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Design and Simulation of a COTS-Based Electrical Power System for High-Altitude Balloon Missions

***Abstract*—Near-space exploration using High-Altitude Balloons (HABs) presents a cost-effective platform for scientific research, particularly for institutions advancing their space science capabilities. The success of these missions critically depends on a robust and reliable Electrical Power System (EPS). This paper details the design and simulation of a low-cost, reliable EPS for short-duration HAB missions, leveraging Commercial Off-The-Shelf (COTS) components and open-source solutions. The design process follows the V-model methodology, adhering to the project life cycle outlined in the NASA Systems Engineering Handbook.The resulting design features a 2s2p Li-ion battery configuration, a linear regulator based on the LM1117 for dual 3.3V and 5.0V bus regulation, and an instrumentation and control system.**

***Index Terms*—High-altitude balloon, Electrical Power System (EPS), DC-DC Converter, Systems Engineering, Commercial off-the-shelf (COTS).**

I. Introduction

High-Altitude Balloons (HABs) are emerging as effective and low-cost platforms for institutions initiating space exploration activities. These platforms enable the simulation of near-space conditions for short-duration missions and serve as an accessible entry point for scientific research before advancing to more sophisticated technologies [1]. The development of HAB technology is an active field, with applications ranging from atmospheric data collection to astronomical observation and even proposals for missions on other planets [2]–[4].

For any mission, the Electrical Power System (EPS) is a critical component that supplies, stores, and distributes the necessary power for all onboard instruments. Its efficiency and reliability are paramount for mission success. This research addresses the design and simulation of a robust EPS tailored for HAB missions, adapting principles from the well-established CubeSat standard and leveraging Commercial Off-The-Shelf (COTS) components to accelerate development and reduce costs [5].

This work is particularly relevant for the Latin American region, where the use of HABs represents a valuable opportunity to foster space exploration capabilities [6]. Specifically, this project contributes to the EOHAB mission at Don Bosco University in El Salvador [7]–[9]. Following the V-model project cycle approved by NASA, this paper presents a systematic approach to developing a reliable EPS [10].

This paper is organized as follows. Section II presents the system methodology, and Section III delineates the system requirements. Section IV details the architecture and justifies the design choices for key subsystems, including the battery bank and linear regulators. Section V explains the system-integration process. Section VI analyzes the results, and Section VII summarizes the conclusions and outlines directions for future research.

II. System Methodology

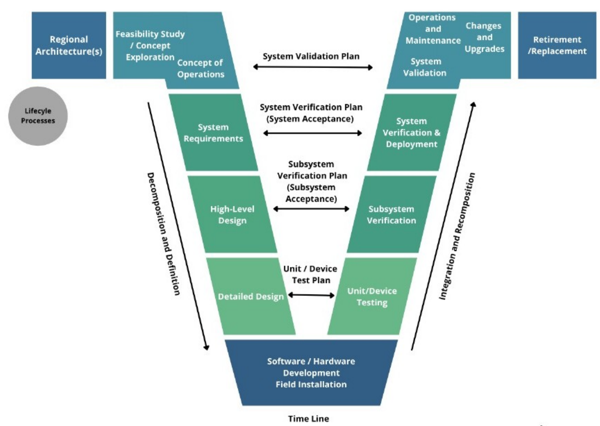

Fig. 1. The V-Model project phases applied to the EPS design.

The project follows the V-model (see Fig. 1)recommended in the *NASA Systems Engineering Handbook* [10]. For this paper, the process is pursued only to the **Detailed Design** level; verification is performed exclusively through software-based simulations. These results provide traceable evidence that the design meets all stated requirements and establish a solid baseline for future prototype fabrication. Physical implementation, hardware integration, and operational validation therefore remain outside the scope of this paper.

III. System Requirements

A. Needs and Constraints

1) Environmental Conditions: The StratoBalloon flight profile subjects the EPS to temperatures as low as $-56.5°C$ and pressures near 1% of sea-level atmospheric pressure. The steepest thermal gradients occur around the tropopause (around 11 km), informing component derating and thermal-insulation choices adopted in the detailed design presented here [9].

