Application Brief

Motor Control in Humanoid Robots

Introduction

Humanoid robots have the potential to transform industrial environments where demand for automated solutions continues to grow. Unlike traditional fixed-automation systems, humanoid robots offer unique advantages in navigating human-centric workspaces, manipulating tools designed for human hands, and collaborating safely alongside human workers in dynamic environments.

However, realizing this potential requires addressing the technical complexity of adding more degrees of freedom (DOF) in humanoid robot joints. Modern humanoid robots incorporate up to 70 DOF to achieve human-like dexterity and mobility, an increase from the six to 12 DOF typically found in industrial robotic arms. Figure 1 shows the typical locations for DOF in a humanoid robot.

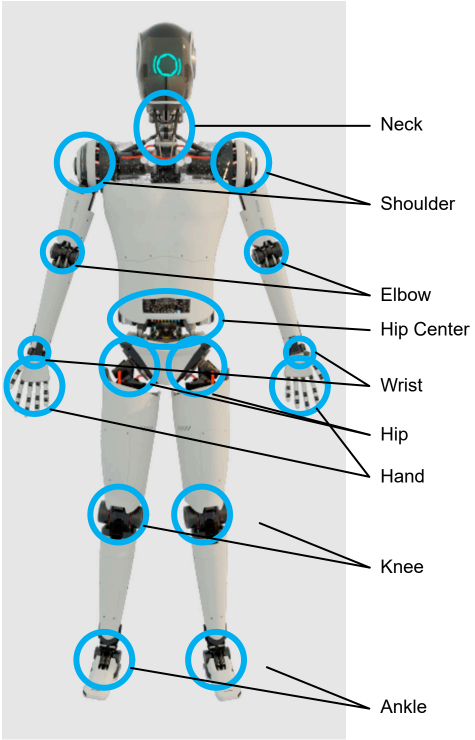


Figure 1. Typical DOF Locations in a Humanoid Robot

Supporting additional DOF requires precise actuation, sensing, and control capabilities, which can increase system design complexity. Having more DOF in a system requires more electric motor drives, with the location of the motor drive defining the various requirements to support it. Table 1 provides an overview of some of these key requirements.

Table 1. Key Specifications for Humanoid Motor Drive Design

Specification	Importance
Communication Interface Architecture	Determines system-level coordination, latency and scalability up to 70 actuators. Inadequate bandwidth or non-deterministic timing causes motion instability and coordination failures.
Position Sensing	Provides feedback for closed-loop control; accuracy directly impacts motion precision and stability. Insufficient resolution causes limit-cycle oscillations and poor trajectory tracking.
Motor Type	Defines efficiency, torque density, control complexity, and thermal characteristics. Motor selection can impact system performance, battery life, and form factor.
Motor Control Algorithms	Determines torque ripple, efficiency, acoustic noise, and dynamic response. Advanced algorithms enable higher performance from the same hardware.
Power Stage Requirements	Defines efficiency, thermal performance, and power density. Inefficient power stage design causes excessive heat, reduced battery life, and bulky actuators.
Electronic Circuit Size	Determines whether electronics fit within anthropomorphic joint envelopes. Oversized circuits prevent human-scale form factors.
Functional Safety Considerations	Ensures safe human-robot interaction and regulatory compliance. Inadequate safety design prevents deployment in collaborative environments.

Adding to this complexity is the need to maintain dynamic stability during bipedal locomotion and dexterous manipulation, which requires control loop response times in the sub-millisecond range, with position updates occurring at 1-4kHz and current regulation exceeding 10kHz.

To meet these challenges, engineers must simultaneously optimize actuator performance across mechanical, electrical, thermal, and control domains while managing constraints in size, weight, power consumption, and cost. Embedded Processor selection is also crucial to help balancing computational workload between centralized motion planning and decentralized joint control while supporting deterministic real-time communication protocols.

Communication Interface Architecture

Due to the location of the drives in the robot, optimizing communication with all drives while minimizing the amount of cabling is important. There are many options for achieving optimization; the most commonly used methods are daisy chained communication systems and linear bus topology, as shown in Figure 2 and Figure 3.

