Deciphering Humanoids from Hardware to Software

This white paper offers an introductory overview of the hardware and software considerations involved in humanoid design. It begins with a diagram illustrating the key operational blocks that define the mechanical and electronic subsystems of a humanoid robot. Next, it discusses the various layers of software components that enable humanoid functionality. Following this, several valuable resources that describe and support the software ecosystem for humanoid development are provided. Finally, the paper concludes with recommendations for electronic components in your humanoid design.

What Is a Humanoid Robot?

Humanoid robots are highly sophisticated robots designed to replicate human motion, behavior, and interaction. They are a subset of professional service robots and play an increasingly critical role in augmenting or automating tasks traditionally performed by humans. These robots deliver significant value across industries by improving operational efficiency, enhancing safety, reducing labor costs, and enabling consistent productivity.

From an engineering perspective, the development and deployment of humanoid robots present a wide array of challenges and learning opportunities. Their complexity stems not only from intricate mechanical design but also from the integration of advanced semiconductor technologies, embedded systems, artificial intelligence, and control architecture.

In 2024, the global market for humanoid robots was estimated at approximately USD $6 billion. This market is projected to reach USD $38 billion by 2035.

Hardware Components of Humanoid Robots

Humanoid robots are among the most intricate machines in robotics, combining diverse engineering disciplines into a single, cohesive system that mimics human anatomy, cognition, and interaction. The effectiveness of a humanoid robot depends on the harmonious integration of multiple subsystems each carefully designed to replicate or complement specific aspects of human capabilities. A comprehensive breakdown of the core components of humanoid robots is shown in Figure 1.

1. Mechanical and Kinematic Systems

1. **Actuators and Motors:** High-performance actuators such as servo motors, pneumatic actuators, or hydraulic systems serve as the “muscles” of the robot. They enable a wide range of movements from gross locomotion to fine motor tasks like gripping a bolt or using a touchscreen.
2. **Dexterous Manipulation:** Humanoid hands are often equipped with multiple degrees of freedom, mimicking the human hand’s ability to grasp, pinch, and manipulate

