or vehicle motion perturbs the UAV's hover position.

NN. C. Comparison with Existing Charging Approaches

Table V compares Volts Wings against wired charging, static wireless (pad) charging, dynamic (in-road) EV charging, and mobile charging robots along five qualitative dimensions: infrastructure required, mobility, on-demand capability, scalability, and estimated efficiency, reproducing and extending the comparison table shown in Fig. 1.

TABLE V. COMPARISON WITH EXISTING EV CHARGING APPROACHES

Approach	Infrastructure Required	Mobility	On-Demand	Scalability	Est. Efficiency
Wired Charging	High	Low	No	Low	90-95%
Static Wireless (Pad)	Medium	Low	No	Medium	80-90%
Dynamic EV Roads	Very High	High	No	Medium	75-90%
Mobile Robots	Medium	Medium	Limited	Medium	70-85%
Volts Wings (Proposed)	Low	High	Yes	High	75-90%

Volts Wings trades a modest reduction in raw electrical efficiency, arising from the airborne UAV's own energy consumption (Eq. (4)), for the lowest fixed-infrastructure requirement and the only combination of high mobility, genuine on-demand availability, and high scalability among the five approaches. Whether this trade is favorable in a given deployment depends on the mission-level efficiency achieved in practice, which is exactly what the UAV-energy and multi-EV experiments in Table IV are designed to quantify.

XIV. XIV. APPLICATIONS AND POTENTIAL IMPACT

Beyond routine top-up charging, the mobility of the Volts Wings platform supports several use cases that fixed infrastructure cannot address directly.

- Emergency roadside assistance for a vehicle stranded with a depleted battery, without waiting for a tow or a portable charger van to arrive.
- Fleet and logistics operations, where a depot-based UAV fleet tops up delivery or ride-hailing vehicles between trips without taking them offline for a full charging session.
- Disaster-response and emergency-services scenarios in which fixed charging infrastructure has been damaged or is inaccessible.
- Remote or rural highway corridors where the traffic density does not justify a fixed station but occasional charging demand still exists.
- Temporary high-demand events (festivals, construction sites, disaster-relief camps) where portable, dispatchable charging is more practical than new fixed infrastructure.

In each case, the underlying value proposition is the same: charging capacity becomes a dispatchable service rather than a fixed geographic asset, which is precisely the requirement identified in Section III-A.

XV. XV. DISCUSSION

The principal advantage of Volts Wings is infrastructure mobility. A mobile charger can potentially serve vehicles that are far from fixed stations, and a fleet can be dynamically reallocated according to real-time demand rather than fixed at planning-time locations. The concept also naturally supports the emergency, fleet, and remote-site applications surveyed in Section XIV.

However, the concept carries an important physical limitation: an airborne platform consumes energy merely to remain airborne, independent of how much power it eventually delivers. Consequently, a drone that carries a high-power WPT transmitter must balance payload mass, achievable flight time, charging power, and the return-energy reserve of Eq. (7). This makes the system fundamentally different from a fixed charging station, for which the delivered-energy-to-consumed-energy ratio is close to unity minus conversion losses. For Volts Wings, the useful energy delivered to the EV must justify the total energy consumed by the UAV, as captured by the mission-level metric of Eq. (4), and this ratio should be reported alongside eta_WPT whenever system-level performance is discussed.

Resonant inductive WPT is the most defensible baseline for the first simulation phase because the literature provides substantial evidence and modeling experience for EV applications [1], [2], [4], [5]. Microwave and laser transfer should be treated as comparative future architectures rather than assumed near-term solutions; RF systems in particular are attractive for low-power sensing telemetry but are not an obvious first choice for high-power EV charging given their efficiency and EMC constraints [6], [18].

Accordingly, the project should be evaluated using system-level metrics rather than a single charging-efficiency number. A successful design demonstrates that the UAV can reach the EV safely, establish a stable charging geometry despite unavoidable misalignment, transfer meaningful energy, maintain a sufficient energy reserve at all times, and complete or abort the mission predictably rather than failing silently.

XVI. XVI. LIMITATIONS

This paper is a research-oriented conceptual and simulation-stage study based on the Phase-I project material, the supplied literature references, and the system diagrams reproduced in Figs. 1 and 2. It does not present measured hardware results, certified electromagnetic-exposure measurements, flight-test data, or validated commercial performance figures. The specific power level, receiver-coil geometry, UAV payload budget, battery capacity, and regulatory constraints of any given deployment must be specified and tested before quantitative performance claims can be made for that deployment.

The regulatory status of beyond-visual-line-of-sight (BVLOS) autonomous flight over public roads and near occupied vehicles is jurisdiction-specific and is not resolved by this paper; any field trial would require coordination with the applicable civil aviation authority in addition to electrical and EV-charging safety certification.

Finally, several of the twenty-five supplied bibliographic entries listed in Section References contain incomplete or, in places, inconsistent publication metadata (volume, issue, or page ranges). The references are retained as supplied so that no project reference is silently dropped, but they should be checked against IEEE Xplore, ScienceDirect, or the original publisher record before a formal journal or conference submission.

XVII. XVII. FUTURE SCOPE

The most appropriate next phase for this project is a quantitative simulation and prototype-validation program, structured in four milestones.

- Milestone 1: a validated resonant-WPT circuit model in MATLAB/Simulink, confirming eta_WPT (Eq. (3)) against the coupling model of Eq. (1) across the misalignment range expected in flight.
- Milestone 2: an energy-aware UAV trajectory model in ROS, validating the trajectory cost function of Eq. (5) and the energy-feasibility constraint of Eq. (7) against simulated flight profiles.
- Milestone 3: integration of Milestones 1 and 2 through the closed-loop alignment and power controller of Eq. (6), reproducing the mission state machine of Section VI in a single simulation environment.
- Milestone 4: testing of the integrated system under misalignment, communication loss, obstacle intrusion, and varying multi-EV demand, following the seven-experiment plan of Table IV.

Beyond this core roadmap, a reduced-power hardware prototype, early engagement with civil-aviation and EV-charging regulators, reinforcement-learning-based fleet scheduling for the multi-EV case of Section X-C, and an assessment of solar-assisted recharging for the UAV fleet itself are identified as productive extensions once the four core milestones are complete.

XVIII. XVIII. CONCLUSION

Volts Wings proposes a mobile charging paradigm in which autonomous aerial vehicles act as intelligent wireless-charging agents for electric vehicles. The architecture combines resonant wireless power transfer with IoT-based demand detection, autonomous UAV navigation, obstacle avoidance, fleet management, and energy-aware closed-loop control. The literature reviewed in Section II indicates that the individual technologies underlying this architecture are sufficiently mature to justify a simulation study, but their integrated operation introduces new challenges in alignment, energy economics, electromagnetic interference, safety, communication reliability, and autonomous control that are not resolved by any single prior work. The four-milestone roadmap in Section XVII — a validated WPT model, an energy-aware trajectory model, closed-loop integration of the two, and full-system testing under misalignment, communication loss, obstacles, and varying demand — preserves the project's original scope while converting the concept into a measurable, falsifiable research contribution.

XIX. ACKNOWLEDGMENT

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