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Single Pair Ethernet (SPE) for Humanoid In-Robot Network

Whitepaper

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1. Introduction

Market forecast

Amid the growing hype, an influx of new players and startups, and strong venture capital funding, the market is widely viewed from both optimistic and realistic perspectives as a large opportunity by 2030. While Goldman Sachs Research forecasts a global market size of USD 38 billion by 2035 – likely too optimistic – other outlooks such as the Interact Analysis forecast suggest a more balanced view. See Figure 1.

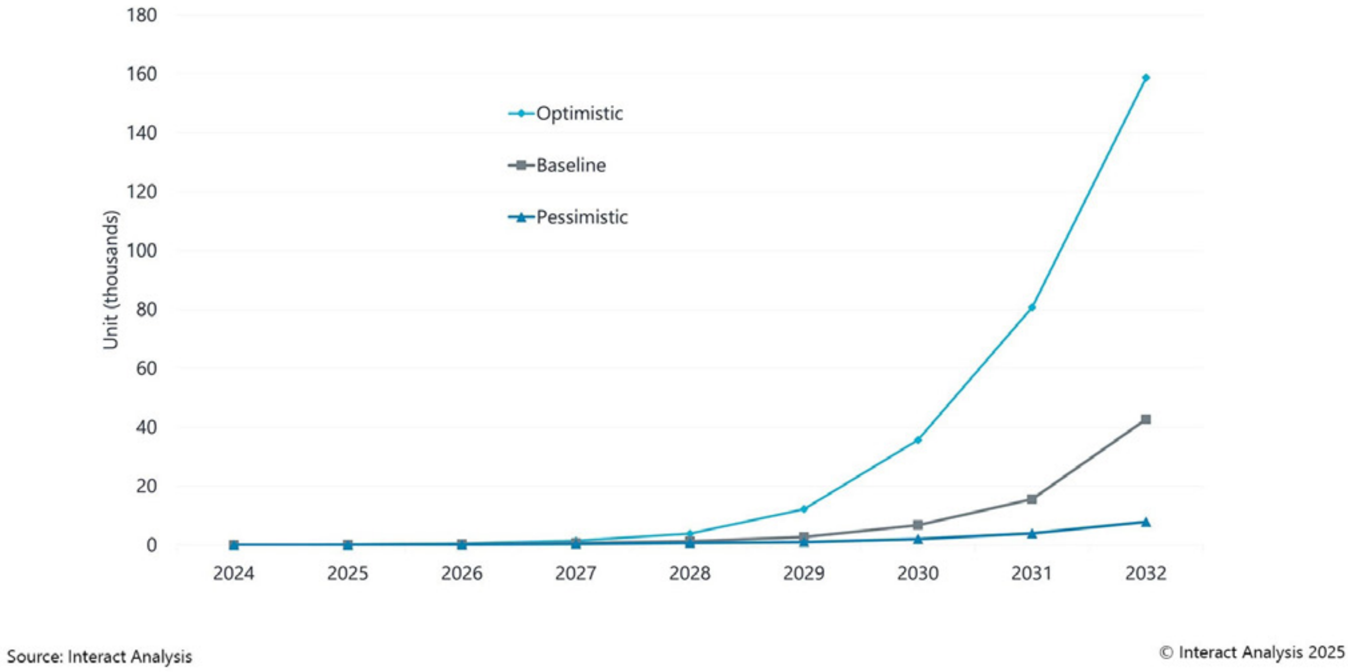


Figure 1: Global Humanoid Robot Shipment by Scenarios

Market drivers

LLM (large language models), LBM (large behavior models), VLA (vision language action models), Agentic and Embodied AI, demographic development and aging society, labor shortage, doing repetitive or dangerous work, and decreasing costs connected with a fast ROI are the main drivers.

2. Evolution of robotics

Historic development
The development goes from industrial robots to cobots, AMRs (autonomous mobile robots) /AGVs (automated guided vehicles), service robotics to humanoids

Why humanoids
Humanoids are intended as a kind of mechanical twin to humans, with the special advantage of training these robots by recording human labor and activities. Therefore, they are smart and cognitive, operate in environments built for humans, feature text and language understanding (including voice commands), allow for multipurpose use, and enable the handling and use of tools. They are intended for high-mix, low-volume factory work, repair, and maintenance tasks (with over-the-air proprietary skill upload) and home/residential scenarios.

Humanoids need a new approach
Humanoids are very different from previous types of robots and therefore need a new approach (Figure 2).

