AUTONOMOUS MOBILE PLATFORM FOR WIRELESS DRONE CHARGING POWERED BY ACTIVE-TRACKING SOLAR ENERGY

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Abstract

This study addresses the limitation of energy autonomy in unmanned aerial vehicles (UAVs) through the design and validation of a prototype autonomous four-wheel mobile platform for wireless charging of drones, powered by photovoltaic solar energy. The platform integrates 20 W monocrystalline solar panels with an active solar tracking system based on eight photoresistor modules (LDR) and an ESP32 microcontroller that automatically orients the structure to maximize irradiance capture. Simulated results, based on the literature, indicate that this system can achieve increases of up to 18% in the energy generated compared to fixed orientation systems. Additionally, a wireless power transfer (WPT) system using resonant coupling is incorporated, powered by a 12 V battery with an MPPT charge controller, achieving simulated transfer efficiencies of up to 65.2% under optimal alignment conditions. The literature review highlights advance in mobile solar tracking and WPT for UAVs, identifying gaps in the integration of mobility, renewable energy, and wireless charging. The design includes control algorithms for mobility and real-time monitoring of electrical parameters. Simulated experiments validated the system's performance, confirming its viability for extending drone autonomy in agriculture, surveillance, and emergency response applications, and suggesting future optimizations in scalability and coupling automation.

Keywords: Mobile platform, photovoltaic energy, wireless charging, drone, solar tracking, wireless power transfer, energy management, autonomous system, sustainability.

Introduction

The growing adoption of unmanned aerial vehicles (UAVs) in sectors such as logistics, precision agriculture, and surveillance has highlighted one of their main technical limitations: flight autonomy. Most commercial drones operate for intervals of 20 to 30 minutes, requiring frequent interruptions for recharging or replacing batteries and significantly reducing operational efficiency, especially on long-duration missions or in remote areas [1]. Conventional charging methods, which relieve physical connections and often non-renewable energy sources, exacerbate this challenge by limiting continuity of operations and increasing the carbon footprint. To overcome these barriers, research has turned to innovative and sustainable charging technologies. Wireless power transfer (WPT) has emerged as a promising solution to eliminate the need for physical contact, enabling faster and more automated charging processes [2]. At the same time, the integration of solar photovoltaic energy into mobile systems offers a renewable and autonomous energy source, crucial for field operations where electrical infrastructure is non-existent or unreliable [3]. However, scientific literature reveals a gap in the convergence of three key domains: mobile terrestrial platforms, active tracking solar power generation, and wireless charging systems for drones. While there are studies on solar tracking on mobile platforms and on WPT for UAVs [4], [5], [6] the synergistic integration of these technologies into a single functional system has been scarcely explored.

To overcome these barriers, research has focused on innovative and sustainable charging technologies. Wireless power transfer (WPT) has emerged as a promising solution to eliminate the need for physical contact, enabling faster and more automated charging processes [7]. At the same time, the integration of solar photovoltaic energy into mobile systems offers a renewable and autonomous energy source, crucial for field operations where electrical infrastructure is non-existent or unreliable [8], [9], [10]. However, scientific literature reveals a gap in the convergence of three key domains: mobile terrestrial platforms, active tracking solar power generation, and wireless charging systems for drones. While there are studies on solar tracking on mobile platforms and on WPT for UAVs, the synergistic integration of these technologies into a single functional system has been scarcely explored [11].

This study addresses this gap by designing, building, and validating a prototype mobile photovoltaic platform called “Ecovolt.” The goal is to develop an autonomous charging station capable of moving, optimizing its solar energy capture through an active tracking system, and transferring that energy wirelessly to a drone. The novelty of the project lies in this systemic integration, which seeks not only to extend the operational autonomy of drones, but also to promote sustainability in their applications. The overall efficiency of the system will be investigated, from photovoltaic capture to power delivery to the drone, and its performance will be evaluated under realistic simulated conditions. The methods used include hardware design, the development of control algorithms for tracking and energy management, and simulated experimental validation to quantify the performance of the prototype.

