
High-Performance Battery Systems for Next-Generation Humanoid Robots

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Abstract

Humanoid robots impose unique requirements on battery systems due to highly dynamic load profiles, compact mechanical integration, and close human interaction. These constraints challenge conventional Battery Management System (BMS) designs that are primarily optimized for electric vehicles or stationary energy storage applications. This white paper presents a system-level architecture for a humanoid-oriented BMS with integrated active thermal management, focusing on cell monitoring, protection, real-time state estimation, and controlled power delivery under transient operating conditions. The proposed architecture is discussed using representative humanoid operating scenarios and is informatively mapped to established functional safety and battery standards without asserting formal compliance. The purpose of this document is to provide a technical reference for engineers developing safe and high-performance battery systems for next-generation humanoid robots.

Humanoid Energy System Requirements

Humanoid robots operate under electrical, thermal, and mechanical conditions that differ fundamentally from those encountered in electric vehicles or stationary energy storage systems. Frequent load changes, asymmetric operating cycles, high peak currents and limited heat dissipation volumes place high demands

on battery systems. As a result, the Battery Management System must support dynamic power delivery while maintaining safety, reliability, and predictable performance throughout the robot's operational lifetime.

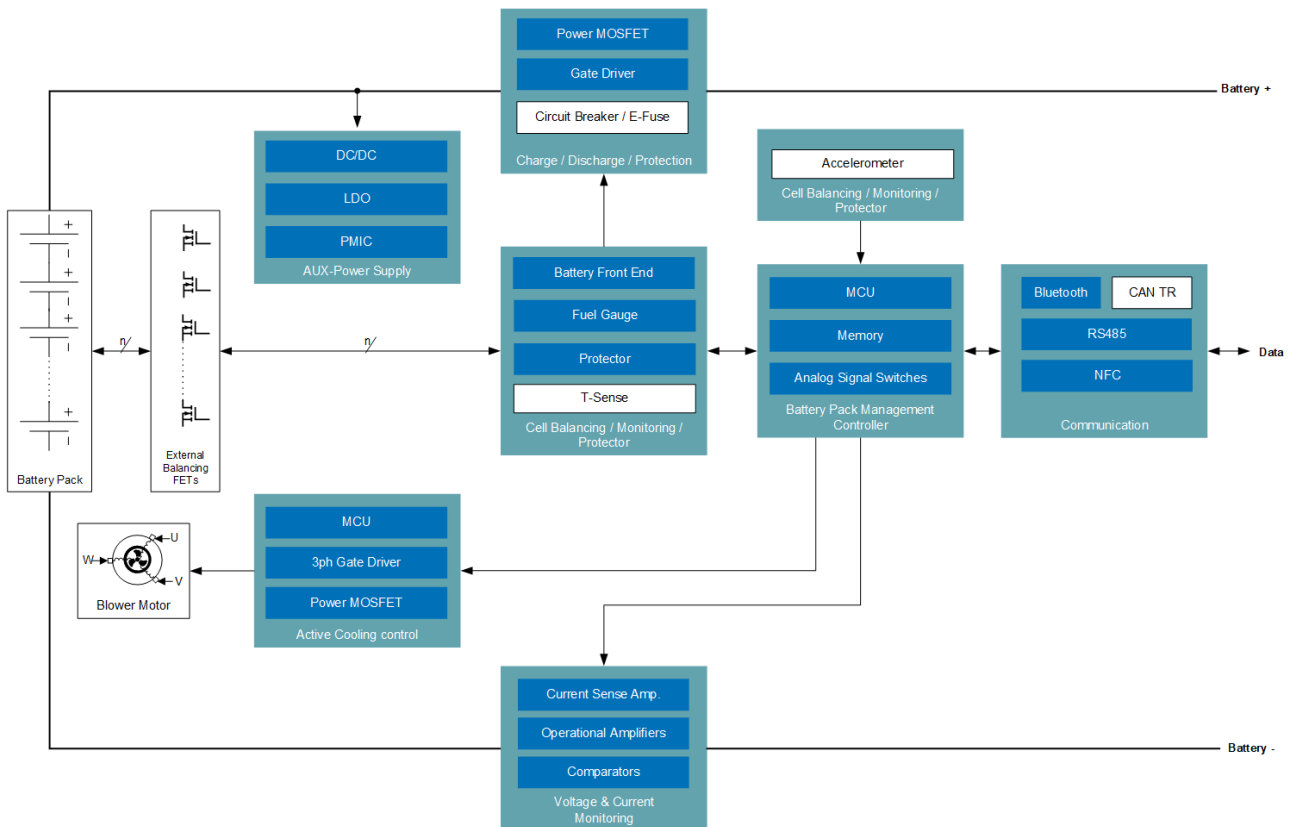


Figure 1: The block diagram represents entire battery pack with integrated Battery Management System and thermal management. The battery pack is typically integrated within the robot's torso. Functional blocks demonstrate the functions of each individual module within entire BMS and may include multiple chips. monitoring of individual cell temperatures and real-time current flow (also load current profiles), emphasizing the importance of the Battery Management System (BMS) in maintaining safety and performance during transient operating scenarios