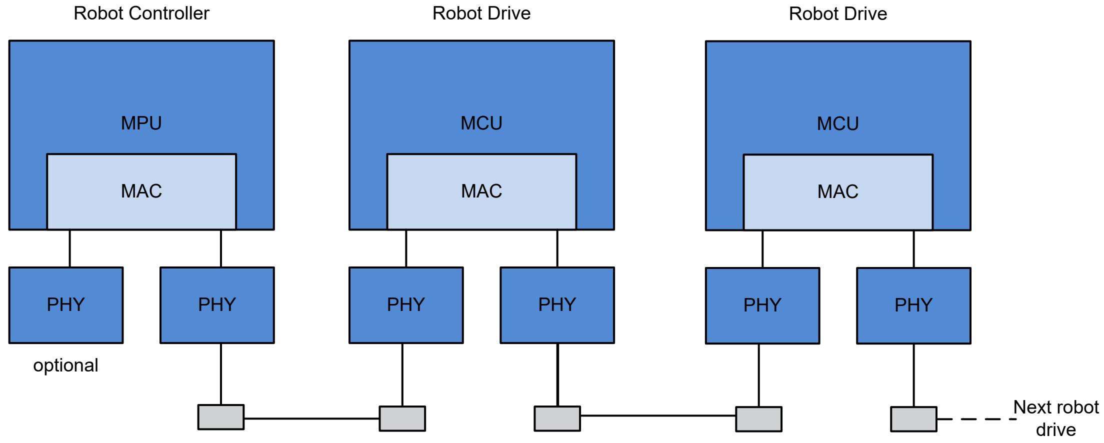


Figure 2. Daisy Chained Communication

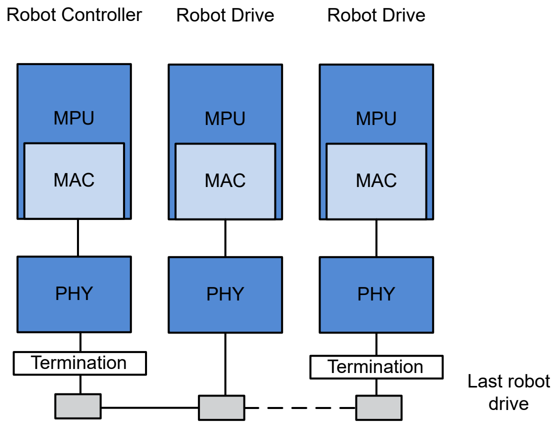


Figure 3. Linear Bus Topology

Engineers must consider bandwidth, timing and latency requirements after selecting the topology to achieve adequate response time of the drive. The response time can determine which real-time capable communication protocol is required based on the defined data frame size. The bandwidth requirement of the communication interface is also impacted by the decision of how to split the motor control algorithms between the decentralized motor drive, and the centralized and outer robot motion controller to minimize the needed communication frame size between the nodes.

Typically, the minimum bandwidth requirement of communication systems is approximately 8Mbit/s. However, trends indicate increasing requirements for system diagnostic and safety capabilities due to evolving design trends.

Depending on system requirements, the communication interface typically used in humanoid systems is either CAN-FD or Ethernet-based (including EtherCAT). TI offers both physical layer (PHY) transceivers and embedded processors designed to enable these communication protocols.

CAN transceivers and *Ethernet ICs* are devices used in humanoid system development.

Position Sensing

The actuators in a humanoid robot must receive motor position data to define the path planning to control motion. To achieve controlled movement with high precision the robot must have rotor position sensors to capture information at the motor and the ability to efficiently pass information through the motor drive to the centralized processing computer. Designers can use a variety of rotor position sensors, depending on the precision required for the motor.

The most commonly used encoders include:

- Optical Encoder
- Magnetic Encoder
- Incremental Encoder
- SIN/COS Resolver

These encoders have different interfaces to connect to the drive and provide rotor angle data, which is needed to conduct position control. These interfaces require specific hardware, so the motor control processor needs to support at least one of following encoder configurations:

- Specialized serial interfaces such as BiSS, Endat, Hiperface, or other digital absolute encoders
- ADC converters with sample and hold for resolver interfaces
- Quadrature encoder pulse for incremental encoders
- Serial interface for interface to magnetic encoders

Multiple encoders may be required for a single motor, depending on how the motor and the gearing of the motor. TI offers both the analog and embedded processors and MCUs [MS1] to enable encoder interface systems. *RS-485 and RS-422 transceivers* and *Multi-axis linear and angle position sensors* are used in position sensing methods.

Motor Type

Motor drives are designed to maximize efficiency to extend operational timeframe of the robot because humanoid robots are battery powered.

Humanoid robots can incorporate motors like PMSM motors when requiring high power levels. Brushed DC motors can be used in some low power cases such as hand and finger control. However, current design trends indicate that most motors will likely be brushless in the future.

