ElectronicDesign

EXECUTIVE SUMMARY

Solving the Hardware Challenges of Next-Generation Humanoid Robots

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INNOVATOR IN ELECTRONICS

Solving the Hardware Challenges of Next-Generation Humanoid Robots

OVERVIEW

Humanoid robotics is evolving quickly, bringing new challenges in system architecture, integration, and reliability. Successful designs must balance multiple interconnected systems within a complex platform to provide efficient power distribution, reliable low-latency communications, accurate motion and environmental sensing, synchronized control, effective thermal monitoring, and robust safety mechanisms. Achieving this balance on schedule and within budget has become one of the biggest challenges facing today's robotics teams.

Murata products help simplify integration, improve reliability, and reduce development risk. Murata's component portfolio addresses fundamental system interaction challenges through power conversion, capacitors, inductors, electromagnetic interference (EMI) suppression, wireless connectivity, and sensing technologies.

CONTEXT

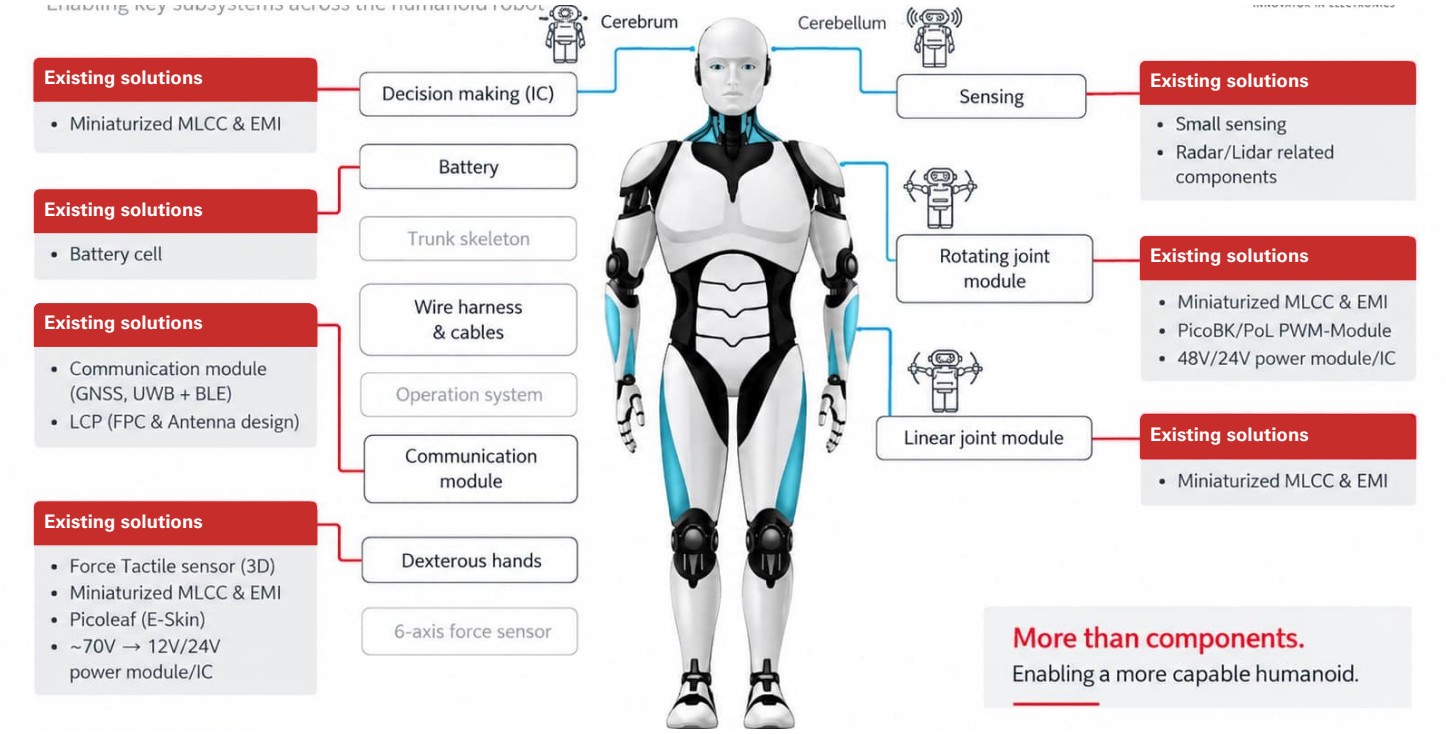
The presenters discussed key architectural and component considerations in humanoid robotics system design.

KEY TAKEAWAYS

Advances in humanoid robotics depend on the quality of the underlying electronic architecture.