System-Level BMS Architecture for Humanoid Robots

Figure 1 illustrates a high-level block diagram of a humanoid-oriented battery pack with an integrated Battery Management System and active thermal control. The battery pack is typically embedded within the robot's torso, where volume constraints and proximity to sensitive electronics limit passive cooling options. The architecture includes cell-level voltage and temperature monitoring, current sensing, protection circuitry, power switching elements, and a central control unit responsible for state estimation and system coordination. Continuous monitoring of individual cell temperatures and real-time current flow enables the BMS to react rapidly to transient operating conditions, ensuring both safety and performance.

Humanoid-Specific Operating Scenarios and Implications

Dynamic Locomotion and Balance Control

During bipedal walking, stair climbing, or balance recovery, humanoid robots experience short-duration but high-magnitude power demands from multiple joint actuators. These conditions result in rapid current transients, localized heating within the battery pack, and temporarily reduced available discharge power.

The proposed BMS addresses these challenges through high-bandwidth current sensing and real-time State of Power (SoP) estimation. By continuously evaluating electrical and thermal constraints, the BMS can provide higher-level controllers with realistic power availability limits, enabling adaptive gait planning and torque limitation strategies.

Manipulation and Load-Bearing Tasks

Manipulation tasks such as lifting, pushing, or tool operation often impose sustained and directional discharge currents. Compared to locomotion, these tasks can produce prolonged thermal stress on specific cell groups within the battery pack.

Active cooling control allows localized and pack-level temperature stabilization under such conditions.

Maintaining battery temperature within a controlled operating window improves performance consistency and mitigates long-term degradation effects.

Fault Recovery and Safety-Critical Maneuvers

In response to external disturbances such as collisions or loss of balance, humanoid robots may require brief bursts of high power to execute corrective maneuvers or controlled shutdown sequences. Battery availability during these events is safety-relevant.

Fast-acting over-current protection combined with conservative derating strategies based on SoP and thermal feedback enables the BMS to prioritize safety-critical power delivery while preserving protection boundaries.

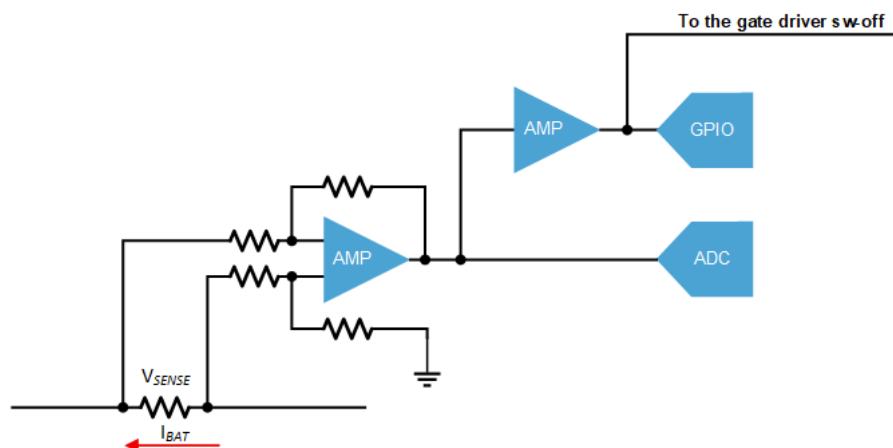


Figure 2: BMS current monitoring

The diagram illustrates a shunt-based current measurement integrated into a BMS, designed to support both fast safety-critical current monitoring and high-accuracy current acquisition for charge and discharge tracking.

A low-ohmic shunt resistor is placed in the main battery current path, producing a small differential voltage proportional to the instantaneous battery current. This voltage is amplified by a precision differential amplifier stage, which conditions the signal while rejecting common-mode disturbances.