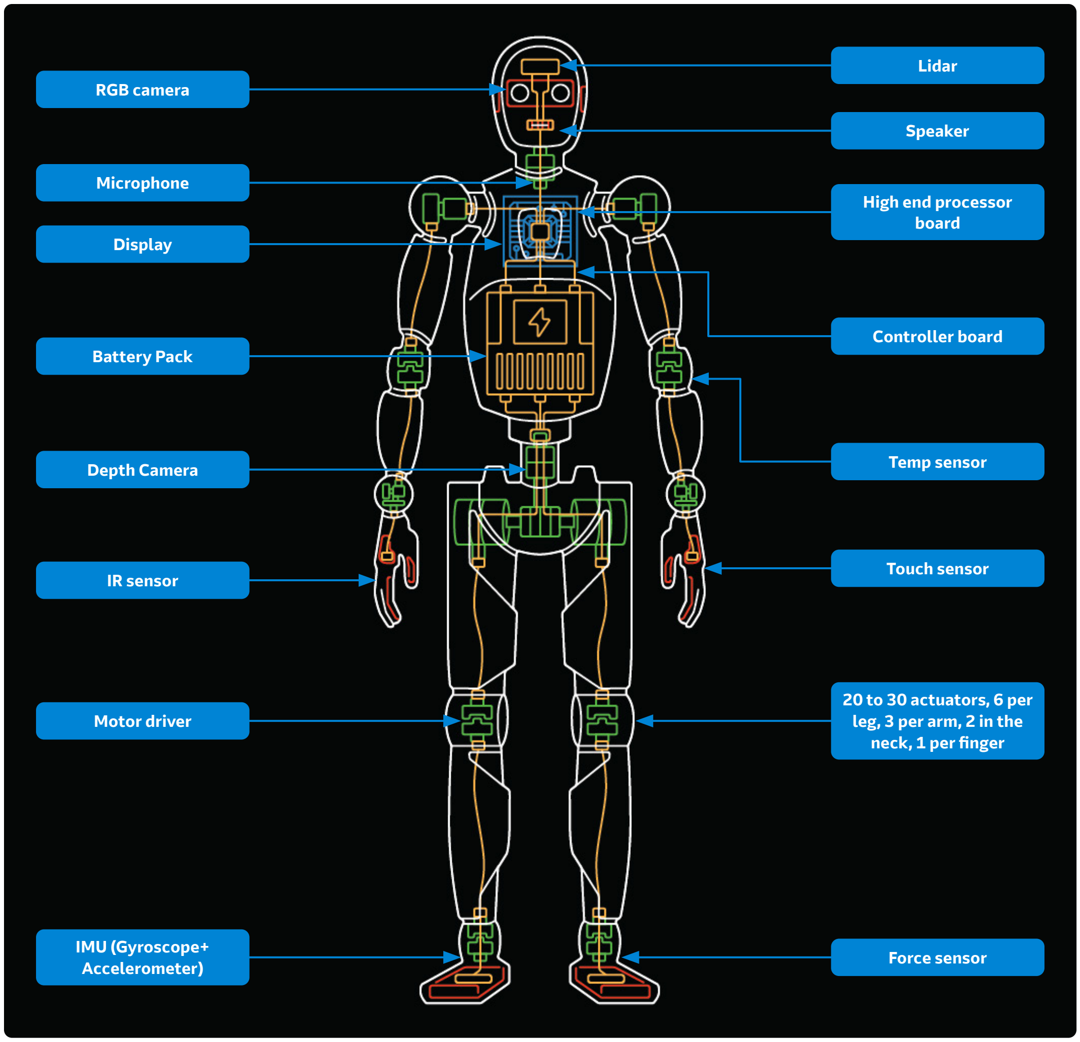

Figure 1: Components of a Humanoid Robot

objects with precision. This is essential in industrial tasks such as part assembly, packaging, and machine tending.

3. **Bipedal Locomotion:** Advanced balance and gait algorithms allow the robot to walk, climb stairs, or crouch in constrained spaces. This human-like mobility is crucial in navigating uneven or cluttered industrial environments.

2. Control Systems

1. **Microcontrollers and Edge Processors:** These serve as the computational core, managing real-time input from sensors and generating motor commands. They coordinate motion, balance control, sensor fusion, and decision-making.
2. **Motor Drivers and Actuator Controllers:** These driver modules convert control signals into precise motor commands for position, velocity, or torque control. They are integrated with safety features such as overcurrent protection, thermal shutdown, and emergency stop capability.

3. Sensing and Perception Systems

1. **Vision Systems:** Cameras (RGB, depth, stereo) enable object recognition, workspace mapping, and gesture interpretation. Integrated computer vision allows humanoids to detect machine states, recognize components, and identify human co-workers.
2. **Environmental Sensors:** LiDAR, ultrasonic, infrared, and proximity sensors build spatial awareness, enabling the robot to navigate dynamic environments and avoid obstacles on the fly.
3. **Tactile and Force Sensors:** These allow the robot to feel contact, measure grip pressure, and handle fragile objects critical for tasks like quality inspection or assembling delicate components.
4. **Inertial Measurement Units (IMUs):** IMUs