Designing next-generation humanoid robots requires more than advances in AI, software, and mechanical design. Underlying those capabilities is an intricate electronics system that must distribute power efficiently, maintain reliable communication, manage complex motion control, and operate safely within strict size and weight constraints.

Figure 1: A humanoid robot depends on a highly distributed electronic system



These factors are all closely interconnected; no single challenge can be effectively solved in isolation. Humanoid design must therefore be approached as a system-level engineering problem rather than a collection of independent subsystems.

In each major subsystem, there are several hardware decisions to consider that will influence the performance of the overall system.

Power Distribution and Architecture

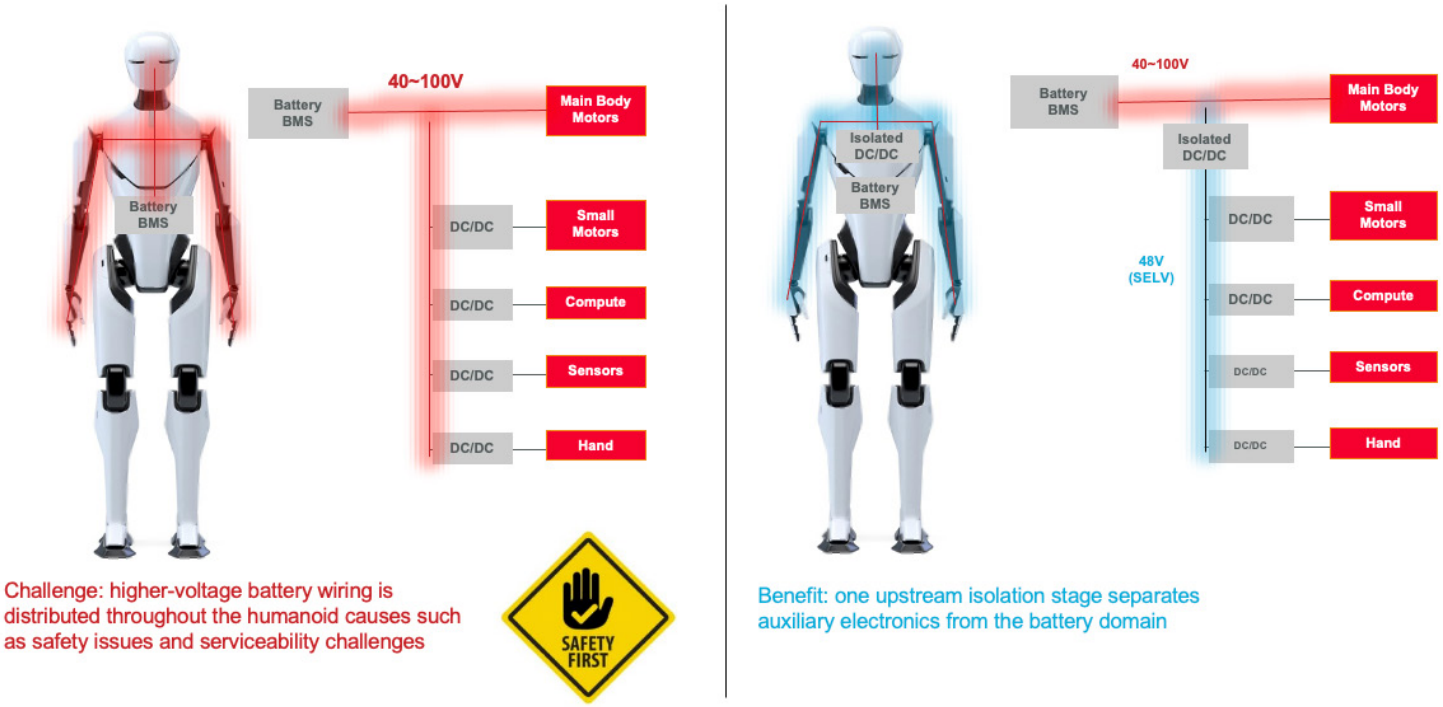
Humanoid robots contain electrical loads with widely varying power requirements—from higher-voltage motors and processors to lower-voltage devices, such as sensors, MCUs, cameras, and wireless modules. But all operate from the same power source, meaning a single battery system must support multiple voltage rails distributed throughout the robot.

At the same time, engineers must minimize conversion losses and heat generation, maintain voltage stability, reduce electrical noise, and avoid unnecessary wiring weight. These considerations become particularly important in the arms and legs, where power travels through long cables and moving joints.