There are two options when designing with PMSM: trapezoidal or sinusoidal winding. The choice of winding and control algorithm affects how precisely the motor is controlled.

The option to switch the FETs faster is another key topic of motor design. This approach provides new design options that can improve the torque per weight of the motor.

Motor Control Algorithms

After selecting a motor type, users need to determine the method for how to control the motor. There are several options for implementing control loops, although motor control is typically similar to what is shown in Figure 4, which shows the needed analog sub systems and processor peripheral.

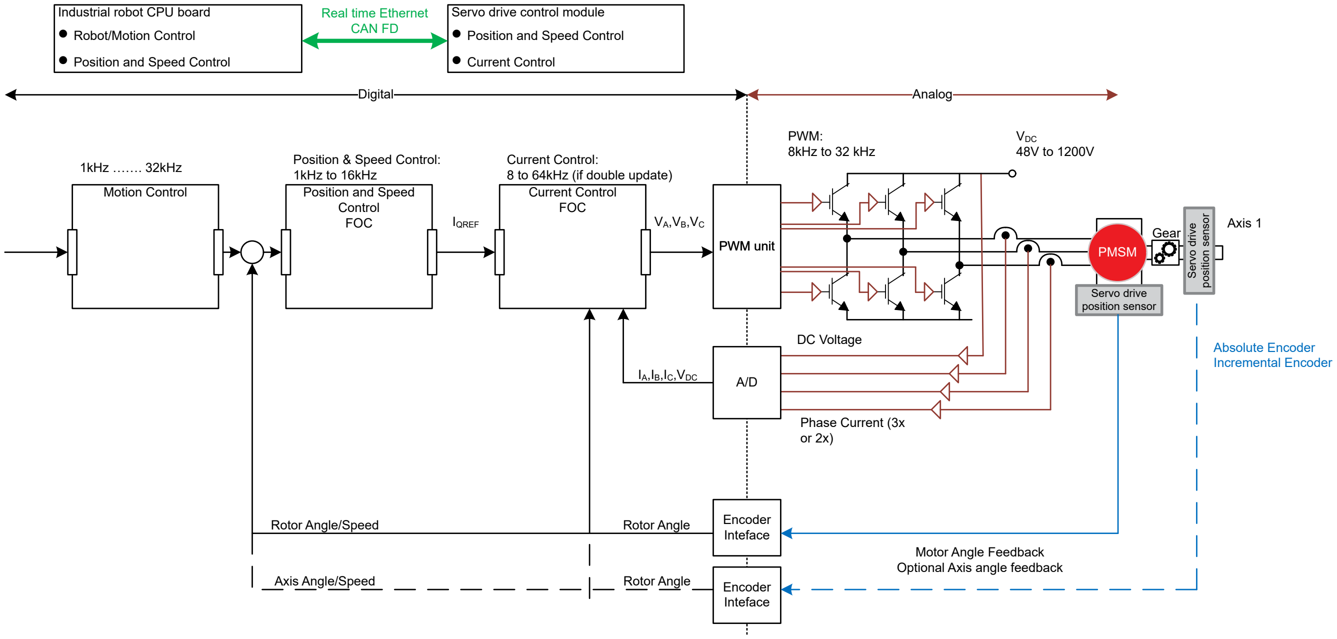


Figure 4. Real-Time Communication Timing Needs for Robot Control

Using Figure 4 as a general template, Table 2 lists the required peripherals and performance when selecting an algorithm FOC or block commutation.

Table 2. Peripheral and Circuit Needs for Motor Control Type

Motor Type	Brushed Motor	Trapezoidal PMSM	Sinusoidal PMSM
Half bridges	×2	×3	×3
Current sense	×1	×1	×2 to ×3
Voltage sense DC link	×1	×1	×1
Angle sensor accuracy	≤1°	60°	≤1°
Processing power	Low	Low	Medium
Efficiency	Low	Medium	High

TI has many different MCU's which fit algorithm and angle sensor requirements for humanoid robots, important factors are the size of the IC and the real time capability to enable high performance drive system. C2000™ real-time microcontrollers and Arm®-based microcontrollers are used in motor control algorithms.