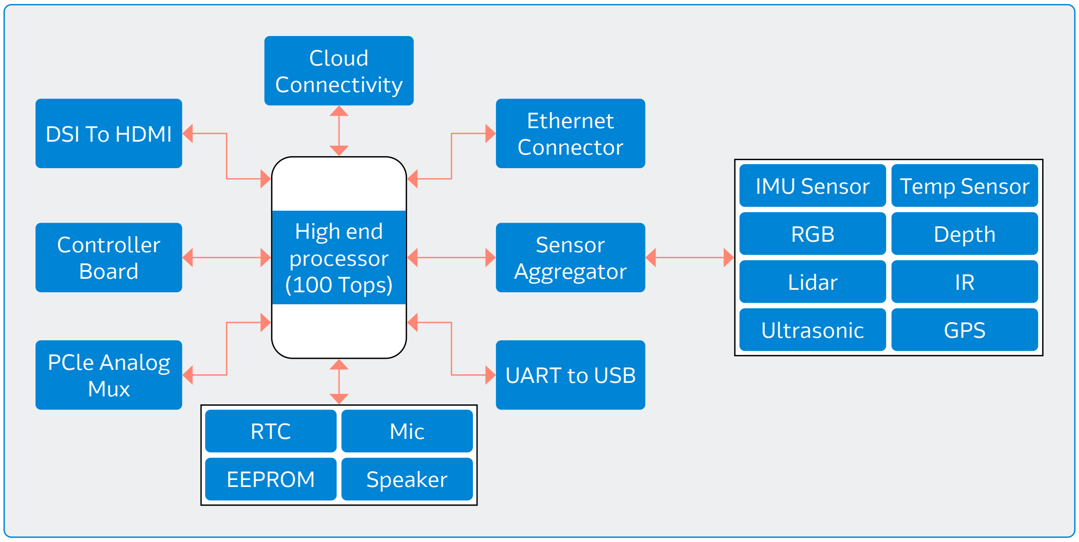

Figure 2- High-End Processor Board

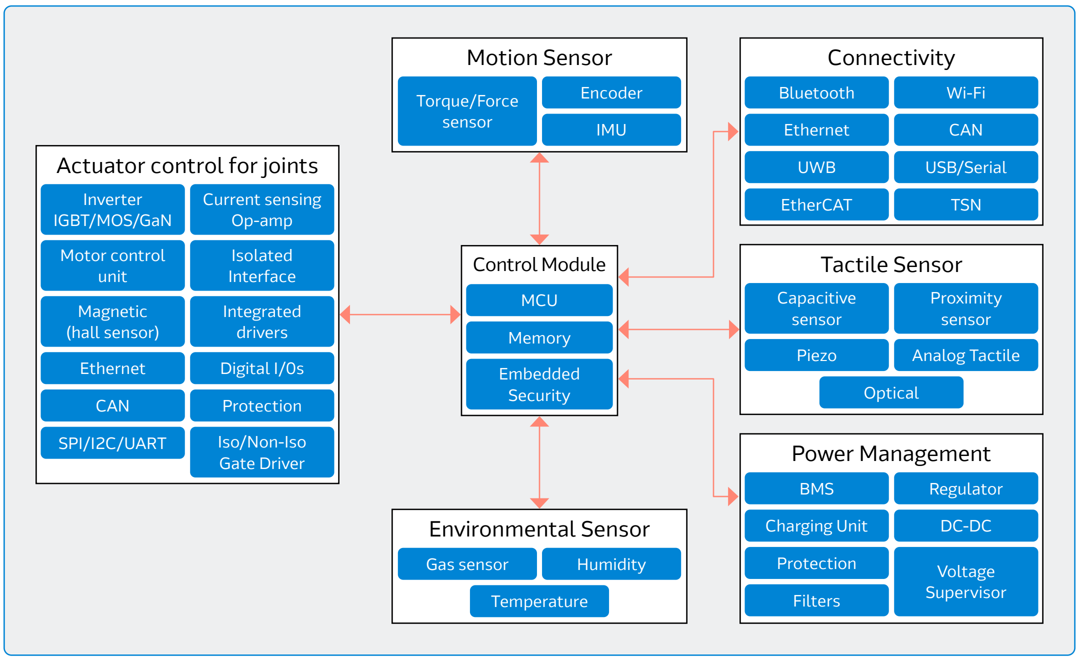

Figure 3- Controller Board

track orientation and movement, helping the robot maintain balance and posture even on sloped or moving surfaces.

4. Power and Energy Management

1. **Battery Systems:** High-density lithium-ion or solid-state batteries provide the primary energy source. Power management modules regulate supply across motors, sensors, and compute units to optimize runtime and safety.
2. **Energy-Efficient Design:** Lightweight actuators, low-power electronics, and smart power-routing strategies are crucial to extending operational time and reducing downtime for recharging or maintenance.

System Level Block Diagram

Figure 2 illustrates the connections between the sensors, the high-end processor board, and the controller board. The sensors are interfaced with the processor through a sensor aggregator to ensure low-latency data transmission. Sensors such as the microphone and speaker are connected to enable voice control tasks, while LiDAR and camera modules are used for artificial intelligence tasks, simultaneous localization and mapping (SLAM), and navigation.