One of the key decisions that needs to be made when designing the power architecture is identifying where electrical isolation may be appropriate. Distributing the battery's higher voltage throughout the robot with local DC-to-DC conversion is a more straightforward approach, but introduces additional safety, grounding, fault conditions, and serviceability considerations.

Alternatively, introducing an isolation conversion stage between the main battery and lower-voltage auxiliary electronics enables downstream electronics to operate within a lower voltage domain, while higher-power motor systems remain connected to the higher-voltage bus. This electrical separation provides benefits to safety, grounding, and system separation.

Figure 2: Isolation conversion offers potential safety, grounding, and/or system partitioning benefits



Distributed Power Architecture: An Overview

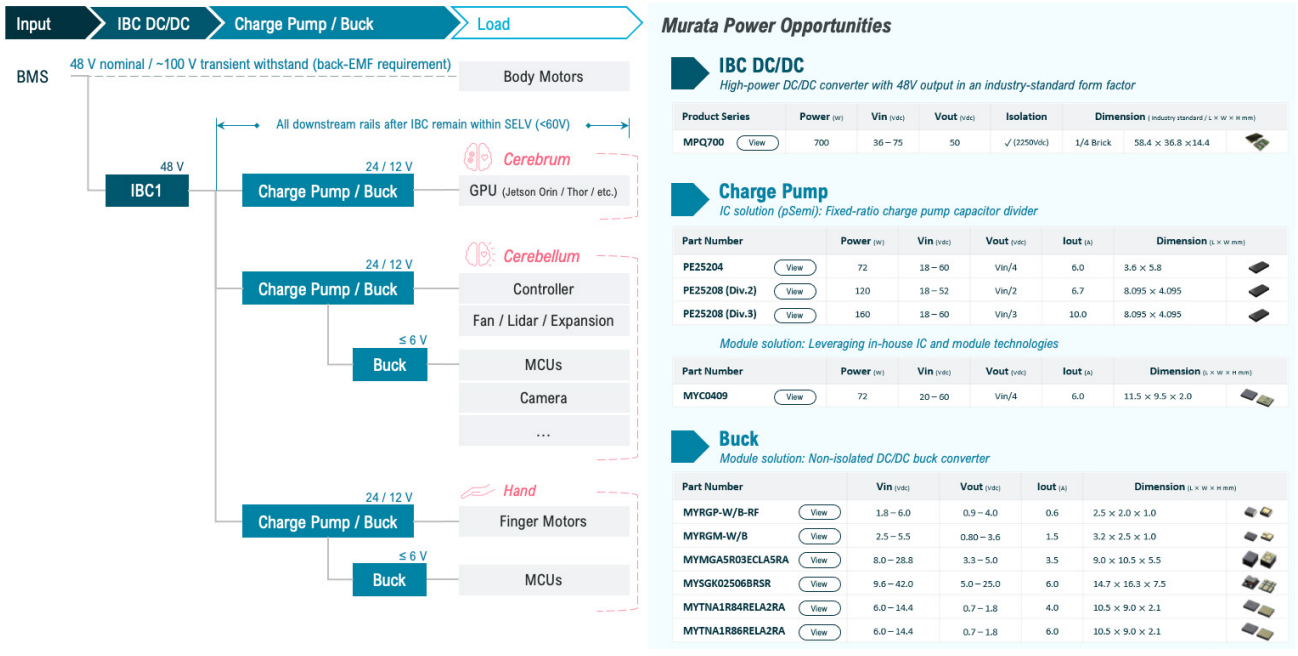
A distributed power architecture uses the battery and battery management system to supply the main bus—to which larger motor loads are connected—with an intermediate bus converter generating an additional voltage rail for downstream electronics. Local converters can be used as needed to supply specific voltage rails for GPUs, controllers, cameras, MCUs, and other lower-voltage electronics, allowing smaller conductors, reducing wiring weight, and simplifying power distribution.

Distributing power at a higher voltage reduces current for a given power level, which in turn reduces resistive losses in wiring. Rather than route multiple low-voltage, high-current rails throughout the robot, engineers can distribute a higher intermediate voltage through a single rail, with conversion performed close to the final destination.

A humanoid robot's electrical loads are highly dynamic. Motors and processors can change their power demands rapidly. Local power rails must remain stable during these transient loads. Using other components can help with power management. For example, multilayer ceramic capacitors (MLCCs) provide low impedance decoupling close to the load, inductors support power conversion, and EMI components prevent noise from coupling into sensitive sensors and communication circuits. Thermal sensors are also important, as heat monitoring is a crucial function in such a dense system.

