Application Brief

Motor Control in Humanoid Robots

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Introduction

Growing demand for more automation in manufacturing and service industries is driving development of humanoid robots. Humanoids have become more complex and precise with a higher number of degrees of freedom (DOF) and fast response time (in milliseconds) to the surrounding environment to better mimic human movement. Figure 1 shows typical motor and motion functions of humanoid robots.

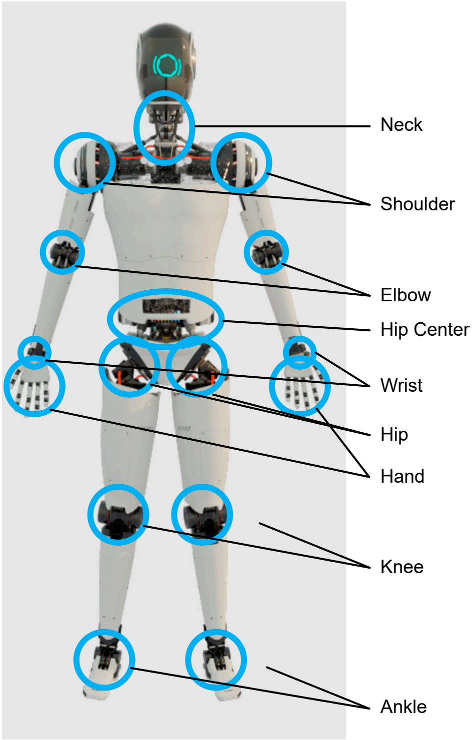


Figure 1. Showing Location Adding to DOF for the Humanoid Robot

Having a higher DOF means more electric motor drives are needed in humanoid robots. The location of the drive in the design of a robot defines different requirements of the drive. Some of the key specifications are:

- Communication interface architecture
- Position sensing
- Motor type
- Motor control algorithms
- Power stage requirements
- Electronic circuit size
- Functional safety considerations

Currently, there are no standards that define the functional safety requirements of humanoid robots, though there are standards for cobots and industrial robots. Expectations are that in the future standards bodies are going to specify safety requirements for humanoid robots as demand continues to grow. Until safety 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.

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 methods used are daisy chained communication and linear bus topology, as shown in Figure 2 and Figure 3.

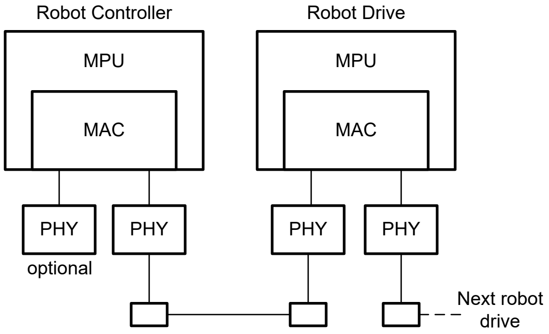


Figure 2. Daisy Chained Communication

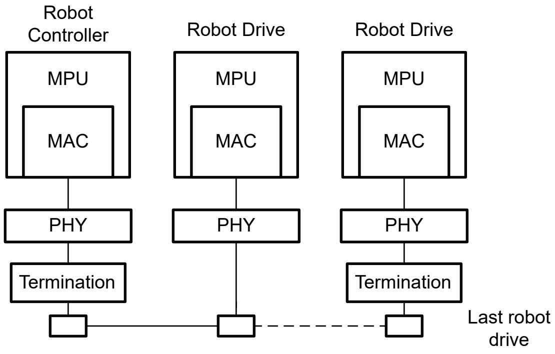


Figure 3. Linear Bus Topology

After selecting the topology, to achieve adequate response time of the drive consider bandwidth, timing and latency requirements. 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, 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. 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 the 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 motion of a humanoid robot must receive motor position data to define the path planning. The position data enables the controlled movement of the humanoid robot. 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. A variety of rotor position sensors are used, depending on the precision required for the motor. Here are some of the most commonly used encoders:

- 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 interface 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

Several encoders can be needed for one motor, depending on how the motor and the gearing of the motor is implemented. TI offers both the analog and the processors IC’s 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

Because humanoid robots are battery powered, motor drives are designed to maximize efficiency to extend operational time-frame of the robot.

When high power levels are used, humanoid robots can incorporate motors like PMSM motors. Brushed DC motors can be used in some low power cases such as hand and finger control. However, current design trends indicate that all motors are going to be brushless in the future.

There are two options for PMSM motors: trapezoidal or sinusoidal winding. This choice of winding and control algorithm effect how precise the motor is controlled.

Another key topic of the motor design is option to switch the FET faster, which leads to new design options that improve the torque per weight of the motor.

Motor Control Algorithms

After selecting a motor type, users 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.