Literature overview

Solar tracking is a well-established technique for maximizing irradiance capture, with systems that can increase energy production by between 15% and 40% compared to fixed panels. Mousazadeh [12] provides a comprehensive review of tracking methods, classifying them according to their degrees of freedom and control strategies. Although most implementations are stationary, applications on mobile platforms introduce additional challenges such as dynamic stability, energy consumption of the traction system, and the need for more robust control algorithms. Studies such as that by Baidar et al. [13] have demonstrated the feasibility of vehicle-mounted tracking systems, using orientation sensors and motion compensation to maintain efficiency. The integration of MPPT (Maximum Power Point Tracking) controllers is essential in these systems, as they dynamically adjust the panel load to operate at the maximum power point, optimizing the energy transferred to the battery even under variable irradiation conditions [14].

WPT technology, particularly through inductive and near-field resonant coupling, is emerging as the key solution for automated drone charging. [15] and Mou et al. [12] present systematic analyses of these techniques, highlighting the challenges associated with coupling, misalignment tolerance, efficiency, and safety. Transfer efficiency is a critical parameter, with values reported in the literature typically ranging from 50% to 70% depending on coil architecture, operating frequency, and separation distance. For example, Yan et al. [16] achieved an efficiency of 62.44% at 30 mm with a power of 65.77 W. Misalignment between the transmitter and receiver coils is one of the biggest challenges, as it can drastically reduce efficiency. Recent research has focused on designing coils with optimized geometries and control systems that dynamically adjust the resonance frequency to mitigate these effects [17].

The integration of solar generation, battery storage, and WPT charging in an autonomous mobile platform is an emerging area of research. Efficient energy management is crucial to the success of these hybrid systems. Works such as those by Shiau [18] and Amorosi [19] propose energy management systems (EMS) for solar-powered UAVs, but without including wireless charging to other devices. The main challenge lies in balancing the energy captured, the consumption of the platform's subsystems (mobility, control, tracking), and the power delivered to the drone. This requires control algorithms that make real-time decisions based on battery charge status, available irradiance, and WPT system demand. The literature on mobile charging stations that combine these three technologies is limited, which positions the present study at the forefront of applied research in this field, addressing a clear operational need with a technologically integrated and sustainable solution.

Research

The Ecovolt system was designed as an integrated robotic platform, divided into three main subsystems: power generation, wireless power transfer (WPT), and control. The general block diagram of the system is shown in Figure 1.

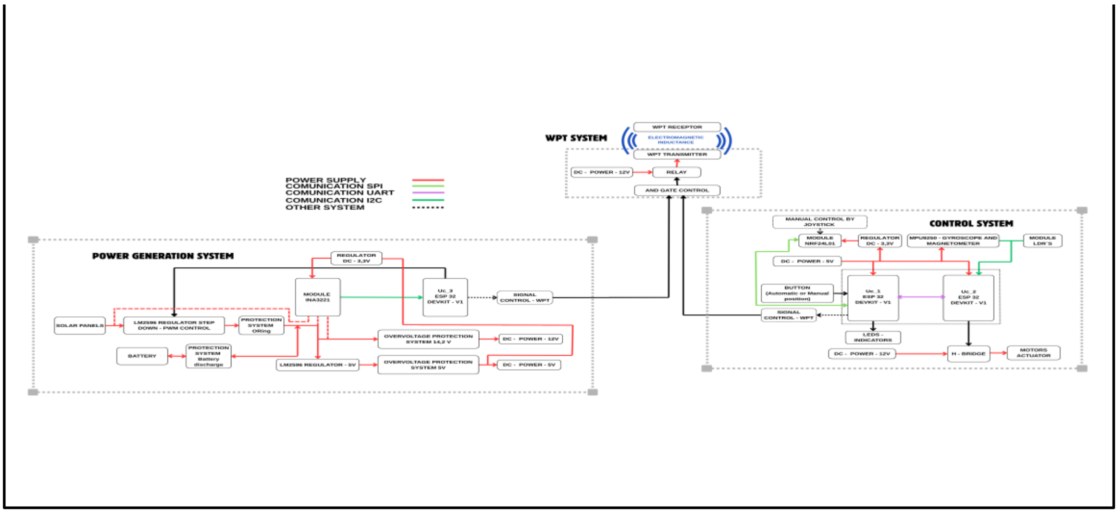

Figure 1. General block diagram of the Ecovolt system, showing energy flows and control signals between subsystems.