> "This is where multiple technologies come together: power conversion, capacitors, inductors, EMI suppression, and thermal sensing all contribute to the performance of the overall power network."
>
> – *Amirali Haghighi, Murata*

Figure 3: An example distributed power architecture



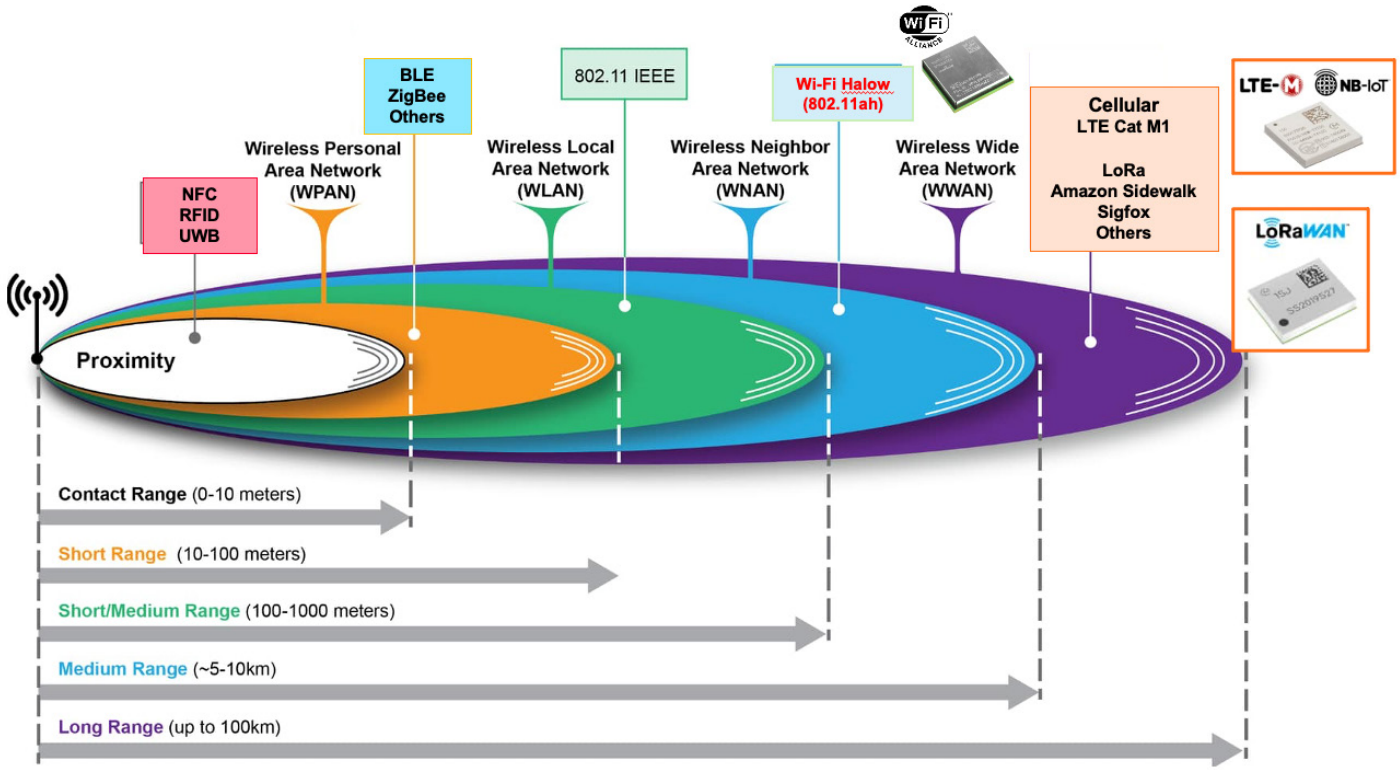
Network Architecture and Reliability

Humanoid robots depend on reliable communication with both their surroundings and external computing systems. No single protocol is ideal for every humanoid application. Technology selection depends on bandwidth, range, throughput, and power consumption.

Operating environment also influences technology selection. For example, warehouses are particularly difficult environments for RF communication, as they typically contain a lot of metal racks and machinery, numerous access points, and multiple wireless devices operating simultaneously, while continuous robot movement adds further complications. Engineers must therefore evaluate a wireless solution based on coverage, latency, roaming behavior, interference, antenna placement, and power consumption—not simply on peak data rates.

In many cases, the most practical architecture may involve multiple wireless technologies, with each one serving a different function.