	Industrial Robot (Arm)	Humanoid
Market Players	Established for decades	New companies and start-ups
Market Dynamics	Low, slow	High, very fast
Axis / Degrees of Freedom	Some: 6 + Gripper/Tool	Massive: Total up to 72+ (28 DoF + 2 dexterous hands (e.g. 11 to 22 DoF each))
High-Level Control	Programmable Logic Controller PLC with kinematics motion model, PLC-in-the-loop	AI Robotic Computer with humanoid robot foundation model (System 1 + System 2) Stable Locomotion + Voice Interaction + Dexterous Manipulation
Low-Level Control protocols	ProfiNet®, EtherCAT®, EtherNet/IP®, POWERLINK, Sercos III and CC-Link	CAN/CAN FD, EtherCAT®, ProfiNet®, EtherNet/IP®, and TSN
Sensors	Some: Joint positions and robotic state (encoders)	Massive: Joint position and robotic state (encoders), force/torque, 3D environment (cameras, radars, lidar, ultrasonic), tactile/touch, IMU, sound/microphone, Tactile sensing, etc.
Robot-Human interaction	No interaction, protected environment	Direct collaboration with humans and other robots/machines
Flexibility / Target Application	Low, defined/programmed single task, equipped manipulator Low Flexibility/ Fixed application	High, reinforcement learning, Sim2Real, multi-purpose, using tools High Flexibility / Adoptable application
Costs	High	High, but decreasing fast (target price 20k USD) Price challenger example: Unitree G1/R1 for 16k/5.8k USD
Functional Safety	Yes	Not defined yet, adoption from cobots (proximity detection, stable emergency stop)
Open / Closed System Architecture	Open and Closed system	Closed system

Figure 2: Comparison of Industrial to Humanoid Robots

3. Specific challenges and requirements for humanoids

Lightweight and Powerful

Humanoids must balance mass and mechanical output, striving for a high weight-to-peak-performance ratio. The ability to carry payloads exceeding 25 kg while maintaining agility and durability is a hallmark of advanced humanoid robotics. The electric motors (incl. gears) for robotic joints need to be very powerful, with torque up to 300 Nm. Modern systems employ lightweight materials, such as magnesium alloys and carbon composites, to minimize inertial load without sacrificing structural strength.
Recent Chinese demonstrations, including robots performing front- and back-flips, exemplify this trend and highlight significant progress in both actuation and real-time control algorithms. Events like the Humanoid Robot Half-Marathon in Beijing (April 2025) challenge endurance, agility, and payload capacity, pushing the boundaries of design innovation. Furthermore, the first World Humanoid Robot Games (Beijing, August 2025) set new benchmarks for performance through competitive trials of locomotion and manipulation skills. These public demonstrations not only validate hardware designs but also demand robust failure handling and repeated operation under stress, both of which are vital for real-world deployment in industrial and service environments.

Thermal Management in Dense Mechatronic Systems

High-torque actuators, compact joint modules, and power-dense AI compute boards create significant thermal loads in the confined volume of a humanoid body. Without a dedicated thermal management strategy, heat accumulation degrades actuator efficiency, shortens electronic lifetime, and can trigger derating or emergency shutdowns, interrupting mission-critical tasks. Modern humanoid designs therefore integrate distributed heat paths using aluminum housings, internal heat spreaders, and targeted active cooling (compact DC fans and directed airflow channels) in thermally critical areas such as the torso, thighs, and head. From a requirements perspective, continuous-duty operation under industrial duty cycles entails specifying maximum junction temperatures, allowable temperature rise during peak loads, and coordinating thermal sensors with control software for dynamic power management. Thermal constraints feed back into mechanical layout (component placement, cross-section of limbs), selection of actuators with high torque-to-loss ratio, and enclosure design that balances aesthetics with ventilation and acoustic noise constraints in human environments.

Battery Technology

Battery technology underpins operational flexibility and endurance for humanoid robots. Extended operational life—several hours on a single charge—is now a baseline requirement, pressing manufacturers to adopt high-density lithium-ion or emerging solid-state cells. The integration of automated charging stations with hot-swappable battery modules enables near-continuous operation, facilitating 24/7 deployments in logistics, manufacturing, or healthcare settings. Battery management systems (BMS) now coordinate energy load management, thermal control, and predictive maintenance routines, reducing downtime from battery failures. Advances in rapid charging protocols further minimize out-of-service intervals. To meet energy needs without compromise in safety or mass, novel cell architectures—including semi-flexible and ultra-slim formats—are being trialed for next-gen humanoids. The convergence of battery and system design becomes essential as robots become more autonomous and undertake longer missions and operations.