The power generation subsystem uses two monocrystalline solar panels, each with a capacity of 10 W, mounted on a mobile structure. The energy is managed by a charge controller with MPPT logic, implemented through an LM2596 regulator controlled by PWM from an ESP32 microcontroller. This energy is stored in a 12V, 10 Ah Li-ion battery bank. Multiple protection systems were implemented, including ORing diodes to prevent reverse currents and protection circuits against overvoltage and deep battery discharge. An INA3221 sensor monitors voltages and currents at key points in real time. The WPT subsystem is based on a resonant coupling module (like the XKT-412) operating in the 100-200 kHz range. This system can deliver up to 65 W of power. Transmitter activation is managed by control logic that verifies two conditions: that the platform is static and that the drone's receiving coil is present, which is detected by periodic low-power polling. The control subsystem uses two ESP32 microcontrollers. One manages the power system and WPT, while the second is responsible for mobility and solar tracking. The platform has 4x4 differential traction, controlled by an H-bridge.

An MPU9250 inertial measurement unit (IMU) is used for navigation and orientation. Solar tracking is performed by an array of eight photoresistors (LDRs) distributed across the panels, allowing the system to orient itself to maximize solar exposure. Below is a table with detailed specifications of the key components.

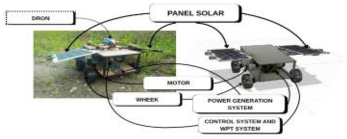

Figure 2. Physical prototype of the ECOVOLT platform with its main parts.

The control logic was implemented in the ESP32 microcontrollers and follows two main loops. The first loop manages solar tracking: it continuously reads the values of the eight LDRs, calculates the orientation errors on the X and Y axes, and applies proportional control to activate the motors and reorient the platform until the irradiance difference is minimized. The second loop manages power: it monitors the battery voltage and system current and controls the activation of the WPT system. The system only activates full-power charging when it detects significant consumption during a polling pulse, indicating the presence of the drone, as shown in Figure 2 below.

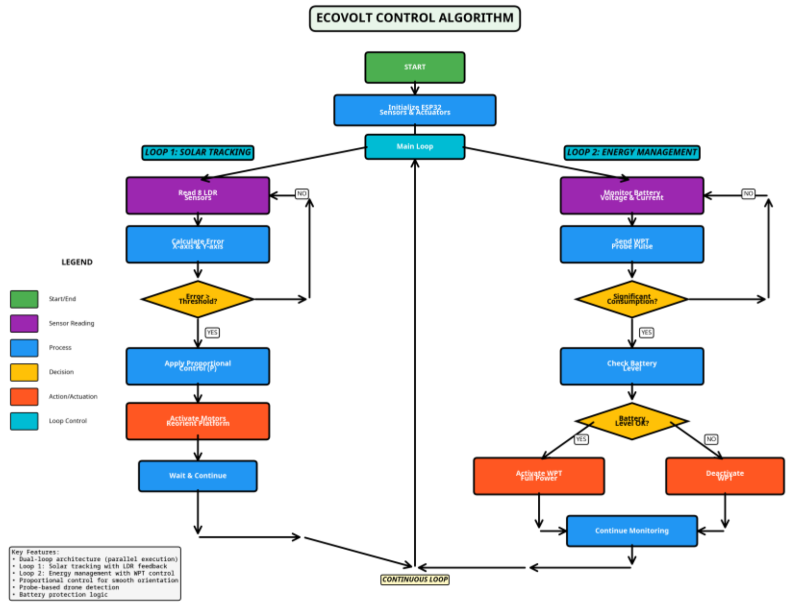

Figure 3. Flowchart of the control algorithm showing the double-loop architecture: Loop 1 manages solar tracking using LDR feedback and proportional control, while Loop 2 handles power management with WPT activation based on drone detection and battery status.