- TMS320F28P650DK **:** TMS320F28P65x series MCUs feature up to three CPUs (2 × 32-bit C28x DSP CPUs and 1 CLA CPU) all running at 200MHz, delivering processing power equivalent to 1000-MHz Arm Cortex-M7 for real-time control performance. The devices include floating point units and accelerators like Trigonometric Math Unit (TMU), Fast Division (FINTDIV), and CRC engine for enhanced computational efficiency. F28P65x series offer a new ultra-small 9 x 9 mm**2** BGA package with an integrated EtherCAT controller. It is functional safety certified for IEC 61508 SIL 2, with systematic capability up to SIL 3.
- AM2612 **:** AM2612 MCUs feature up to two Arm Cortex-R5F cores at 500MHz with industrial communication subsystems, delivering high-performance real-time processing, and low-latency control. It supports EtherCAT and Gbps Time Sensitive Networking (TSN) ethernet and enables <2us ultra-low ethernet cut-through latency. AM261x family MCUs offer a compact footprint as small as 10 x 10 mm**2** BGA and are functional safety certified for IEC 61508 SIL 3.
- AM13E23019 **:** AM13E23x family MCUs like the AM13E23019 are the industry's first to integrate a high-performance Arm Cortex-M33 core, TinyEngine NPU and advanced real-time control architecture into a single chip. These MCUs can maintain precise real-time control loops for up to four motors while the TinyEngine NPU runs adaptive control algorithms for load sensing and energy optimization. It has an integrated trigonometric math accelerator that performs calculations 10 times faster than coordinate rotation digital computer (CORDIC) implementations, delivering more precise, responsive motor-control performance. AM13E23x MCUs target IEC 61508 SIL 2 compliance.

Power Stage Requirements

Power levels in a humanoid robot can vary from 4kW to 10W, with most of the drives between 10W and 1.5kW depending on the drive location of the robot.

Drives typically function within the SELV voltage range, which is below 60V. As a result, components must be operational up to 60V. To reduce effects of potential noise in the system for the amplifiers, FETs, and gate drivers, components that operate up to 100V are preferable.

After defining the electrical specification for the drive, there are other design considerations such as the physical size available to implement the printed circuit board (PCB), temperature management and current sensing.

Small-size ICs and highly optimized power-density designs are crucial to achieving small-space design goals. High-power density leads to potential temperature limitations of the robot where the exterior of the robot is not allowed to be higher than 55°C. At 55°C, full-thickness skin burns occur in 30 seconds. Temperature management methods must not include additional cooling such as fans or liquids.

Balancing temperature management and space constraints requires optimizing power stage design for maximum power density, which directly impacts the power stage architecture. Higher switching frequencies enable smaller passive components and improved power density but present thermal challenges, particularly for MOSFETs. GaN FETs offer advantages in temperature-sensitive systems due to minimal switching losses compared to MOSFET technology, resulting in higher theoretical efficiency. However, increasing switching frequency requires MCU support for high-resolution PWM signaling to maintain precise control at elevated frequencies.

Table 3 lists key characteristics of MOSFET and GaN FET technologies for humanoid robot applications:

Table 3. MOSFET vs GaN FET Comparison for Motor Drives

Characteristic	MOSFET	GaN FET
Switching Speed	Moderate	High
Switching Losses	Higher	Lower
Power Efficiency	Good	Excellent
Power density	Medium	High
Typical Applications	General-purpose drives	High-frequency, space constrained applications

Humanoid robots are battery operated, typically using 48V nominal voltage with an operating range of approximately 39V to 54V depending on battery charge state. At the minimum operating voltage of 39V, a 4kW drive requires approximately 102 A_rms to deliver maximum power. This wide current range—from near 0A during low-torque operation to over 100A at peak power—demands precise current sensing across the full operating spectrum. Reducing FET dead time improves measurement linearity at low currents, enabling more accurate sensing throughout the operating range.

TI offers gate drivers, discrete GaN FETs, and integrated power stage solutions to address diverse power and space requirements across humanoid robot joints. Integrated solutions combine FETs, gate drivers, current sensing, and protection features to reduce design complexity and PCB footprint while minimizing EMI. These solutions enable engineers to quickly evaluate MOSFET and GaN FET technologies for specific joint locations and power levels.

Key TI devices include:

- DRV7167A: 100V integrated GaN half-bridge in a compact 7.00mm × 4.50mm package for BLDC Motor driver applications.
- DRV8378: Integrated three-phase power stage with 70V capability, integrated current sensing, and support for FOC, sinusoidal, or trapezoidal control.

Current Sensing

Current sensing is also an important design consideration when assessing power stage requirements and selecting appropriate current sensing parts to achieve desired performance levels.