Figure 3 illustrates a modular controller board architecture, emphasizing the microcontroller's integration with actuators and various high-frequency, low-bandwidth sensors — including motion, tactile, and environmental types. The actuator control for joints includes components such as motor control units, magnetic (Hall) sensors, current-sensing operational amplifiers, and protection circuits to ensure precise and efficient actuation. It communicates with control modules through isolated interfaces and standard communication protocols such as Ethernet, CAN, and SPI/I2C/UART. The power management block includes a battery management system (BMS), charging units, protection devices, and filters to ensure reliable and safe operation.

Now that we have provided some background on the hardware considerations for humanoids, let's examine the software components and their different layers. We will also include useful links to the software ecosystem.

Software Components of Humanoid Robots

There are various software frameworks available for configuring and controlling humanoid robots. Due to their multi-degree-of-freedom (multi-DOF) systems, bipedal locomotion, and interactive features such as vision, speech, and emotion recognition, humanoid robots are inherently more complex. Consequently, it is not feasible to have a single software protocol that controls all its functions. A high-level overview of the software functions required for humanoid robots is shown in **Figure 4**.

Here's a step-by-step explanation of each layer in the simplified humanoid robot software architecture:

1. Sensors

This is the first layer where the robot collects data from the physical world.

1. Cameras provide visual information (used for object detection, face recognition, etc.).
2. LiDAR measures distances by emitting laser pulses and analyzing their reflections. It is commonly used for simultaneous localization and mapping (SLAM), obstacle detection, and navigation.
3. Microphones capture sound for speech recognition and voice commands.
4. IMUs (inertial measurement units) detect motion, orientation, and acceleration.
5. Force sensors measure the amount of force or pressure applied, making them essential for applications such as robotic grippers, collision detection, and tactile feedback.
6. Piezoelectric sensors convert mechanical stress into electrical signals and are commonly used for vibration detection, touch sensing, and impact monitoring.
7. Encoders track the rotational position or speed of motors and shafts, which is essential for precise motion control and odometry.
8. Sensor aggregation can be implemented using either a USB hub or an FPGA-based module, depending on the system requirements.

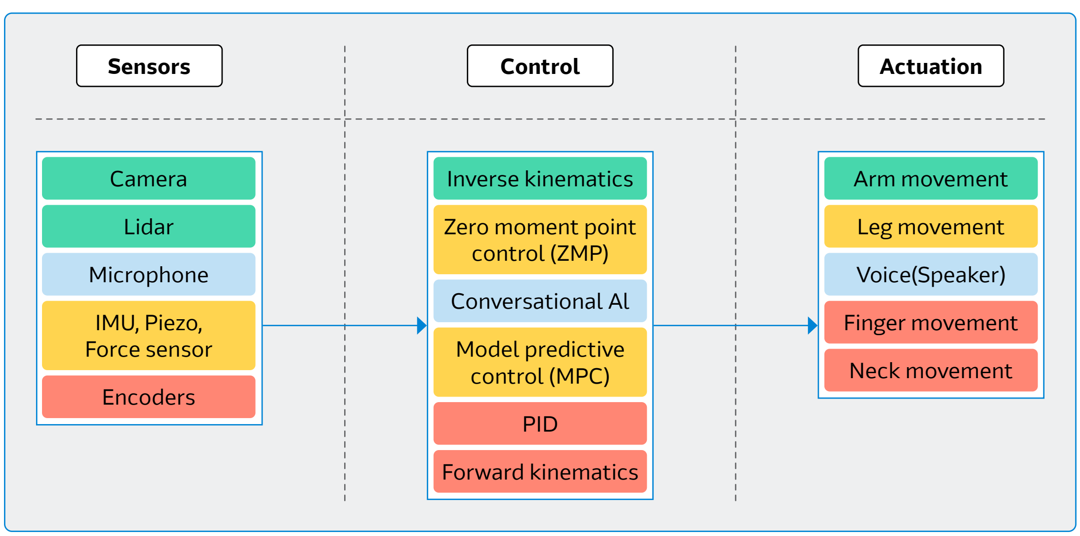

Figure 4: High-Level Software Functionality

2.Control

Here, the robot determines subsequent actions based on the interpreted data.