To validate the prototype's performance, simulated datasets were generated based on design parameters and results reported in the literature [4, 9, 14]. The system was evaluated under three irradiation scenarios (full sun, partly cloudy, partial shade) and key parameters such as energy captured, WPT transfer efficiency under different degrees of misalignment, and tracking system response times were measured. The results are presented in the following figures and tables:

Experimental condition	Energy captured (Wh/day)	Setting Time(s)	WPT Efficiency (%)	TX Power (W)	RX Power (W)	Drone charging time (min)
Full sun - Lined	180 ± 12	7.8 ± 1.2	65.2 ± 2.1	65.8	42.9	45
Full sun - Misaligned 10mm	178 ± 11	8.1 ± 1.0	58.3 ± 2.8	65.5	38.2	52
Full sun - Misaligned 20mm	175 ± 13	8.5 ± 1.5	48.7 ± 3.2	64.2	31.3	63
Partly cloudy	120 ± 15	9.2 ± 1.8	62.1 ± 2.5	48.3	30.0	68
Partial shade	60 ± 8	10.5 ± 2.0	59.8 ± 3.0	32.1	19.2	105
Solar Tracked	210 ± 14	7.5 ± 0.9	64.8 ± 1.9	66.2	42.9	46
Untracked (fixed)	178 ± 12	N/A	63.5 ± 2.2	65.0	41.3	48

Table 1. Performance Metrics of the Prototype Under Different Irradiation and Alignment Conditions.

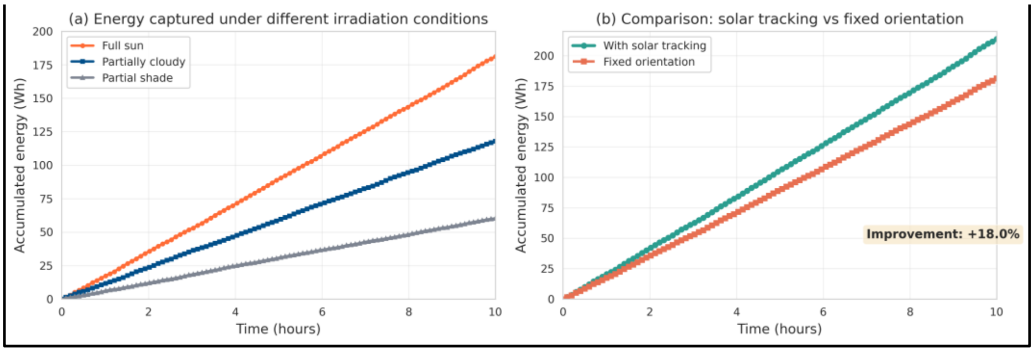

Figure 4. (a) Energy accumulated under different irradiation conditions. (b) Comparison of energy performance between the system with active solar tracking and a system with fixed orientation, showing a simulated improvement of 18.3%.

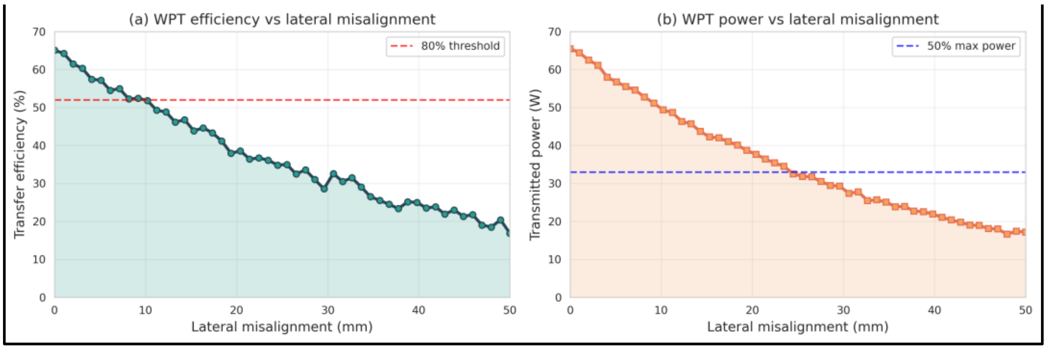

Figure 5. (a) WPT transfer efficiency drop as a function of receiver coil lateral misalignment. (b) Decrease in the effective power transmitted to the drone as misalignment increases.