Wheeled or Bipedal Locomotion?

The question of mobility form factor—wheels versus legs—reflects the tension between function and anthropomorphism. Wheels offer efficiency and speed in predictable environments such as warehouses or factories, and significantly simplify navigation over flat surfaces. However, bipedal or multi-legged locomotion, while energetically costly and mechanically complex, is invaluable in human-centric, chaotic outdoor[GD2.1] spaces, where stairs, uneven terrain, and obstacles are common. A hybrid approach, typified by platforms like the Hexagon AEON (combining legs and wheels), delivers both adaptability and efficiency: switching modes depending on terrain or task. This modularity improves deployment flexibility and future-proofs investments against fluctuations in industrial requirements. The ultimate choice hinges on use case, with legged and wheeled variants co-existing in both commercial and research applications.

High Performance AI Computer, Low Energy Consumption

At the heart of modern humanoids is a computational subsystem capable of running sophisticated AI models in real time with minimal power consumption. Requirements now include total tera-operations-per-second (TOPS) and exceptional TOPS-per-watt for edge inferencing, coupled with ample RAM and storage for foundation models. Quite popular in the humanoid ecosystem is the use of the Nvidia Jetson Orin (previous model) or the Jetson Thor (current model). The rise of Large Behavior Models (LBMs), Vision Language Action Models (VLAMs, such as Nvidia GR00T or Google Gemini Robotics), and dedicated pathway architectures (Figure.ai Helix) has enabled new levels of cognitive flexibility, perception, and action integration. This enables capabilities such as reinforcement learning, imitation learning, teleoperation, and sim2real techniques, in which physical robots are trained on synthetic data in high-fidelity simulations before transferring skills to the real world. High-fidelity model transfer and continued data-driven learning demand robust storage, rapid local processing, and self-optimization controls, all while keeping power consumption within the constraints of onboard battery systems.

Functional Safety, Safe and Efficient Operation

Functional safety requirements set critical boundaries for humanoid system engineering. Operations must be not only efficient, but also inherently safe - protecting both humans and the environment. Orchestrating robot fleets often leverages cloud/edge architectures, enabling coordinated behaviors and fleet-level monitoring. Proximity tracking uses both „inside-out" (robot-based navigation) and „outside-in" (environmental sensors or beacons) methods to avoid collisions and maintain safe interaction distances. Emergency stops must bring robots to a stable, non-damaging pose instantly, regardless of what action was underway. Safety protocols also encompass real-time response to sensor anomalies, predictive failure monitoring, and secure fail-overs. In collaborative contexts - humans and robots working side-by-side - compliance with international standards (ISO 10218, ISO/WD 25785-1) is mandatory, emphasizing risk assessment and mitigation in every operational mode.

Large Number of Sensors

Humanoids require a large number of distributed sensors and sensor[GD3.1] arrays to perceive both their own state and the external environment with high fidelity. These typically include joint position encoders, force and torque sensors, multi-spectrum cameras, distance sensors[GD4.1], tactile arrays, accelerometers (IMUs), and microphones. Collecting and fusing this heterogeneous data in real time is a major engineering challenge: centralized processing architectures, often built on high-speed FPGAs or custom ASICs, must handle gigabytes of incoming data per second. Sensor fusion algorithms synthesize this torrent into actionable information while minimizing latency and maximizing reliability. Improvements in tactile sensors and 3D perception systems (e.g., multi-layer lidar/camera fusion) are enabling new manipulation and exploration capabilities, especially for complex pick-and-place or collaborative tasks

Large Number of Actuators

A humanoid typically integrates 50-80 actuators—linear and rotary—to achieve agile, expressive movements. Increasingly, joint modules are designed to be integrated, modular, and size-optimized to support the physical requirements of the hands, arms, legs, and torso. Hierarchical control architectures enable deterministic, real-time actuation at every degree of freedom (DoF), improving both speed and precision while reducing unwanted oscillations or noise. The ongoing challenge is to minimize denoising and eliminate mechanical interference when large numbers of actuators operate simultaneously. Deterministic networking and closed-loop control strategies ensure that every command translates into the intended motion, with integrated feedback loops to correct errors dynamically (Figure 3).