2) Energy Budget: The StratoBalloon mission lasts two hours in ascent/float plus four hours as maximum time of recovery beacons. Tables I and II list the loads on the energy budget for the 3.3 V and 5.0 V buses.

TABLE I
ENERGY BUDGET — 3.3 V BUS

Component	**Qty**	I **[mA]**	P **[W]**	t **[h]**	E **[Wh]**	Q **[mAh]**
MCU 1	1	93	0.31	6	1.84	558
LoRa Module	1	630	2.08	6	12.47	3780
MCU 2	1	61	0.20	6	1.21	366
GNSS	1	100	0.33	6	1.98	600
RTD Sensor	1	3.5	0.01	6	0.07	21
IMU	1	0.6	0.00	6	0.01	3.6
MCU 3	1	70	0.23	2	0.46	140
IR Camera	1	25	0.08	2	0.17	50
Total		**983**	**3.24**		**18.21**	**5519**

TABLE II
ENERGY BUDGET — 5.0 V BUS

Component	**Qty**	I **[mA]**	P **[W]**	t **[h]**	E **[Wh]**	Q **[mAh]**
RTC Clock	1	0.3	0.00	6	0.01	1.8
Buzzer	1	24	0.12	6	0.72	144
Barometer	1	0	0.00	6	0.00	0
Multiplexer	1	100	0.50	6	3.00	600
Datalogger 1	1	6	0.03	6	0.18	36
Camera	1	260	1.30	2	2.60	520
Datalogger 2	1	12	0.06	2	0.12	24
Total		**402**	**2.01**		**6.63**	**1326**

3) Mass and Volume Limits: The Table III presents the mass and volume constraints for the EPS.

TABLE III
EPS BAY SPECIFICATIONS

Parameter	Value
Bay dimensions	10 cm $\times$ 10 cm $\times$ 2.5 cm
Number of bays	2
Total volume	250 cm^3
Mass limit	600 g

B. Requirement Summary

The Table IV presents the complete system requirements for the EPS project, encompassing operational, structural, and safety specifications that must be met throughout the mission lifecycle.

TABLE IV
EPS REQUIREMENTS

ID	**Description**	**Rationale**	**Verification**
R1	Survive –56.5 °C, 1.2 % atm.	Flight environment.	Thermal-vacuum test.
R2	Provide 3.3 V ±1 %, 983 mA.	Power bus.	V/I measurement.
R3	Provide 5.0 V ±1 %, 402 mA.	Power bus.	V/I measurement.
R4	Mass 600 g.	Launch limit.	Scale check.
R5	2 PCBs 10 × 10 cm, height 2.5 cm.	Structural limit.	Caliper check.
R6	Log V [V] and I [mA].	Post-flight data.	Functional test.
R7	Log T [°C] and P [atm].	Post-flight data.	Functional test.
R8	I²C comms; ON/OFF cmd; SoC TX.	Subsystem int.	Interface test.
R9	ON/OFF control of payload.	Power saving.	Functional test.
R10	RBF safety switch.	Launch safety.	Continuity check.
R11	External charger port.	Battery recharge.	Voltage check.

IV. SYSTEM ARCHITECTURE

A top-down methodology, similar to that recommended for nanosatellite EPS design [11], guided the progressive decomposition of the system:

- **Level 0** (Fig. 2) sets the system context and identifies four external interfaces: ambient pressure/temperature measurements (R7), the ON/OFF control signal (R9), the remove-before-flight (RBF) switch (R10), and an external VDC source (R11). The EPS outputs are the regulated 3.3 V bus (R2), the 5.0 V bus (R3), SoC telemetry (R8), and the return ON/OFF control line (R9).
- **Level 1** (Fig. 3) decomposes the EPS into six functional blocks: charger, battery bank, inhibits, voltage regulators (typically DC-DC converters, though linear regulators may also be used), MOSFET power stage, and the control & telemetry subsystem (microcontroller + datalogger). All components are overseen by the instrumentation block.
- **Level 2** (Fig. 4) further refines the instrumentation block into four sensors—voltage, current, barometer, and temperature. The voltage and current meters provide Analog 1–2 signals, while the barometer and temperature sensor share an I^2C bus. Each module operates on 5.0 V and uses dedicated reference lines (R6–R7).