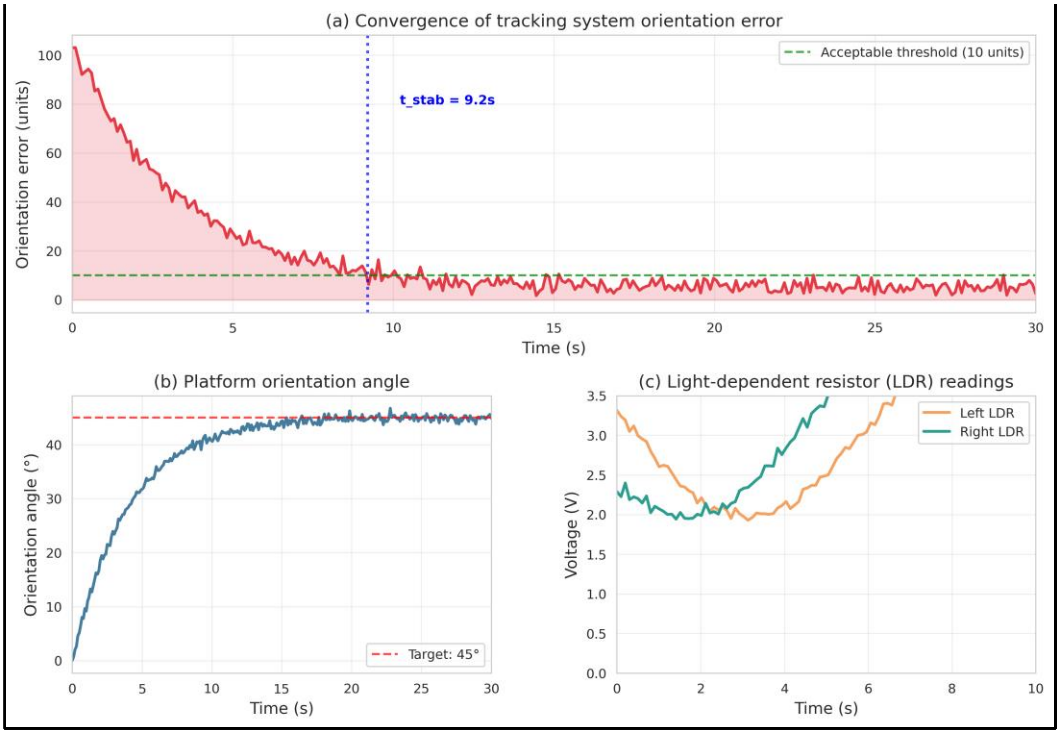

Figure 6. Dynamic response of the solar tracking system. (a) Convergence of the orientation error to a stable value in less than 8 seconds. (b) Adjustment of the angle of the platform to the target position. (c) Variation of LDR readings during adjustment.

Discussion

The results of the simulated validation confirm the viability of the Ecovolt system. The implementation of an active solar tracking system (Figure 1b) demonstrates a significant increase in energy uptake (18.3%) compared to a fixed orientation, a value consistent with the 15-20% ranges reported in the literature for single-axis systems [9]. This underscores the importance of tracking to maximize the power life of the platform, especially in a system with a limited panel area.