Cabling and Connector Requirements

I/O connectivity and internal cabling remain a significant practical challenge, often neglected in high-level discussions. As sensor and actuator counts grow, complex cabling for power, data, and networking is required under tight geometric and mass constraints. Migration toward Ethernet-based control systems, which support deterministic communication and robust error handling, is gaining

traction, enabling effective integration of heterogeneous subsystems (sensors, actuators, and compute nodes).
Connectors and cables for humanoid robots must offer a high degree of flexibility to meet mechanical, electrical, environmental, and design requirements.

Mechanical Requirements	▪ Millions of bending cycles in robotic joints ▪ Torsion-resistant for joints that rotate or twist like wrists and necks ▪ Small bending radius for limited space ▪ Integrated strain relief to prevent stress on contacts during movement
Electrical Requirements	▪ EMI-shielded cables to protect sensitive signals from motor noise and switching electronics ▪ High-speed, low-latency data transmission for sensors and vision systems ▪ Efficient power transmission for reliable transmission even under environmental conditions
Environmental Requirements	▪ Cables and connectors that withstand vibration and temperature change ▪ Abrasion-resistant for integration inside a robot joint ▪ Chemical resistance
Design Requirements	▪ Compact size for limited installation space ▪ Hybrid solutions – data and power in one single connector / cable

Dexterous Hand Manipulation

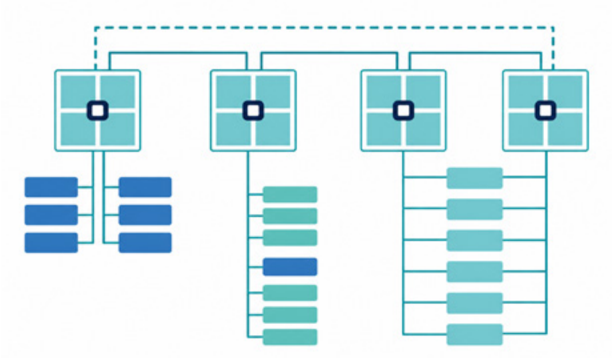
While remarkable advances have been made in locomotion, achieving dexterous hand manipulation remains the „holy grail“ of humanoid robotics. Hands with high DoF (such as the Shadow Robot's 24-DoF Dexterous Hand) enable nuanced control and object handling, but introduce immense mechanical, sensing, and control complexity. Tactile sensors embedded in fingertips provide critical feedback, simulating human-like touch and handling capabilities. However, these hands often have a mean time between failure (MTBF) below 100 hours, limiting practical deployment. Specialized vendors (e.g. Schunk SVH) now offer modular, servo-electric hands designed for mounting and rapid interchange, improving adaptability but not entirely solving durability and control integration challenges. Advances in model-based and learning-driven control architectures are being tested to bring robust, flexible hand manipulation closer to reality.

4. Humanoid In-Robot Network and the case for SPE

Technology adoption from the Automotive Industry

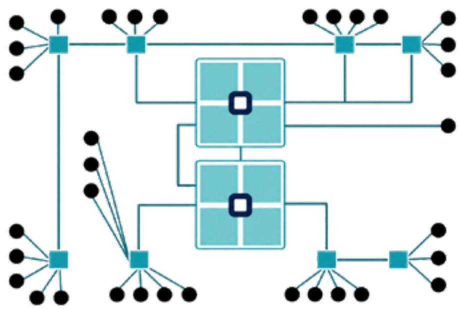
The automotive industry is undergoing fundamental changes. Traditional domain architectures are increasingly being replaced by zonal architectures, which enable more efficient integration and scalability.

Domain architecture



- System split into Domains: Driver assistance, Infotainment
- Higher speed requirements
- Logical structure

Zone architecture



- Reduced complexity: Fewer control units and shorter wiring harnesses lower costs and vehicle weight.
- Improved scalability: New functions can be integrated more easily without redesigning the entire architecture.
- Greater flexibility: Hardware and software can be decoupled, paving the way for Software-Defined Vehicles.
- Optimized data processing: Local pre-processing within zones reduces latency and eases the load on central computing units.

At the same time, 3D environmental sensor technology is becoming increasingly important to provide precise perception for advanced driver assistance systems and autonomous driving.
Another critical step is the consolidation of heterogeneous network architectures toward Automotive Ethernet, which serves as a unified communication backbone, offering higher data rates and lower latency. These developments are essential for enabling ADAS (Advanced Driver Assistance Systems) and fully autonomous driving functions.
Furthermore, the concept of the Software-Defined Vehicle (SDV) is gaining traction: vehicles are increasingly shaped by software, unlocking new possibilities for over-the-air updates, feature activation, and flexible customization to meet customer needs.