TI offers both in-phase current sense and low-side current sense analog options, and design guidelines for how to implement systems efficiently. Typically, in-phase current sensing is used to always be able to the current and *increase* the precision of the measurement.

There are three different options to measure currents:

Table 4. Typical In-Phase Current Sensing Options for the In Phase Current Measurement

	Current Sense Amplifier	Delta Sigma Modulator	Hall Sensor
Performance	High/Medium	High	Medium
Size	Medium	Medium	Small

The current is typically possible up to 200A on all technologies and are limited due to thermal performance for the components.

- *Current sense amplifier*
- *Delta sigma modulator*
- *Hall sensor*
- *GaN Fet power stage*
- *Gate drivers*

Refer to the following technical content for more information:

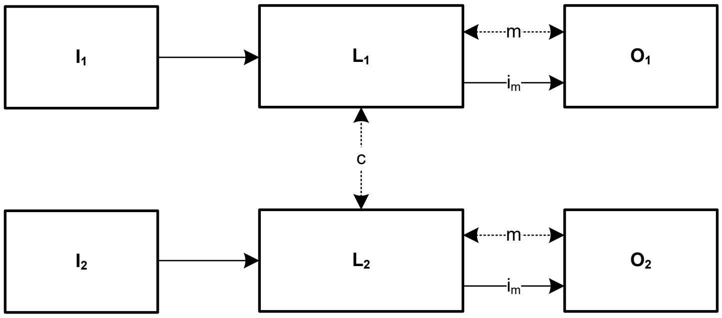
"High Resolution, Small Form Factor Phase Current Sense for 48V Robotics and Servo Drives"

"Selecting amplifiers for shunt-based current sensing in 3-phase motor drives"

Functional Safety

Standards bodies are expected to continue specifying safety requirements for humanoid, like ISO 25785-1, which is intended to address robot mobility. However, as requirements are defined, humanoid designers must conduct due diligence of the current system designs to minimize redesign efforts in the future. ISO13482, ISO10218, and ISO 3691-4 can elucidate future expectations.

When planning for future designs, selecting devices that simplify functional safety certifications is important. ISO13482, ISO10218 and ISO 3691-4 standards elucidate what to expect in the future for humanoids. Both Class C standards (ISO10218 and ISO3691-4) refer to ISO13849, stating that the system must be PLd. However, the ISO3691-4 leaves the architecture up to the implementer and the ISO10218 mandates a CAT3 architecture. Considering the worst-case scenario from these standards at least CAT3 PLd safety considerations need to be taken for a humanoid robot. The safety architecture shown in Figure 5 must be in place when implementing a CAT3 system.



Key *Illustration from IEC13849-1:2023 figure 10*

i_m	Interconnecting means
c	Cross Monitoring
I_1,I_2	Input device
L_1,L_2	Logic
m	Monitoring
O_1,O_2	Output device

Dashed lines represent reasonably practicable fault detection

Figure 5. Illustration from IEC13849-1:2015 Figure 10

TI offers many devices with *extensive safety documentation* to enable customers to build safety enabled systems.

Example System

In Figure 6, a block diagram shows a proposed solution with TI components to solve a 1.5kW system design, the following components can be used.

