

# Enabling closed-loop motor control in humanoid robots with torque and force sensing

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# At a glance

- 1 Understanding torque in robotic systems.** Torque is a vital real-time control variable for precise movement and operational stability of humanoid robots.
- 2 How torque and force sensors work.** Resistive strain gauges in a Wheatstone bridge configuration detect material deformation, converting mechanical strain into small electrical signals.
- 3 Torque and force sensing across humanoid robots.** Multiaxis torque and force sensors in humanoid robots enable precise grip control, load handling, balance maintenance and safe environmental interaction.
- 4 Signal-chain design considerations for torque and force sensing.** How to select between simultaneous-sampling analog-to-digital converters (ADCs) and integrated conditioners for humanoid robot designs.



Humanoid robots need precise, real-time awareness of the forces acting upon them.

## Introduction

In terms of capabilities, mechanical structures and electrical complexity, humanoid robot development is progressing quickly. To achieve human-like motion, such as grasping delicate objects, maintaining balance while standing or walking, and interacting safely in any given environment, the systems inside a humanoid robot must have precise, real-time awareness of the forces acting upon it.

In other words, from dexterous hands to load-bearing hips and knees, torque and force sensing play a fundamental role in enabling safe interaction and reliable performance; smoother, refined, controlled motion; and accurate, real-time motor feedback. When combined with properly designed control algorithms, diagnostics and safety limits, torque and force sensing can help detect overload conditions and reduce the duration or severity of overstress events.

## Understanding torque in robotic systems

Every movement, from lifting an object to stabilization while walking, depends on accurate and precise torque measurements. When a humanoid robot picks up an object, the torque at each joint changes dynamically based on the object's weight and position with respect to the body, and these changes occur in real time. The control system must detect and respond quickly – and accurately make adjustments – in order to maintain stability and prevent damage to itself.

In robots, torque is not just a mechanical concept; it is an important real-time control variable contributing information into the system.

Torque sensing is fundamental for translating physical interaction into electrical data, enabling the internal controllers to maintain stability on the robot. This allows the system to measure the amount of force being applied to the body, and whether that level of force is appropriate for the task. Out-of-bound measurements may indicate an issue such as the robot being jammed or stuck, having picked up something too heavy, or experiencing a malfunction because of a damaged component.

## How torque and force sensors work

Most torque and force sensors used in humanoid robot systems rely on resistive strain gauges, typically known as foil strain gauges. These gauges are typically arranged in a Wheatstone bridge configuration and bonded to a structural element that is expected to strain under load. When applying torque or force to the structure, the material experiences a strain – either stretching or compressing slightly – that causes a corresponding change in electrical resistance. Figure 1 shows a typical signal-chain configuration of a Wheatstone bridge and foil strain gauge.

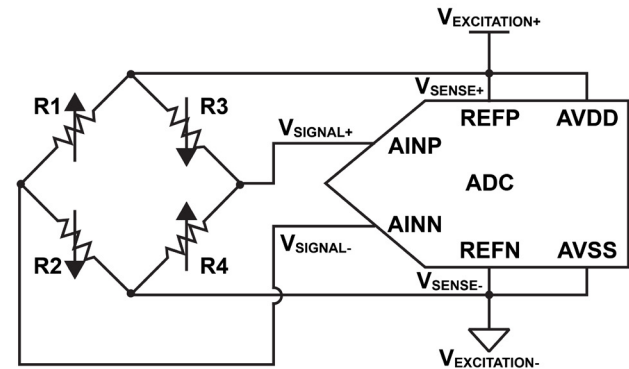


**Figure 1.** Single-channel ratiometric foil strain gauge configuration with an ADC.

The resistance changes are very small and appear as a small differential bridge-output voltage, typically expressed relative to the excitation voltage in millivolts per volt. Depending on the bridge sensitivity, excitation voltage and applied load, the ADC input may range from microvolts at small strains to millivolts or tens of millivolts near full scale. Accurately capturing these changes requires a high-performance analog front end that amplifies and digitizes the signal without introducing significant noise or errors into the measurement.