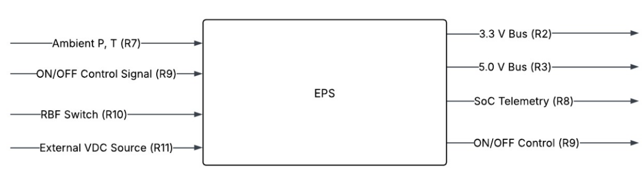

Fig. 2. EPS Level-0 context diagram showing external interfaces.

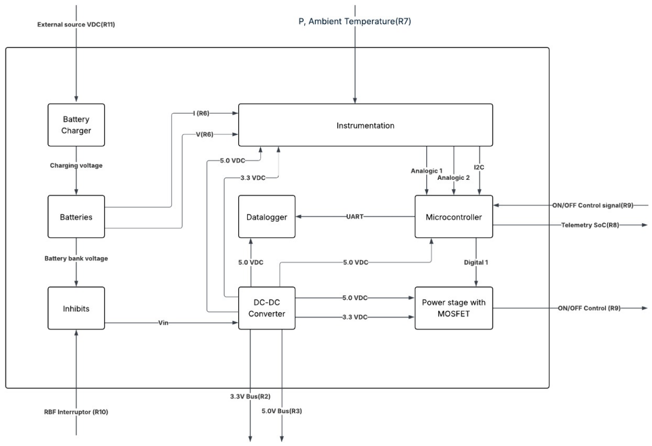

Fig. 3. EPS Level-1 decomposition into main functional blocks.

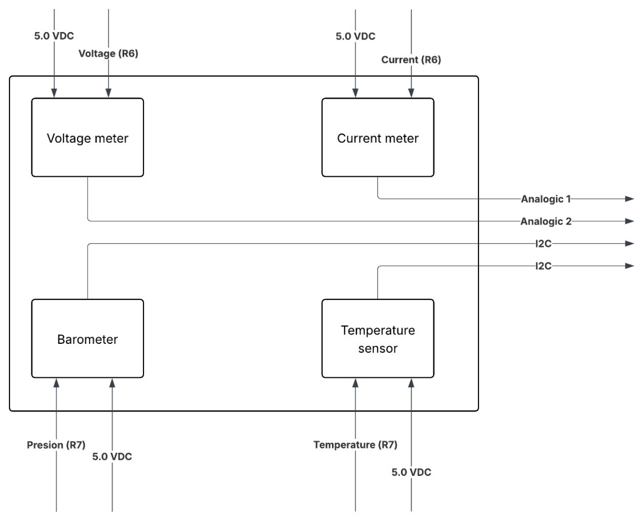

Fig. 4. EPS Level-2 detail of the instrumentation block.

V. Component Design

The Electrical Power System (EPS) is subdivided into seven COTS-based hardware blocks, matching the Level-1 architecture in Fig. 3 and for instrumentation in Fig. 4.

A. Micro-controller

An *Arduino Nano* (ATmega328P, 16 MHz) handles command and data handling. Twenty-two general-purpose I/O lines cover two analog inputs for voltage and current sensing, a UART for the data logger, and an I^{2}C bus for environmental sensors. The board is qualified down to –40 °C, consumes 93 mA in the worst case and a low cost device [12].

B. Data Logger

The *SparkFun OpenLog* records housekeeping telemetry to a micro-SD card (512 MB–32 GB, FAT16/32) over a three-wire UART interface. It draws 2–3 mA when idle and up to 20 mA while writing, which fits the energy budget while providing black-box recovery of raw data [13].

C. Power-Switch Stage

A single low-side N-channel *BS170* MOSFET disconnects the payload on command. Compared with a 2N2222A BJT, the MOSFET halves conduction loss ($R_{\mathrm{DS(on)}} \approx 5\ \Omega$ at 100 mA) and maintains a positive temperature coefficient, mitigating thermal run-away below 0 °C [14]. The gate is driven directly by a Nano digital pin (5 V, 20 mA).