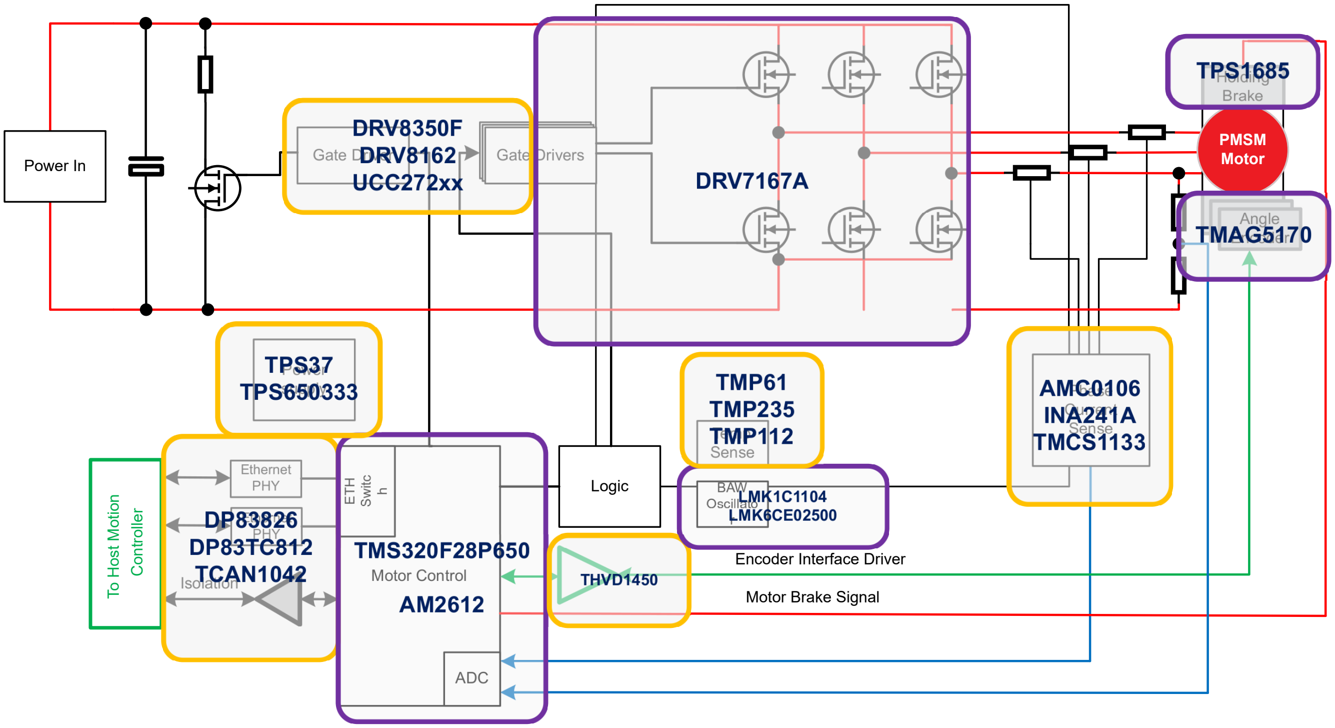


Figure 6. Motor Drive Solution Showing Potential Parts to Implement a System

Please refer to the following TI designs and EVM's to see system-level performance results for these devices:

- TIDA-010936
- TIDA-010956
- TIDA-010979

- LAUNCHXL-F28P65X
- DP83TC812-IND-SPE-EVM
- TIDA-060040

Summary

Designing humanoid robot drivers requires precision, flexibility, and innovation. TI offers a comprehensive portfolio of integrated circuits that empower engineers to meet diverse design specifications for building robots capable of seamlessly interacting with a robots environment. With a wide range of evaluation modules, reference designs, and safety-qualified devices, TI simplifies the development process—helping accelerate time-to-market and achieve functional safety certifications with confidence. Designers can partner with TI to bring their vision for smarter, faster, and safer robots to life.

Trademarks

All trademarks are the property of their respective owners.

IMPORTANT NOTICE AND DISCLAIMER

TI PROVIDES TECHNICAL AND RELIABILITY DATA (INCLUDING DATASHEETS), DESIGN RESOURCES (INCLUDING REFERENCE DESIGNS), APPLICATION OR OTHER DESIGN ADVICE, WEB TOOLS, SAFETY INFORMATION, AND OTHER RESOURCES “AS IS” AND WITH ALL FAULTS, AND DISCLAIMS ALL WARRANTIES, EXPRESS AND IMPLIED, INCLUDING WITHOUT LIMITATION ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE OR NON-INFRINGEMENT OF THIRD PARTY INTELLECTUAL PROPERTY RIGHTS.

These resources are intended for skilled developers designing with TI products. You are solely responsible for (1) selecting the appropriate TI products for your application, (2) designing, validating and testing your application, and (3) ensuring your application meets applicable standards, and any other safety, security, regulatory or other requirements.

These resources are subject to change without notice. TI grants you permission to use these resources only for development of an application that uses the TI products described in the resource. Other reproduction and display of these resources is prohibited. No license is granted to any other TI intellectual property right or to any third party intellectual property right. TI disclaims responsibility for, and you fully indemnify TI and its representatives against any claims, damages, costs, losses, and liabilities arising out of your use of these resources.

TI’s products are provided subject to TI’s Terms of Sale, TI’s General Quality Guidelines, or other applicable terms available either on ti.com or provided in conjunction with such TI products. TI’s provision of these resources does not expand or otherwise alter TI’s applicable warranties or warranty disclaimers for TI products. Unless TI explicitly designates a product as custom or customer-specified, TI products are standard, catalog, general purpose devices.

TI objects to and rejects any additional or different terms you may propose.

Copyright © 2026, Texas Instruments Incorporated

Last updated 10/2025