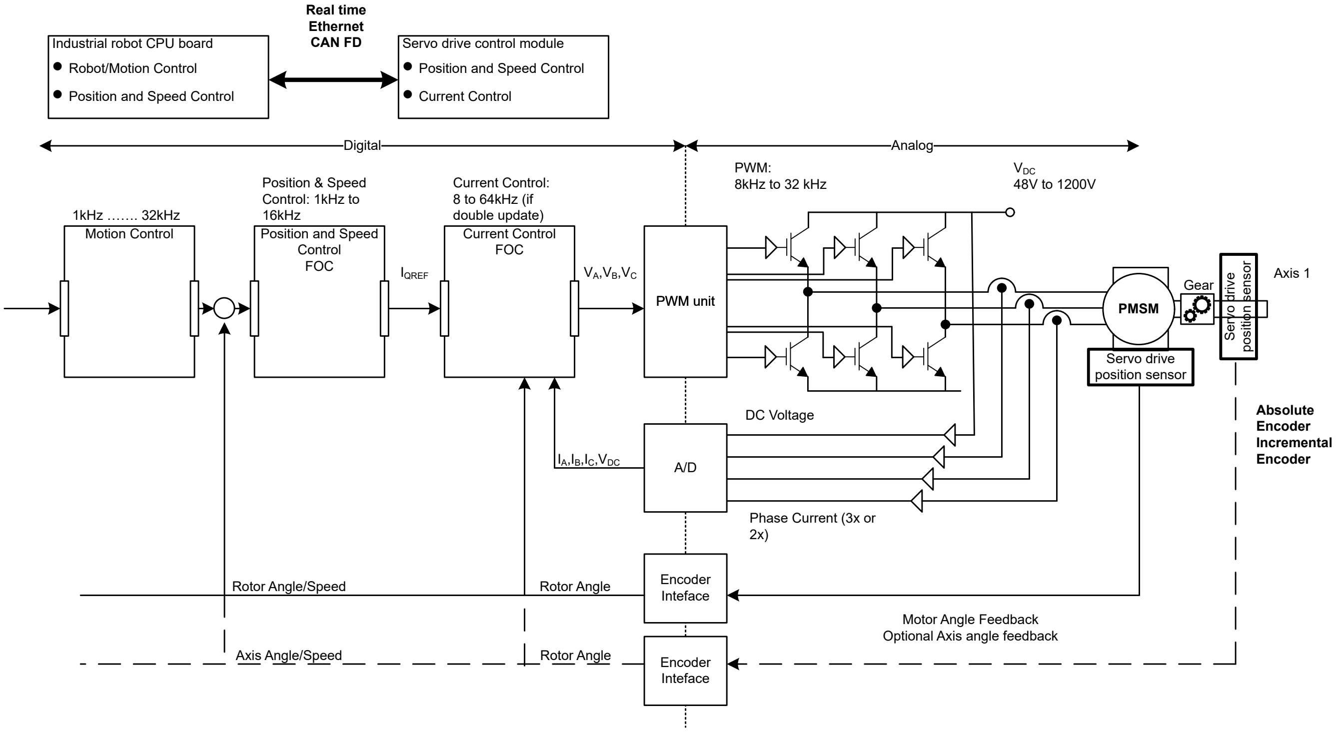


Figure 4. Real-Time Communication Timing Needs for Robot Control

Using Figure 4 as a general template, Table 1 lists the required peripherals and performance when selecting an algorithm FOC or block commutation.

Table 1. 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, 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.

Power Stage Requirements

Depending on the drive location of the robot, the power level varies between 4kW to 10W, with the majority of the drives between 10W and 1.5kW.

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 are operation up to 100V are preferable. After defining the electrical specification for the drive, there are other design considerations.

The physical size available to implement the printed circuit board (PCB) is another design consideration. Small-size IC's and highly optimized power-density designs are crucial to achieve 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.

The balance of temperate management and space results in balancing the power stage in relation to watt per size, which impacts the power stage architecture. One issue that can arise is if the power stage needs to work at higher frequencies. This issue typically is present in MosFETs, however new technologies, such as the GaN FET, also improve switching performance, compared to MosFET-based systems. For temperature sensitive systems, the GaN FET has a higher theoretical efficiency, as the switching losses are minimal in comparison to MosFET technology. Frequency increase leads to the need for additional functions in the MCU to support the required signaling necessary to achieve higher frequency switching at high-enough resolutions.

TI MosFET gate drivers enable customers to switch the MosFET at the highest possible speed and TI Low voltage GaN FETs enable customers to quickly compare and consider the best FET type per location in the robot.

High-performance MosFETs or GaN FETs are needed to implement the drive and therefore increase motor efficiency. Sophisticated algorithms help to reduce switching needs and losses of the motors FETs.

Humanoid robots are battery operated, with typically 48V, or approximately between 39V to 54V, pending the battery charge state. The used voltage depends on at the level the battery charge is set as the minimum used. Before it mentioned that the maximum power needed for a drive was 4kW at 39V it can be seen that the robot drive needs to maximum work with approximately 102Arms currents to provide the needed power, but also considering a precise measurement around 0A, here decreasing the dead time for the FET also benefits the linearity of the current measurement around 0A making the measurement more precise at low currents.