1. Inverse kinematics (IK) calculates the joint angles necessary for a robot's end-effector to achieve a desired position and orientation in space. This process is essential for tasks such as grasping objects, manipulating tools, and executing precise arm movements.
2. The zero-moment point (ZMP) is the point at which the net moment of the inertial and gravitational force is zero. This allows the designer to control balance, maintain stability, and prevent tipping.
3. Conversational AI enables robots to understand and respond to human speech or text using natural language processing (NLP). It supports tasks such as answering questions, executing verbal commands, and engaging in interactive dialogue.
4. Model predictive control (MPC) enables a robot to plan optimal foot placements and joint movements over a finite time horizon while respecting physical constraints. It uses a predictive model to adjust actions in real time based on the robot's current state and desired trajectory.
5. PID controllers ensure stability and precision, such as maintaining balance while walking.
6. Forward kinematics (FK) calculates the position and orientation of a robot's end-effector (or other parts) based on known joint angles and link lengths. It's used for motion simulation, collision checking, and pose visualization.

3. Actuation

The final step involves executing software commands in the real or simulated environment.

1. The robot is positioned to maintain stability through ZMP-based foot placement.
2. Upon reaching its destination, the humanoid can extend its arm, precisely grasp a nearby object with its fingers, and lift it gently.
3. The robot uses a text-to-speech (TTS) engine to convert text-based responses into natural, human-like speech.
4. The robot's motors, actuators, and joints perform physical movements.

Software Ecosystem for Humanoid Robots

1. ROS 2 (Robot Operating System)

1. A middleware and development framework for building robotic software.
2. Provides communication infrastructure, drivers, simulation tools, and packages.
3. Backbone of most modern robotic systems including humanoids.

2. MoveIt

1. A motion planning framework for robotic arms and manipulators.
2. Integrates with ROS for tasks such as inverse kinematics, collision avoidance, and trajectory planning.
3. Commonly used in humanoid robot arm movement and manipulation.

3. Isaac GR00T N1.5 (reference: NVIDIA)

1. Isaac GR00T N1.5 is an open, fully customizable foundation model for generalized humanoid reasoning and skills.
2. Takes multimodal input—including language and images—to perform manipulation tasks in diverse environments.
3. Trained on an expansive humanoid dataset consisting of real captured data and synthetic data.

4. Isaac Sim (reference: NVIDIA)

1. NVIDIA's advanced robotics simulation platform built on the Omniverse.
2. It offers realistic physics, high-quality rendering, and deep learning integration.
3. Excellent for training humanoid robots with reinforcement learning and synthetic data.

5. Blender

1. A powerful open-source 3D modeling and animation tool.
2. Used in robotics to create robot models, including meshes and animations.
3. Can export URDF/mesh files for simulation in Gazebo or RViz.

6. Gazebo

1. A physics-based 3D robotics simulator integrated with ROS.
2. Simulates robots in complex environments with gravity, friction, sensors, etc.
3. Used to test locomotion, manipulation, and sensors in humanoid robots.

7. Rviz

1. A 3D visualization tool for ROS data.
2. Displays robot models, sensor data (such as LiDAR or camera feeds), transform frames (TF), and planned paths.
3. Essential for debugging and monitoring robot perception and planning.

8. Qualcomm Intelligent Robotics Product SDK (reference: Qualcomm)

1. A robotics-focused software development kit optimized for Qualcomm platforms like RB5 and QCS series.
2. Provides ready-to-use ROS 2 packages for SLAM, perception, and sensor fusion.
3. Offers a complete embedded toolchain with cross-compilation, deployment, and debugging utilities.

Below, please find suggestions for suppliers and products that can be considered in a humanoid design.