D. Energy Storage

Four commercial 18650 Li-ion cells are arranged in a 2s2p pack that delivers 7.2 V nominal and 6.8 Ah, with a peak discharge capability of 4.9 A [15].

Characterisation campaign.: To validate the nominal capacity and internal-resistance claims, the pack was subjected to a constant-current (CC) discharge at 1 (≈0.15 C) down to a cut-off of 3.0V cell^{-1}. Current was sensed with an *ACS723* Hall-effect transducer, and pack voltage was digitised by the Nano's 10-bit ADC. The resulting voltage–time curve confirmed a usable capacity of $\mathbf{6.4 \pm 0.1}$ Ah and an energy density of $\mathbf{174}\,\mathrm{Wh\,kg^{-1}}$, values adopted in the EPS energy budget. See Fig. 5.

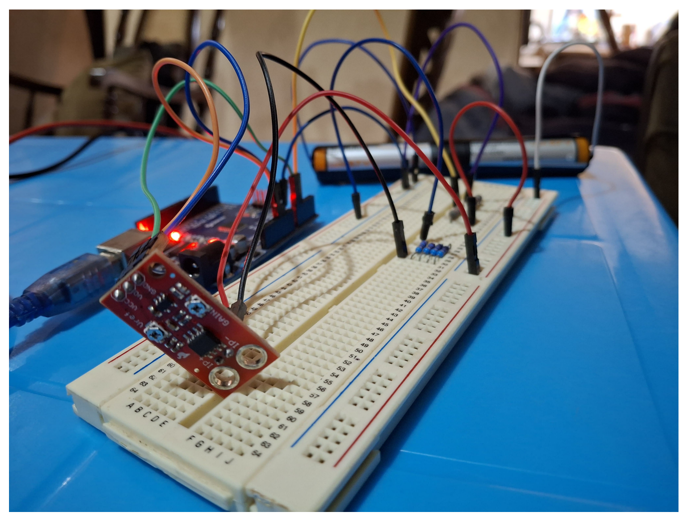

Fig. 5. ACS723 current-sensor calibrattion curve used for Coulomb counting

E. Battery Charger

Each serial pair is re-charged on ground by an *MCP73831* linear charger set to 500 mA through a 2 kohm program resistor. Linear charging avoids radio-frequency noise during functional checkouts and keeps parts count low [16].

F. Voltage Regulation

Two *MC34063A* switching regulators generate the 5.0 V and 3.3 V buses in buck mode. LTspice simulations predict 87–92 the 6.0–8.4 V battery range with output ripple below 100 mV p-p [17]. Optimised values are a 15 µH inductor and 330 µF output capacitor for the 3.3 V rail at 0.75 A, and a 10 µH inductor with 220 µF for the 5.0 V rail at 0.50 A; both settle within 1 ms for a 30

G. *Instrumentation*

Environmental and electrical parameters are monitored by a dedicated sensor suite. Atmospheric pressure and temperature are acquired with an *MS5611* barometer (10–1200 mbar, 0.01 °C resolution), while the power subsystem relies on an *ACS723* Hall-effect current sensor (± 5 A, 80 kHz bandwidth) sampled at 1 Hz to track charge-and-discharge profiles. Battery voltage and auxiliary rails are digitised by the Nano's on-board 10-bit ADC (4.88 mV LSB), which forms part of the EPS's core instrumentation chain.

All sensors operate from the regulated 5 V rail and share the I^2C bus, minimising harness mass and simplifying routing. Prior to integration, the ACS723 and the ADC were subjected to a two-point calibration (offset and gain). The results of the ACS723 calibration process is shown in Fig- 6 and is embedded in the flight firmware to improve state-of-charge (SoC) estimation.