The sensitivity of a foil strain gauge is defined by its gauge factor, which relates the relative change in resistance or voltage across the gauge to the applied mechanical strain. It is then possible to measure even slight deformations from strain of the material with high precision, assuming proper design of the analog signal chain to support foil strain gauge measurements. For humanoid robot systems, the precision required of torque and force sensors is significant, as even small measurement errors can lead to incorrect force estimation, degrading control performance or compromising the safety of the humanoid robot and humans in the vicinity.

## Torque sensing in closed-loop real-time motor control

Torque sensing becomes most valuable when integrated into a closed-loop control system. In humanoid robots, this loop continuously measures joint torque or force, digitizes the data through an analog front end, and transmits the data over several industry-standard communication protocols, including EtherCAT, SPI, and CAN, to either a Texas Instruments (TI) C2000™ or AM261x Arm®-based real-time microcontroller or an Arm® Cortex ®-M0+ MCU.

This feedback loop consists of four types of devices: the sensor, the data converter, the controller and the motor driver. The sensor detects mechanical strain or stress and converts it to an analog signal. The ADC or analog front end converts the signal to a digital value. The controller interprets the data and responds by adjusting the motor driver based on the control algorithm.

With this closed-loop control architecture, the system can:

- Regulate the motor current to achieve precise, fluid motion control.
- Enable safer behavior when the robot interacts with people or objects.
- Detect unexpected forces, such as a collision or overload condition.
- Help improve energy efficiency by reducing unnecessary actuation force.

Such an approach allows humanoid robots to move in a way that appears more natural, rather than rigid or jerky. For example, when grasping a fragile object, the control system can dynamically adjust the grip force of the hands to avoid crushing the object – a capability commonly referred to as tactile sensing. When the resistance exceeds a predefined level, the system can respond by reducing applied force rather than continuing to increase it, which could damage the object. Without torque feedback, reliably and consistently achieving these behaviors is very difficult and would likely require a variety of additional sensors.

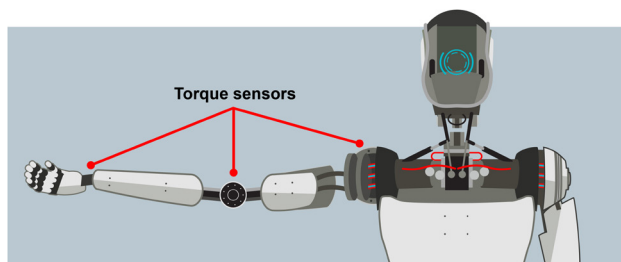


**Figure 2.** Arm and wrist joints in which designers could place torque sensors in a humanoid robot.

## Torque and force sensing across humanoid robots

These actions require very high sensitivity and low latency in order to pick up small or delicate items.

When distributed throughout a humanoid robot, torque and force sensors support a wide range of functions. In hands and fingers, force sensors enable precise grip control and object handling.

In the arms, particularly at the elbows and shoulders, torque sensing supports both smooth articulation and safe load handling. These joints often experience a wide range of dynamic forces as the robot picks up, holds, and places items. In the hips and knees, sensors play an important role in maintaining balance and evenly supporting the weight of the humanoid robot, which can be as much as 100kg. These sensor measurements are essential for walking, climbing and adapting to uneven terrain. In humanoid robot feet, force sensing helps measure ground contact forces, enabling stability control and posture optimization. Figure 3 shows specific joint locations for the placement of torque and force sensors across a humanoid robot.