Humanoid Technology Line Card

Controller Board Specific

Technology	Manufacturer	Part Number	Arrow Links
BLDC motors	MOONS INDUSTRIES KDE Direct, LLC ebm-papst NIDEC Components	57BL120L2 KDE4012XF-400 (D5) ECI-63.40-K4-B00 LA16G324B50MC	Arrow link Arrow link Arrow link Arrow link
Servo motor	TE Connectivity MOONS INDUSTRIES Parallax Incorporated	1372334-1 SM0602DE2-KCF-NNV 900-00360	Arrow link Arrow link Arrow link
Stepper motors	SANYO DENKI MOONS INDUSTRIES SANYO DENKI	103H7123-0440 MS17HD2P4100 SP2566-5260	Arrow link Arrow link Arrow link
Incremental/rotary encoder	TE Connectivity Melexis Grayhill Analog Devices	2416191-2 MLX90382 25BP22-B-1-16F TMCS-28-6.35-10K-AT-01	Arrow link Arrow link Arrow link Arrow link
MCU	Microchip Technology STMicroelectronics NXP Semiconductors NXP Semiconductors	ATSAMD51G18A-MU STM32H743AII6 FS32K118LAT0MLFT SPC5604BK0CLQ4	Arrow link Arrow link Arrow link Arrow link
Temperature sensor	Microchip Technology Melexis Murata Manufacturing	MCP9800DM-DL MLX90632 NCP03XH103D05RL NCP02XH103F05RH	Arrow link Arrow link Arrow link Arrow link
6-axis inertial measurement unit (IMU)	Bosch STMicroelectronics Murata Manufacturing InvenSense	BMI270 ASM330LHHTR SCH16T-K01-1 ICM-42605	Arrow link Arrow link Arrow link Arrow link
Accelerometer	STMicroelectronics ROHM Semiconductor Murata Manufacturing	AIS2DW12TR KX134-1211 SCA3300-D01	Arrow link Arrow link Arrow link
Gyroscopes	STMicroelectronics InvenSense Murata Manufacturing	A3G4250DTR IAM-20380 SCR2100-D08-05	Arrow link Arrow link Arrow link
Force sensor	Honeywell ALPS ALPINE CO., LTD SparkFun Electronics Honeywell	FMAMSDXX005WC2C3 HSFPAR007A SEN-13332 FSS005WNSB	Arrow link Arrow link Arrow link Arrow link

Technology	Manufacturer	Part Number	Arrow Links
Magneto resistive (Hall) sensors	Murata Manufacturing	MRMS591P	Arrow link
Position sensor	Infineon Technologies AG	TLE5501E0002XUMA1	Arrow link
Touch sensors	Microchip Technology	AT42QT1070-MMHR	Arrow link
Motor driver ICS	Infineon Technologies AG Onsemi	BTN8962TAAUMA1 LV8907UWR2G	Arrow link Arrow link
Motor control MCUs	SANYO DENKI Infineon Technologies AG MOONS INDUSTRIES	F5PAE140P100 IMD700AQ064X128AAXUMA1 STF06-R	Arrow link Arrow link Arrow link
Batteries	Panasonic Jauch Quartz GmbH Murata Manufacturing NUENERGY	BR-1225A/FAN CR 2032 CR2032X-HO6 NUELFP12V7X0E	Arrow link Arrow link Arrow link Arrow link
Battery management system (BMS)	MICROCHIP NXP	MCP73842T-820I/UN MC33772BTP1AE	Arrow link Arrow link
DC-DC power converter	TDK ONSEMI ALLEGRO VICOR ST Murata Manufacturing	FS1406-0600-AL NCV898031D1R2G A4447SLJTR-T PI3526-00-LGIZ PM6680ATR MPQ600-28V21-D48NBMC	Arrow link Arrow link Arrow link Arrow link Arrow link Arrow link
Low-noise linear regulators (LDOs)	ONSEMI ST MICROCHIP	NCP563SQ33T1G STLQ020PUR MCP1700T-1802E/TT	Arrow link Arrow link Arrow link
Power management ICs (PMICs)	NXP ALLEGRO LATTICE	PCA9450CHNY A4405KLPTR-T LPTM21-1AFTG237I	Arrow link Arrow link Arrow link
Circuit protection devices	Littelfuse ST BOURNS	LS2405IDD23 CLT3-4BT6-TR GMOV-14D111K	Arrow link Arrow link Arrow link
Magnetic resolver IC	Melexis	MLX90381	Arrow link
Gate drivers and power ICs	Littelfuse Infineon Technologies AG ST ALLEGRO	LF2136BTR IR2010STRPBF L6398DTR A4957SESTR-T	Arrow link Arrow link Arrow link Arrow link
Current sensing ICs	MELEXIS ALLEGRO	MLX91221KDC-ABR-020-RE ACS711KEXLT-31AB-T	Arrow link Arrow link
Optical sensor modules	MELEXIS	MLX75027RTC-ABA-210-TR	Arrow link
CAN transceiver IC	ONSEMI NXP Infineon Technologies AG	NCV7342D10R2G SJA1000T/N1,118 TLT9251VLEXUMA1	Arrow link Arrow link Arrow link
Bluetooth	Infineon Technologies AG Silicon Labs Murata Manufacturing	CYW43455XKUBGT EFR32BG22C224F512IM40-C LBCA1HN2EG-917	Arrow link Arrow link Arrow link
Wi-Fi	AzureWave Murata Manufacturing Murata Manufacturing	AW-CU300 V2 LBEE5KL1YN-814 LBES0ZZ2FR-580	Arrow link Arrow link Arrow link
EtherCAT Junction Slave	Omron	GX-JC06	Arrow link
EtherCAT Coupler	Omron	NX-ECC201	Arrow link
Ethernet TSN Switch	Arrow Development Tools	KSP-RBRB-TRSRR	Arrow link