Fig. 6. Calibration process of the ACS723 Hall effect sensor

H. *Inhibits*

A four-pole toggle switch isolates every cell during integration, while a "Remove-Before-Flight" pull-pin provides an additional human-in-the-loop safety barrier [18]. In flight, an *LTC4361* current limiter trips at 1.5 A via a 0.33 ohm sense resistor to protect wiring and PCB traces [19].

VI. System Integration

As a final stage of the design process we integrate each of the parts with coding. To be more specific we are able to develop a flux of logic as we can see in Fig. 7.

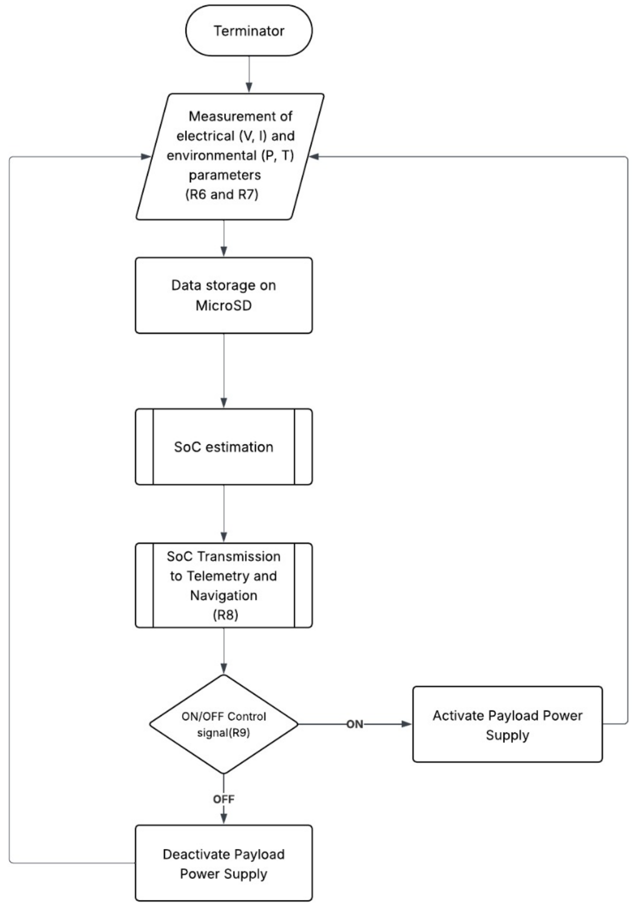

Fig. 7. Sequence of the EPS script

A. *Results and Discussion*

Guided by NASA's phased systems-engineering methodology, the electrical power subsystem (EPS) was designed as a 2 s 2 p Li-ion battery bank, a dual-rail DC–DC converter (5 and 3.3), an n-channel MOSFET load-switch array, and an Arduino-class controller with integrated telemetry. LTspice simulations predict a point efficiency of **87–92**% across the mission load profile and a worst-case junction temperature of the switching MOSFETs below 60, ensuring continuous delivery of 10 with a $\approx$ 20% design margin.

These results demonstrate that a fully COTS EPS can meet both performance and thermal requirements for stratospheric balloon flights without recourse to space-grade components.

B. Conclusions and Future Work

This work shows that NASA's life-cycle approach can be successfully down-scaled for low-budget, high-altitude balloon missions. The proposed COTS-based EPS regulates dual power buses, safeguards the battery, and performs intelligent load-switching at roughly one-third the cost of comparable space-rated solutions. Its modular architecture—battery pack, conversion stage, control logic, and instrumentation—lends itself to rapid scaling towards CubeSat-class platforms.

Integrated voltage, current, temperature, and pressure telemetry enable data-driven optimisation of flight profiles and real-time fault detection, providing a robust foundation for mission reliability. The design therefore offers a concise, affordable blueprint for dependable HAB power systems and establishes a clear upgrade path to CubeSat applications at Technology Readiness Level 5.

Future work will extend environmental qualification through thermal-vacuum cycling, vibration testing, and in-situ stratospheric flights. Incorporating a maximum-power-point-tracking (MPPT) solar input and refining the Coulomb-counting algorithm with higher-resolution ADCs are expected to further enhance endurance and autonomy.

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