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 *increased* the precision of the measurement. There are three different options to measure currents:

Table 2. Typical In-Phase Current Sensing Options for the In Phase Current Measurement

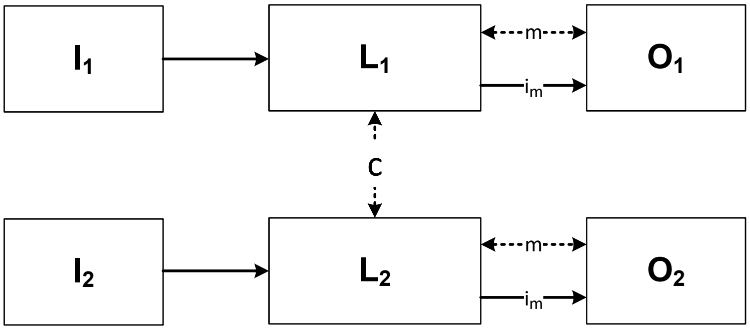
	Current sense amplifier	Delta sigma modulator	Hall sensor
Precision	Medium	High	Low
Current level	50A	50A	100A
PCB difficulty	Medium	Medium	Low

For current sense amplifier and delta sigma modulator the current level usage of these technologies move slowly to around 100A due to improved components.

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

Functional Safety

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 of the 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.

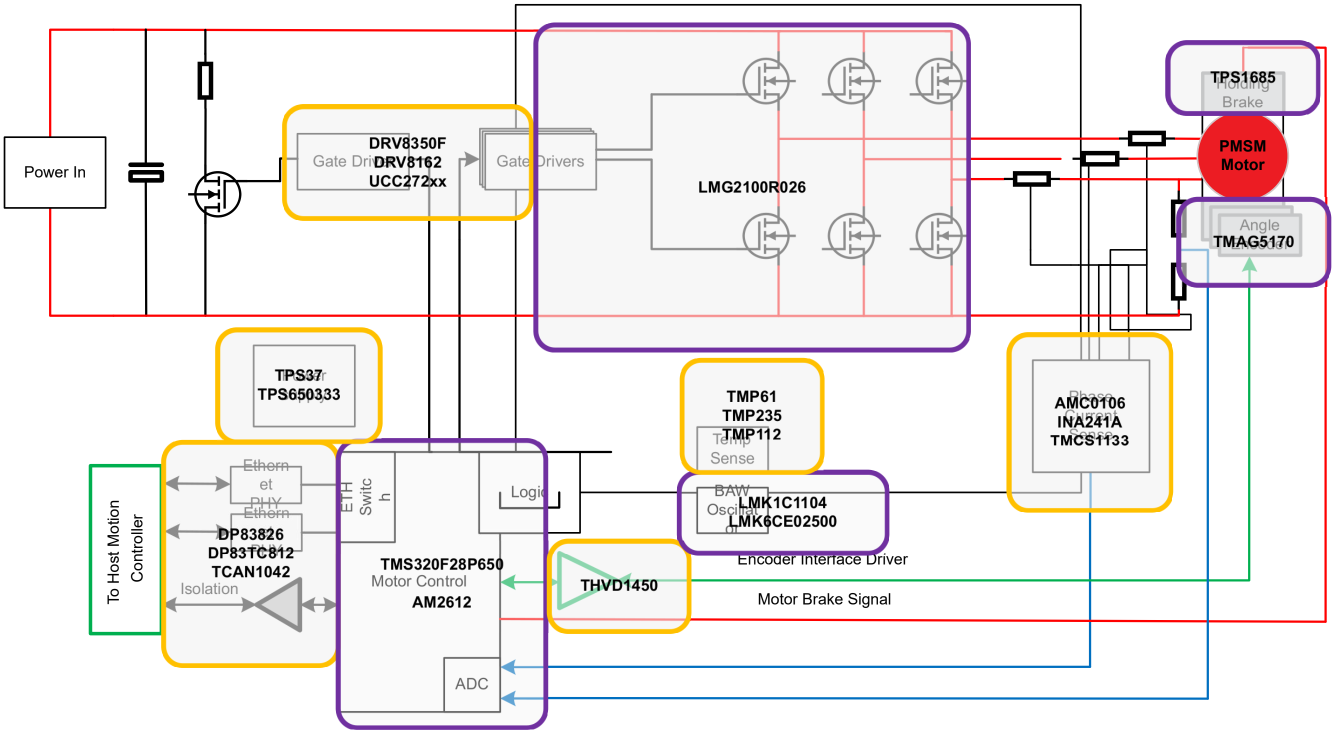


Figure 6. Motor Drive Solution Showing Potential Parts to Implement a System

For further part information, reference the following TI designs and EVM's to see system-level performance results:

- TIDA-010936
- TIDA-010956
- LAUNCHXL-F28P65X
- DP83TC812-IND-SPE-EVM
- TIDA-060040

Summary

Designing humanoid robot drivers requires precision, flexibility, and innovation. Texas Instruments 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. Partner with TI to bring your vision for smarter, faster, and safer robots to life.

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