Humanoid Motion Control Architecture

Designing a humanoid motion control architecture requires a robust, deterministic communication backbone to ensure precise coordination among sensors, actuators, and control units.

Sensor Connectivity and Migration to SPE
Sensors are traditionally connected via various bus systems (e.g., CAN, LIN, or proprietary protocols). To meet increasing bandwidth and real-time requirements, the migration toward Single Pair Ethernet (SPE) is a key trend. SPE offers high data rates, reduced wiring complexity, and compatibility with modern Ethernet-based architectures, making it ideal for humanoid robotics.

Actuator Connectivity and Topology Choices
Actuators can be connected using different topologies:

- Star topology: Each actuator connects directly to a central controller, ensuring low latency and high reliability but requiring more cabling.
- Daisy-chain / Line topology: Actuators are connected in series, reducing wiring but introducing potential latency and fault propagation risks.

The choice depends on trade-offs between wiring complexity, fault tolerance, and timing requirements.

Power Delivery: PoDL vs Separate Lines

- For power supply, two [GD5.1][TK5.2]approaches are common:
- Power over Data Lines (PoDL): Reduces cabling by delivering power and data over the same pair of wires, suitable for low-power (up to 50 watts)[GD6.1] sensors and actuators.
- Separate power delivery: Preferred for high-power actuators to avoid interference and ensure a stable energy supply.

Low-Level Control Protocols for Deterministic Communication
To achieve deterministic motion control, protocols such as EtherCAT®, TSN (Time-Sensitive Networking), ProfiNet®, EtherNet/IP® over Ethernet, or CANopen are widely used. These protocols guarantee real-time data exchange, synchronization, and fault-tolerant communication—critical for humanoid motion precision.

GR00T N1: The Foundation for Generalist Humanoid Robots
(Section based on NVIDIA GR00T N1 research and the technical analysis published by phospho.ai. https://blog.phospho.ai/dissecting-groot-n1-a-foundation-model-for-generalist-humanoid-robots)

NVIDIA's GR00T N1 sets a new benchmark for humanoid robotics. As an open Vision-Language-Action (VLA) foundation model, it integrates visual perception, language understanding, and motor control into a unified architecture. Its purpose: to enable humanoid robots to interpret their surroundings, execute fluid actions, and adapt to new tasks with minimal effort.

Dual-System Architecture
Inspired by cognitive principles, GR00T N1 employs two tightly coupled systems:

- System 2 – Vision-Language Module
  A powerful Vision-Language Model (VLM) that processes image data and natural language commands to generate contextual tokens. This module acts as the "deliberative mind," responsible for reasoning and planning.

- System 1 – Diffusion Transformer
  A high-frequency action generator that uses VLM outputs and the robot's state to produce smooth, real-time motor actions. This represents the "intuitive mind," focused on execution.

Both modules are Transformer-based and trained end-to-end on a diverse dataset of real robot trajectories, human demonstrations, and synthetic scenarios. This synergy enables seamless coordination between high-level reasoning and low-level control – bringing humanoid robots closer to human-like adaptability and precision.