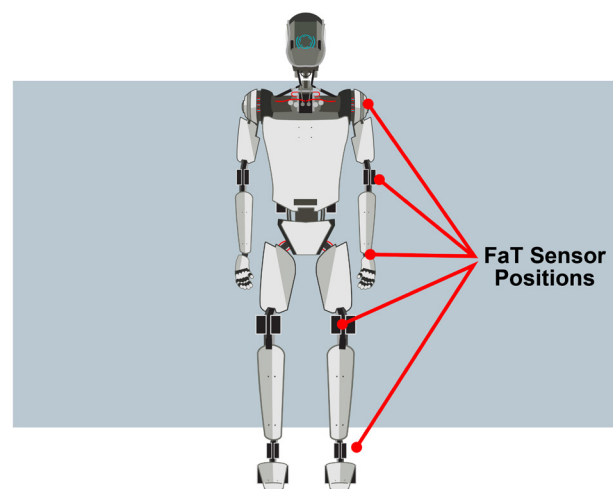


**Figure 3.** Arm and wrist joints in which designers could place torque sensors in a humanoid robot.

Many of these applications require multiaxis sensing that resolves forces and moments across multiple axes: typically  $F_x$ ,  $F_y$ ,  $F_z$ ,  $M_x$ ,  $M_y$  and  $M_z$ . These measurements are often implemented using multiple foil strain gauges or bridge elements within a calibrated multiaxis torque and force sensor, rather than six separate torque and force

sensors per joint. Such an implementation enables control systems to fully characterize how a humanoid robot is interacting with its surroundings and respond accordingly.

Figure 4 shows a torque and force sensing module and the different vectors of torque and force that could be applied to the respective sensors. FUTEK is one example of a force and torque sensing manufacturer with expertise in load cells, torque sensors, multiaxis sensing and supporting measurement electronics, including experience integrating TI components into application-level sensing systems.

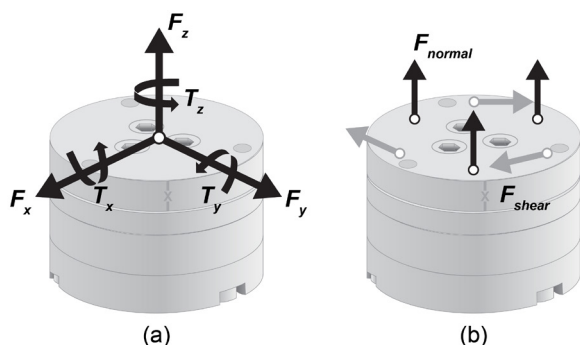


**Figure 4.** Torque and force module indicating force (b) and torque (a) vectors.

### Signal-chain design considerations for torque and force sensing

Designing a signal chain for torque and force sensing involves several trade-offs, including accuracy, channel count, channel density, channel synchronization and system complexity.

For multiaxis or multijoint systems, simultaneous sampling ADCs such as TI's ADS131M06 or ADS131M08 capture multiple signals at the same time, ensuring synchronized measurements in a 4mm-by-4mm quad flat no-lead (QFN) package. This architecture is especially important when calculating forces across multiple axes, where channel sampling mismatches can introduce errors that may result in uneven motion. For ratiometric bridge measurements, the ADC reference should track the actual bridge excitation, often by sensing the bridge excitation voltage at the sensor. Such an approach helps reject excitation voltage drift and common reference noise, while still requiring careful management of input and reference filtering, lead resistance, excitation drive, and layout.

For simpler applications, integrated signal conditioners combine excitation, amplification, digitization and nonlinear compensation. Equipped to handle such measurements, TI's PGA302 and PGA305 can reduce design complexity and calibration effort, but are typically limited to single-channel applications and occupy a larger footprint.

Another approach is to use highly integrated ADCs with a built-in programmable gain amplifier, voltage reference output and excitation current sources. Devices such as TI's ADS122S14 and ADS122C14 reduce overall bill of materials and simplify layout, while still providing high-resolution measurements. The trade-off is that these solutions use multiplexed inputs, meaning that channels are not sampled simultaneously, which introduces latency across channel measurements. The ADS122S14 and ADS122C14 are available in two packages: a 3mm-by-3mm QFN and a 1.9mm-by-2.0mm wafer chip-scale package. Figure 5 shows how the ADS122S14 interfaces with foil strain gauges for torque and force monitoring.