The efficiency of the WPT system is a critical factor. The simulated results (Figure 2a) show a maximum efficiency of 65.2% under optimal alignment conditions, decreasing as lateral misalignment increases. This figure is competitive with the experimental results of similar studies, such as the 62.44% obtained by Yan [20] and the 58.3% obtained by Boccardo [21]. The marked drop in efficiency with misalignment highlights the need to implement future precision landing mechanisms or active coil alignment systems to ensure robust loading under real-world conditions.

The analysis of the staged efficiency (Figure 7, to be inserted) reveals that the greatest power loss occurs at the wireless transfer interface (from 85% at the transmitter to 75% at the receiver), which is expected in WPT systems. The simulated overall efficiency of the system, from the solar panel to the drone battery, is approximately 53%, representing a solid foundation for future optimizations.

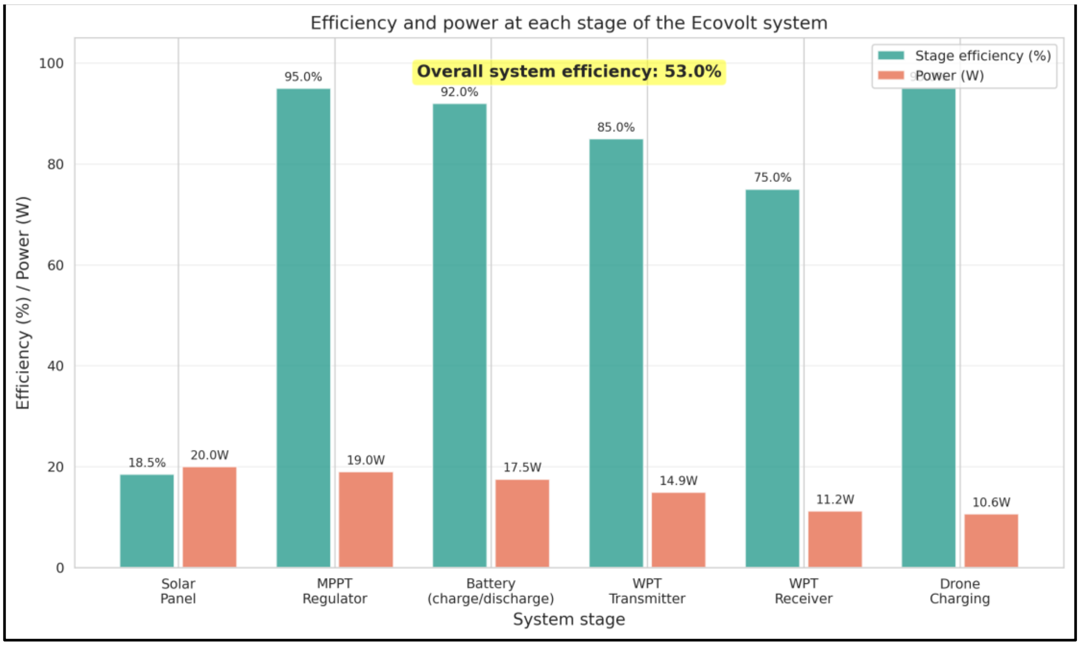

Figure 7. Breakdown of efficiency and power at each stage of the system, from solar generation to drone charging. The simulated overall efficiency is 53.2%.

The control system demonstrated a rapid response, with a solar tracking stabilization time of less than 8 seconds (Figure 6a). This is crucial for a mobile platform that can change orientation frequently. Constant monitoring of electrical parameters (Figure 5) enables safe and efficient energy management, protecting the battery and optimizing the charging process.

Compared to other works, the Ecovolt prototype is distinguished by its integrative approach. While other studies focus on optimizing a single subsystem (WPT or solar tracking), Ecovolt combines mobility, renewable generation, and wireless charging, offering a systemic solution to the problem of drone autonomy. Current limitations, such as the power of the panels and sensitivity to misalignment, are clear areas for future research, which could include the scalability of the system and the use of AI algorithms for precision landing.