Figure 4: Different technologies are best suited for different purposes



Complex Motion Control

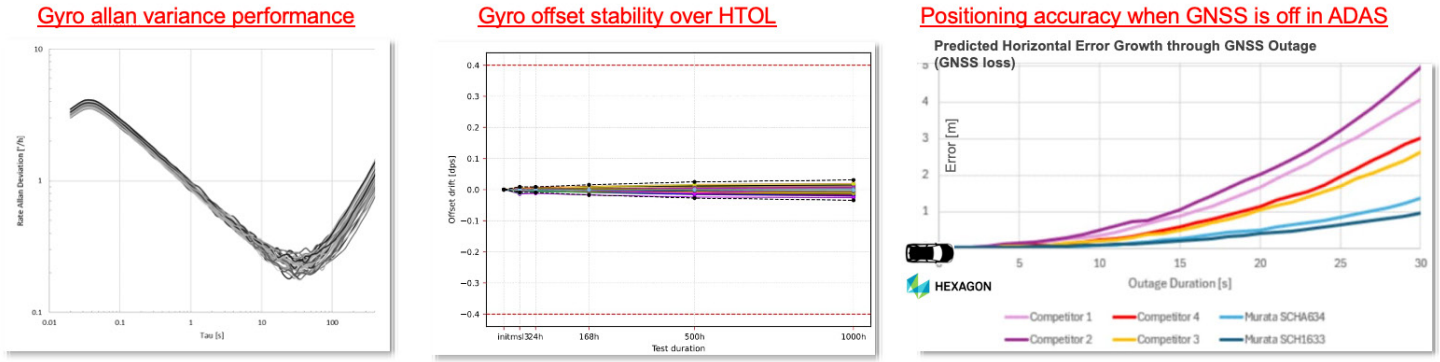
A humanoid coordinates multiple joints and degrees of freedom to achieve smooth, human-like movement and interactions. This requires high-speed, high-precision control algorithms fed with real-time accurate, synchronized sensor information.

Inertial sensing, computer vision, and tactile sensing are particularly important areas of focus:

- **Inertial measurement** units track robot orientation, acceleration, and movement. Data from sensors in the torso or pelvis, which control balance and orientation, can be combined with measurements from the head and limbs to further improve movement coordination.
- **Computer vision** allows robots to interpret their surroundings. Perception depends on visual clarity, which can be impacted by dirty lenses, humidity, low light, or compromised depth perception.
- **Tactile sensing** is especially important in the hands, which must be able to accomplish a range of tasks, from handling fragile objects without applying excessive force to operating simple devices. Not only must hand electronics and sensors fit within small structures, but their wiring must also withstand repeated bending over the robot's operational life.

These subsystems must all operate as a coordinated whole in real time—communication speed and protocol are critical to safe interactions, along with high-resolution sensors and cameras.

Figure 5: Murata MEMS inertial sensor supports stabilization



Human Interaction and Safety

As humanoid robots move from controlled environments into settings where they interact directly with people, safety requirements become more demanding. Safe interaction depends not only on detecting and quickly responding to objects and obstacles; robots must also use appropriate levels of pressure, force, temperature, inertia, distance, and contact. Both physical and psychological safety matter—humans should feel comfortable and confident interacting with humanoid robots.

For the robot to understand its physical condition at any given moment and consistently reproduce expected behavior despite changes in power supply, temperature, noise, and individual component variation requires tight synchronization across sensors, controllers, and processors. Choosing the right protocol to enable rapid communication and response is critical. Implementing decentralized control at individual joints or segments also reduces latency faster and enables higher-quality response.

Using high-performance sensors can further improve event detection, while good power quality and EMI filtering also help prevent unstable behavior and incorrect detections.

Temperature monitoring provides another important protection mechanism—thermistors monitor circuit board and battery temperatures, compensate for temperature-related effects, and detect overheating.

While humanoid safety regulations are still under development, designers are combining existing requirements to prepare for future standards, such as applying automotive-grade component standards and functional safety concepts alongside emerging frameworks for dynamically stable robots. Implementing redundant sensor fusion, which bases decisions on the timing and consistency of combined signals from multiple sources, and fail-safe protocols also improve accuracy and reliability.

Hardware Constraints and Cost Reduction

Humanoid robotics combine expensive components, including multiple joint mechanisms, high-performance processors, sophisticated sensors, motors, communications equipment, and power electronics. All of these components must fit into a single lightweight structure while meeting demanding requirements for power consumption, thermal performance, reliability, and more.

At the same time, robot designs must eventually be sufficiently cost-effective to enable commercial viability. Optimizing individual components and subsystems can have a significant impact on overall system performance, size, weight, energy efficiency, and manufacturing cost, allowing robots to move beyond limited demonstrations and into broader markets.

ADDITIONAL INFORMATION

To learn more, visit TTI and Murata



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