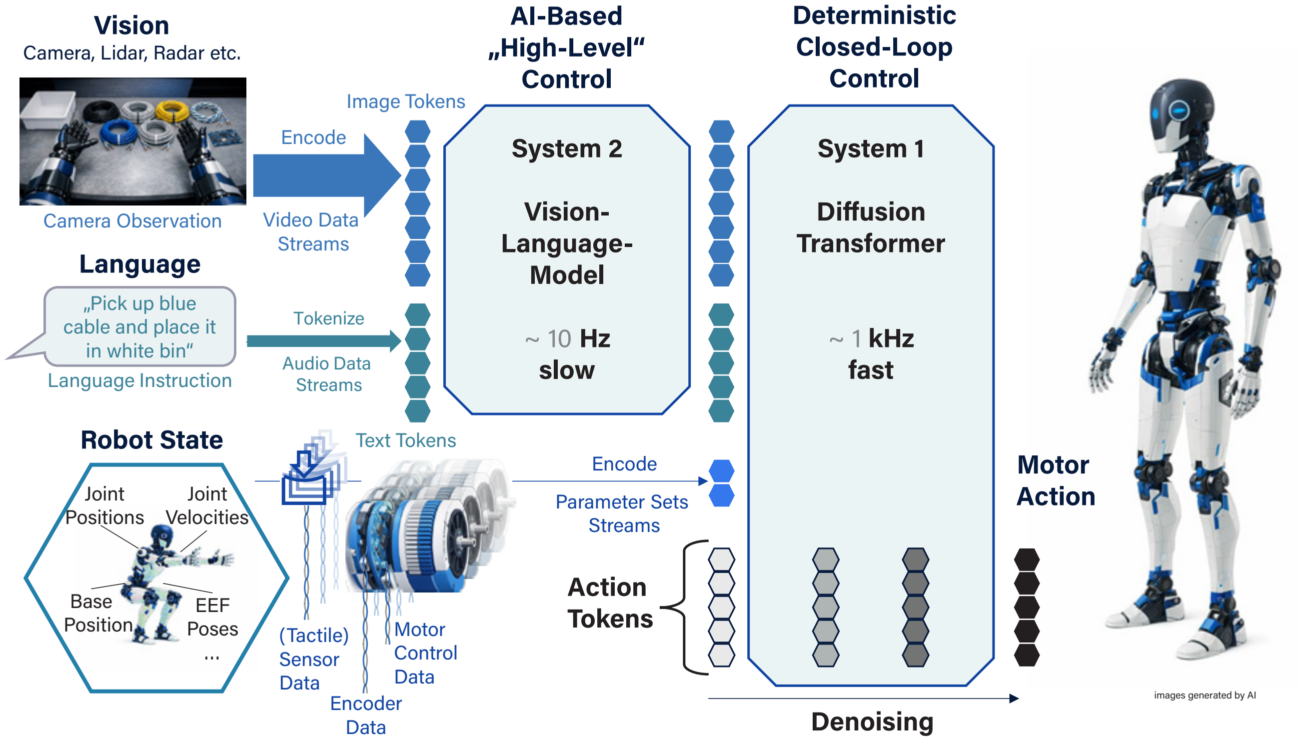
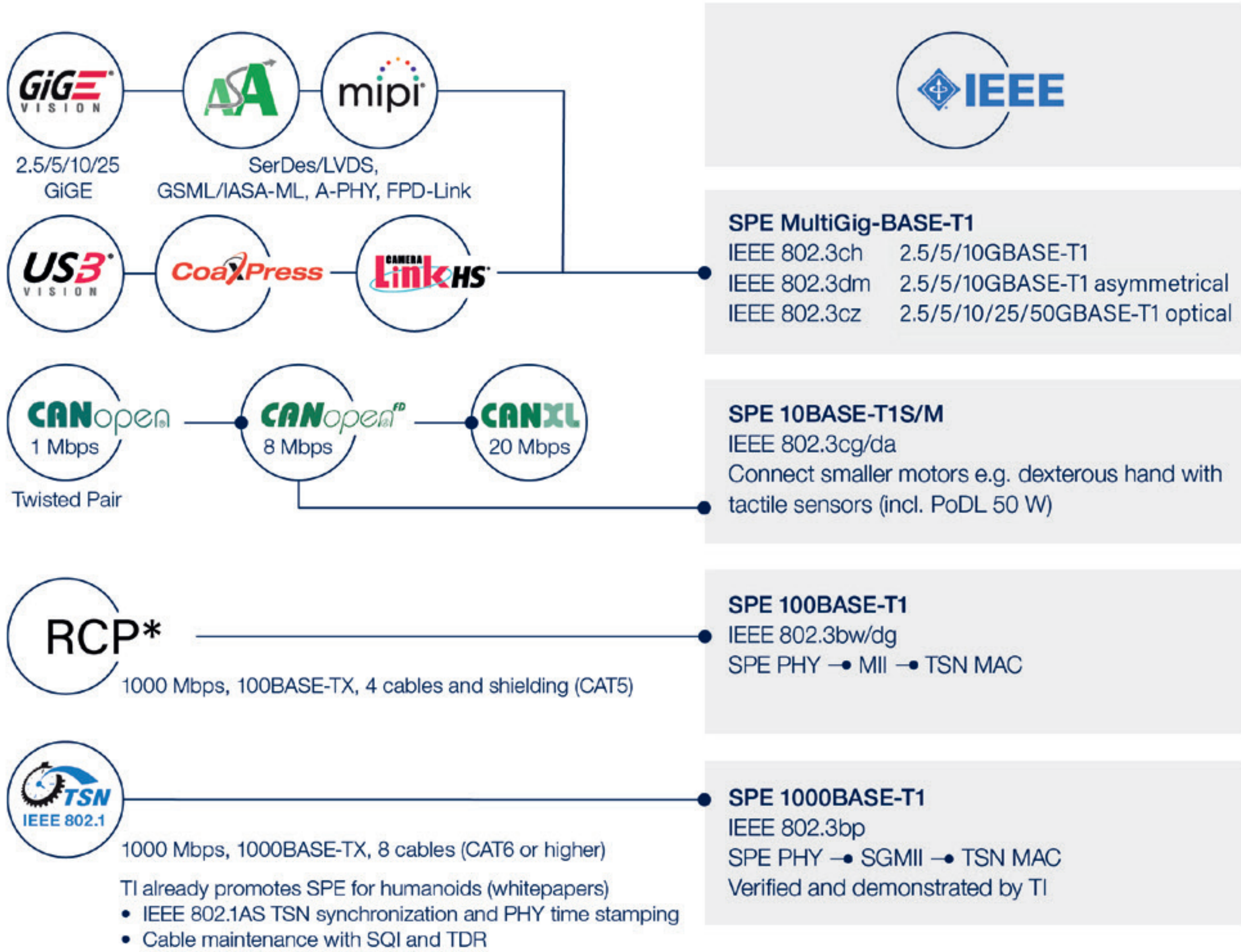