For any questions regarding component selection for Humanoid design, please contact Arrow engineering.

Learn More

Processor board specific

Technology	Manufacturer	Part Number	Arrow Links
Depth camera modules	Basler	107796 - Basler AG	Arrow link
RGB camera modules	Intel RealSense Omnivision	82635ASRCDVKMP 962304 - Intel OV04682-G04A	Arrow link Arrow link
Image sensors	Basler AG STMicroelectronics	106691 CAM-5G0-079CLR	Arrow link Arrow link
High-end processor board	NVIDIA Jetson AGX Thor NVIDIA Jetson AGX Orin Qualcomm NXP Semiconductors ST Microelectronics	945-14070-0080-000 945-13730-0050-000 QRB-5165-0-MPSP1099-MT-02-0-AA MCIMX7S5EVM08SD STM32MP157D-EV1	Arrow link Arrow link Arrow link Arrow link Arrow link
LiDAR	Seed Technology Co.,Ltd	101990386	Arrow link
Proximity sensors	AMSOSRAM INVENSENSE INVENSENSE	TCS37013M CH201-00ABR ICU-20201	Arrow link Arrow link Arrow link
USB 3.0 Type-A connector	AMPHENOL MOLEX TE MOLEX	GSB311131HR 484050001 1932258-1 484050003	Arrow link Arrow link Arrow link Arrow link
USB 2.0 Type-A connector	SAMTEC	USB-A-S-F-B-TH	Arrow link
UWB module	Murata Manufacturing	LBUA0VG2BP-741	Arrow link
Solid-state drive (SSD)	ADVANTECH	96FD42-N128-LIS	Arrow link
microSD card connector	MOLEX SAMESKY AMPHENOL	0475710001 MSD-4-A GTFP08431BEU	Arrow link Arrow link Arrow link
Ethernet port connector	ABRACON PULSE HARTING	ARJ11B-MASBR-QU2 JXD1-0026NL 09350022101	Arrow link Arrow link Arrow link
HDMI connector	ADAM TECH MOLEX SAMTEC TE	HDMI-S-RA-SMT-MF 2086581001 HDMR-19-01-F-TH-PF-L 2013978-1	Arrow link Arrow link Arrow link Arrow link
Micro-USB connector	AMPHENOL MOLEX TE	10118194-0011LF 0473461001 1981568-1	Arrow link Arrow link Arrow link
USB Type-C connector	AMPHENOL MOLEX PULSE	12402075E512A 217184-0001 E8124-001-01	Arrow link Arrow link Arrow link
USB interface controllers	SILICON LABS Infineon Technologies AG MICROCHIP NXP	CP2104-F03-GMR CY7C65215-32LTXIT USB2514B-AEZC PTN5110NHQZ	Arrow link Arrow link Arrow link Arrow link
Antenna	TAOGLAS YAGEO TE UBLOX KAVX	FXUB63.07.0150C ANT1204F002R0433A 1513472-5 ANN-MB2-00 1005392F0-AA10L0600	Arrow link Arrow link Arrow link Arrow link Arrow link
GPS receiver module	ABRACON ST	APAM2764YK0175 STA8088FG	Arrow link Arrow link
DRAM modules	MICRON	MTA16ATF4G64HZ-3G2F1	Arrow link

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