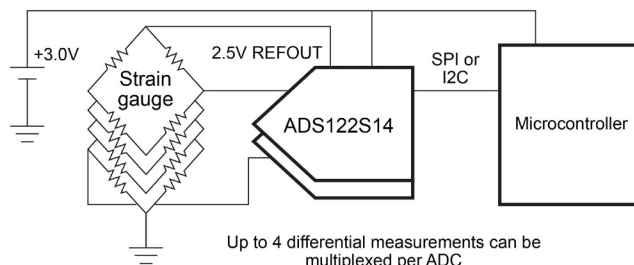


**Figure 5.** The ADS122S14 ADC enables an internal reference to drive as many as four foil strain gauges.

The choice for a system depends on its specific requirements, including the number of sensing axes, required precision and system architecture. Table 1 is an overview of relevant TI devices and specifications.

## Ratiometric measurement techniques

Ratiometric measurement is a technique in which the same reference voltage is used for both the excitation of a sensor and the analog-to-digital conversion of its output, effectively cancelling errors common to both signals. This method of measurement is particularly useful in foil strain gauge bridge applications because the bridge output is proportional to the excitation voltage. Using the sensed bridge excitation as the ADC reference makes it possible to reduce the excitation voltage drift and common reference noise in the conversion result. Sensor temperature effects, bridge self-heating and mechanical drift still require appropriate sensor design, calibration and compensation. TI's PGA305 is an example of a device that enables ratiometric measurements, as shown in Figure 6.

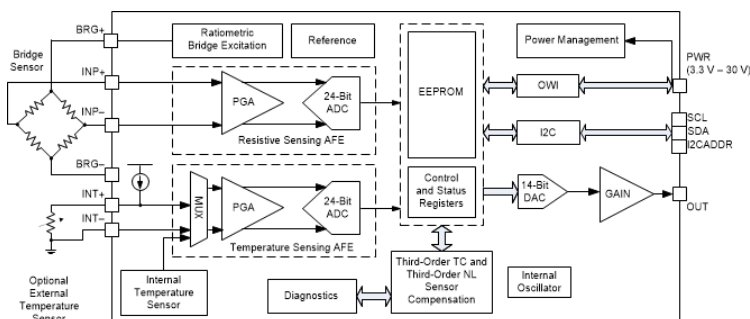


**Figure 6.** Simplified block diagram of the PGA305, with a single foil strain gauge and temperature sensor.

Some TI devices support ratiometric measurement techniques. Beyond individual components, TI offers signal-chain reference designs that support end-to-end solutions from the sensor to the controller. The [48V/16A Small Form Factor Three-Phase GaN Inverter Reference Design for Integrated Motor Drives](#) is a motor-control implementation example.

## Conclusion

As systems in all types of robots continue to advance, the importance of precise, reliable torque and force sensing grows accordingly. These measurements form the basis of closed-loop control, enabling robots to move with greater accuracy, adapt to their environment, and interact more safely with the world around them.

Combining high-quality sensing elements with advanced precision analog signal chains enables designers to unlock new levels of performance in humanoid robot systems. The result is better measurement and the ability to design more capable, responsive and intelligent machines.

## Additional resources

- Check out our [engineer's guide to humanoid robotics resources page](#).
- [Humanoid robots design resources page](#)

## About the author



Kyle R. Stone is a Product Marketing Manager at Texas Instruments, where he focuses on precision analog-to-digital converters (ADCs). He has extensive experience working with a broad range of sensor technologies and signal chain architectures, including

current sensors, magnetic sensors, temperature sensors, and ultra-precision ADCs. His work centers on enabling accurate analog-to-digital conversion for applications requiring precise measurement, monitoring, and control across diverse sensor interfaces.

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