Figure 3: Dual system control architecture for humanoids. Humanoid Control Architecutre with VLA Model (Vision, Language, Action) Different data stream sizes for the two systems at different processing speeds are visualized.

Migrating Towards SPE for Humanoid In-Robot Networks

As humanoid robots evolve into highly complex systems, their internal communication networks must meet stringent requirements for real-time performance, scalability, and reliability. Traditional Ethernet-based architectures often struggle with deterministic latency and synchronization, which are critical for coordinated motion and sensor fusion. This is where SPE becomes a game-changer.

High-Speed Communication Interfaces – Now & Potential Future Implementations



*) RCP = Realtime Communication Protocols (like EtherCAT®, ProfiNet®, EtherNet/IP®)

Figure 4: SPE Migration Considerations

Why SPE is a Future-Proof Solution for Humanoid Robots

SPE offers a unique combination of mechanical, electrical, environmental, and design advantages, making it an ideal cabling technology for the demanding requirements of humanoid robotics. With its compact construction, robust signal integrity, and the ability to supply both data and power (Power over Data Line – PoDL) over a single twisted pair, SPE addresses many limitations of traditional cabling systems.

SPE cables are significantly slimmer and lighter than traditional Ethernet or multicore cables.
As a result:

- Smaller bending radius
- Mechanical stress during bending is reduced
- Resistance inside tight joints decreases
- Overall cable lifetime increases significantly
- High packing density is possible

SPE supports high-speed and low-latency data transmission combined with efficient power delivery

- High-Speed Data Transmission: Up to Multi-Gbps over a single twisted pair.
- Power over Data Line (PoDL): Simplifies power delivery to sensors and actuators. This eliminates the need for separate, heavy copper cables for power and data. Reducing material costs, installation complexity, and weight.
- Deterministic Communication: Supports Time-Sensitive Networking (TSN) for real-time control loops.
- Diagnostic features using SQI measurements to test cable/connector quality of real-time data transmission

This makes SPE an excellent match for highly dynamic humanoid robots and supports scalable, reliable, and maintenance-friendly robotic architectures.

A combination of SPE cables and contactless technology

Future trends indicate rising adoption of wireless Ethernet solutions for short-range links within robotic subassemblies, such as data transmission within highly dynamic joints.
Contactless transmission and SPE complement each other effectively in humanoid robots. SPE provides lightweight, flexible, real-time[GD9.1], and EMI-robust data and power delivery throughout the system, while contactless links eliminate mechanical wear points in high-rotation joints and remove movement constraints entirely. Together, they reduce system weight, increase reliability and lifetime, simplify joint design, and enable smooth, unrestricted motion within a unified, future-proof communication architecture.

Migration Strategy

- **Assess Current Architecture:**
  Map existing communication protocols (CAN, traditional Ethernet, proprietary buses) and identify bottlenecks in latency and bandwidth.