The amplified shunt signal is then distributed to two parallel processing paths, each optimized for a distinct functional requirement:

Fast Protection and Safety Path

One signal path is dedicated to fast protection and safety monitoring and feeds a high-speed analog comparator stage whose output is routed directly to a digital control signal connected to the gate-driver shutdown input. This hardware path enables rapid detection of over-current and short-circuit conditions and provides a deterministic response that is independent of microcontroller software latency. In the event of a fault, the battery can therefore be isolated immediately through power MOSFET gate shutdown. Such a hardware-based protection loop is essential for functional safety, particularly in humanoid robot applications where current transients can rise sharply during locomotion, manipulation, or fault recovery maneuvers.

Measurement and estimation path

In parallel to the fast protection path, the conditioned current signal is routed to an Analog-to-Digital Converter (ADC) of the BMS microcontroller. This digital representation of the battery current is used to characterize dynamic load behavior, support real-time State of Power (SoP) estimation, and enable coulomb-counting-based State of Charge (SoC) estimation during both charging and discharging operation. Since coulomb counting relies on time integration of the measured current, the accuracy, bandwidth, and long-term offset stability of this measurement path directly determine the quality and robustness of the SoC estimate, particularly under highly dynamic load conditions.

Active Thermal Management as a Core Control Function

Thermal behavior strongly influences both battery safety and achievable power output. In humanoid robots, battery packs are commonly integrated into compact structural volumes where passive heat dissipation is limited.

In the proposed architecture, thermal management is implemented as an active control loop rather than a purely supervisory function. Cell-level temperature measurements are used to dynamically regulate cooling fan integrated into the BMS. This approach improves temperature uniformity across the battery pack, reduces thermal gradients during high-power operation, and enhances repeatability of battery performance across operating cycles.

Active thermal control is particularly beneficial during fast-charging or sustained high-load conditions, where elevated temperatures could otherwise accelerate aging or enforce conservative current limits.

Battery State Estimation and Measurement Accuracy

Reliable operation of humanoid robots depends on accurate estimation of battery State of Charge (SoC), State of Health (SoH), and State of Power (SoP). These quantities directly influence motion planning, task scheduling, and safe shutdown behavior.

Accurate current and voltage measurement form the foundation of these estimations. Errors in electrical sensing propagate into state estimates, potentially leading to unexpected shutdowns or overly conservative power limitations.

Coulomb Counting–Based State of Charge Estimation

Coulomb counting estimates the battery SoC by integrating the battery current $I(t)$ over time t , thereby calculating the net transferred charge:

$$\Delta Q = \int I(t) dt \text{ [Ah]}$$

This method enables accurate, real-time tracking of remaining battery capacity (**Figure 2.**), which is critical under the highly dynamic load profiles typical of humanoid robots. Due to the cumulative nature of current integration, however, sensor offset and drift can introduce long-term estimation errors. Periodic recalibration at well-defined reference states, such as full charge or rest conditions, is therefore required. Key functional elements include precision current measurement using shunt-based sensing, continuous numerical integration, initialization based on open-circuit voltage, and capacity correction to account for aging, efficiency losses, and temperature effects.

Key Battery Management Challenges and Design Responses

Battery Degradation

High peak currents, frequent deep cycles, and thermal stress accelerate battery aging in humanoid robots. The BMS mitigates degradation by monitoring SoH through long-term trends in current, voltage, and temperature measurements. These indicators support informed charging and usage strategies that reduce aging without compromising functionality.

SoC Estimation Accuracy

Under dynamic load conditions, inaccurate SoC estimation can lead to unexpected shutdowns or excessive power derating. Combining coulomb counting with voltage-based correction improves robustness across operating regimes, provided that current and voltage measurements are sufficiently accurate.



Figure 3: Humanoid BMS continuously monitoring battery voltage, current and controlling the battery pack temperature

Informative Mapping to Safety and Battery Standards

While humanoid robots are not governed by a single harmonized battery safety standard, existing standards such as IEC 61508, IEC 62133, and UL 2054 provide useful design guidance. The proposed architecture aligns conceptually with principles such as hazard detection, fault containment, and controlled degradation, without implying formal compliance.

Discussion and Limitations

The proposed architecture provides a robust technical foundation but does not, by itself, guarantee functional safety or regulatory compliance. Limitations include reliance on sensor accuracy, limited redundancy in single-MCU designs, and dependence on mechanical integration for thermal effectiveness. These aspects must be addressed at the system level through validation, redundancy strategies, and integration design.

Summary

This white paper has presented a humanoid-oriented Battery Management System architecture that integrates high-resolution monitoring, real-time state estimation, and active thermal control. By addressing the unique operational demands of humanoid robots, the proposed approach supports safe, predictable, and high-performance battery operation without overstating compliance with existing standards.

References

- [Renesas Battery Management ICs](#)

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