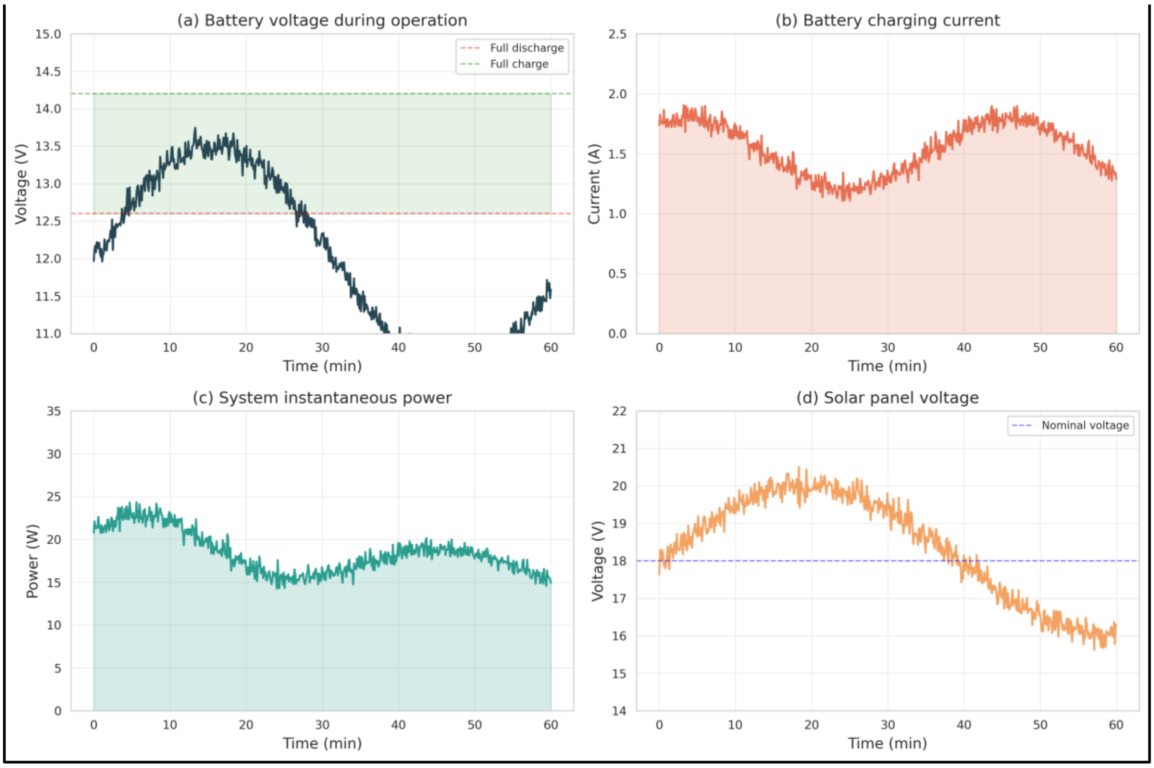

Figure 8. Simulated monitoring of key electrical parameters for 60 minutes of operation, showing the variation of battery voltage, charging current, instantaneous power, and solar panel voltage.

Conclusions

A functional prototype of a mobile photovoltaic platform with wireless charging capacity for drones has been designed and validated through simulation. The Ecovolt system successfully demonstrates the feasibility of integrating terrestrial mobility, solar power generation with active tracking and wireless power transfer to address the UAV autonomy challenge in a sustainable way.

The main conclusions of the study are: 1. The active solar tracking system is essential to maximize energy capture on a mobile platform, achieving a simulated increase of 18.3% in the energy generated. 2. The WPT resonant coupling system is capable of achieving a transfer efficiency of up to 65.2%, which is competitive with the state of the art, although it is highly sensitive to misalignment. 3. The ESP32 microcontroller-based control architecture enables efficient and safe power management, as well as fast dynamic response of the tracking system. 4. Integrating these technologies into a single autonomous platform is a promising solution for extending drone operations in remote areas without charging infrastructure.

Future work will focus on building and experimental validation of the physical prototype, optimizing WPT coils for greater misalignment tolerance, implementing precision landing algorithms based on computer vision, and scaling the system to support larger drones and more demanding missions.

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