- **Define SPE Zones:**
  Segment the robot into functional domains (e.g., vision system, locomotion, haptics) and plan SPE integration where high-speed, low-latency links are essential.

- **Hardware Upgrade Path:**
  Replace legacy connectors with SPE-compatible interfaces.
  Integrate SPE PHYs and switches supporting TSN.

- **Protocol Alignment:**
  Transition from non-deterministic protocols to TSN-enabled Ethernet stacks for synchronized motion control.
  Get existing protocol vendors to enable SPE PHY's for their industrial protocols

- **Testing & Validation**:
  Use simulation environments and real-world stress tests to validate deterministic performance under dynamic loads.

Single Pair Ethernet – The Nervous System of Humanoid Robots

Lightweight connectivity for high-performance, precise and scalable humanoid robotics.

Figure 5: SPE is the nervous system of humanoid robots. Twisted pair wiring is the DNA and backbone that runs throughout the robot, enabling a simple communication architecture with the required bandwidth. (Images generated with AI)

Humanoid robots combine powerful actuators, advanced sensors, and central intelligence in a highly integrated system. SPE provides a unified, lightweight and high-performance communication infrastructure connecting all components – like a biological nervous system.

Technical Architecture & Design Recommendations

Central Control & TSN
Use a real-time capable central control unit with TSN support.
Recommendation: Implement TSN profiles to achieve deterministic control cycles of 4–8 kHz.

SPE Switching Infrastructure
Deploy SPE switches with heterogeneous port speeds.
Recommendation: Combine low-speed sensor ports with multi-gigabit links for vision systems.

Power & Data Separation
High-torque actuators require separate power paths.
Recommendation: Use SPE exclusively for data communication; supply motors via dedicated power lines.

PoDL for Sensors
Power-over-data-line (PoDL) is suitable for low-power devices.
Recommendation: Power sensors and small controllers via PoDL to reduce cabling complexity.

PoDL Technology:
Use tight-tolerance inductors (<< 10%) for PoDL.
Standard 10–20% tolerances may create inductance mismatches, causing impedance discontinuities, common- and differential-mode conversion, and resulting EMC emission and immunity issues.

Synchronization & Real-Time Performance
Precise motion requires high synchronization accuracy.
Recommendation: Design for >1 kHz synchronization, typically 4–8 kHz, across all control loops.

Future Ethernet Standards
Humanoid robots require long-term scalability, which needs to support from existing protocol vendors

These recommendations support the design of a scalable, robust, and future-proof humanoid robot architecture based on Single Pair Ethernet.

Benefits and value proposition for SPE to the point

Reduced Weight & Space
Thin SPE cables minimize mass and installation space.

Flexible Data Rates on a single twisted pair cable
From low-speed sensors to multi-gigabit vision systems.

Scalable Networking
One Ethernet-based network for 100+ in-robot ports.

Deterministic Communication
Highly synchronized real-time control loops.

High Reliability
Fewer cables increase durability in dynamic motion

5. Summary

Humanoid robots present unique challenges for internal communication. Their complex systems require handling data from numerous sensors, controlling powerful actuators, and running real-time AI – all while minimizing weight, and size, and maximizing reliability. This whitepaper demonstrates how **Single Pair Ethernet (SPE),** inspired by automotive zonal architectures with their simplified node structure, offers a compelling solution as a lightweight, scalable, and deterministic backbone for in-robot networks.
SPE, coupled with Time-Sensitive Networking (TSN) – currently the only viable option – and the potential for Power over Data Line (PoDL), facilitates high-performance sensor-actuator loops and dramatically reduces cabling complexity. While established real-time protocols like EtherCAT®, ProfiNet®, and EtherNet/IP® are well-suited for these applications and offer functional safety features, their vendors need to consider the application specific requirements which is changing the usecase for the industrial real time networks, and adapt their protocols to support SPE as a physical layer and enable closed-system communication for industrial environments..
As humanoid robots move toward commercial viability, SPE is poised to become the foundational **„nervous system“** for future software-defined platforms, offering an ideal balance of size, performance, and functionality.

Single Pair Ethernet
System Alliance

The Technology of the Future
Advancing together

The Single Pair Ethernet System Alliance is an open consortium of leading technology companies and scientific organisations from various industries and fields of application. Manufacturers of sensors, cables, connectors, measuring devices, semiconductors, switches and end devices work together to establish SPE solutions for a wide range of applications.

Become a Member

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