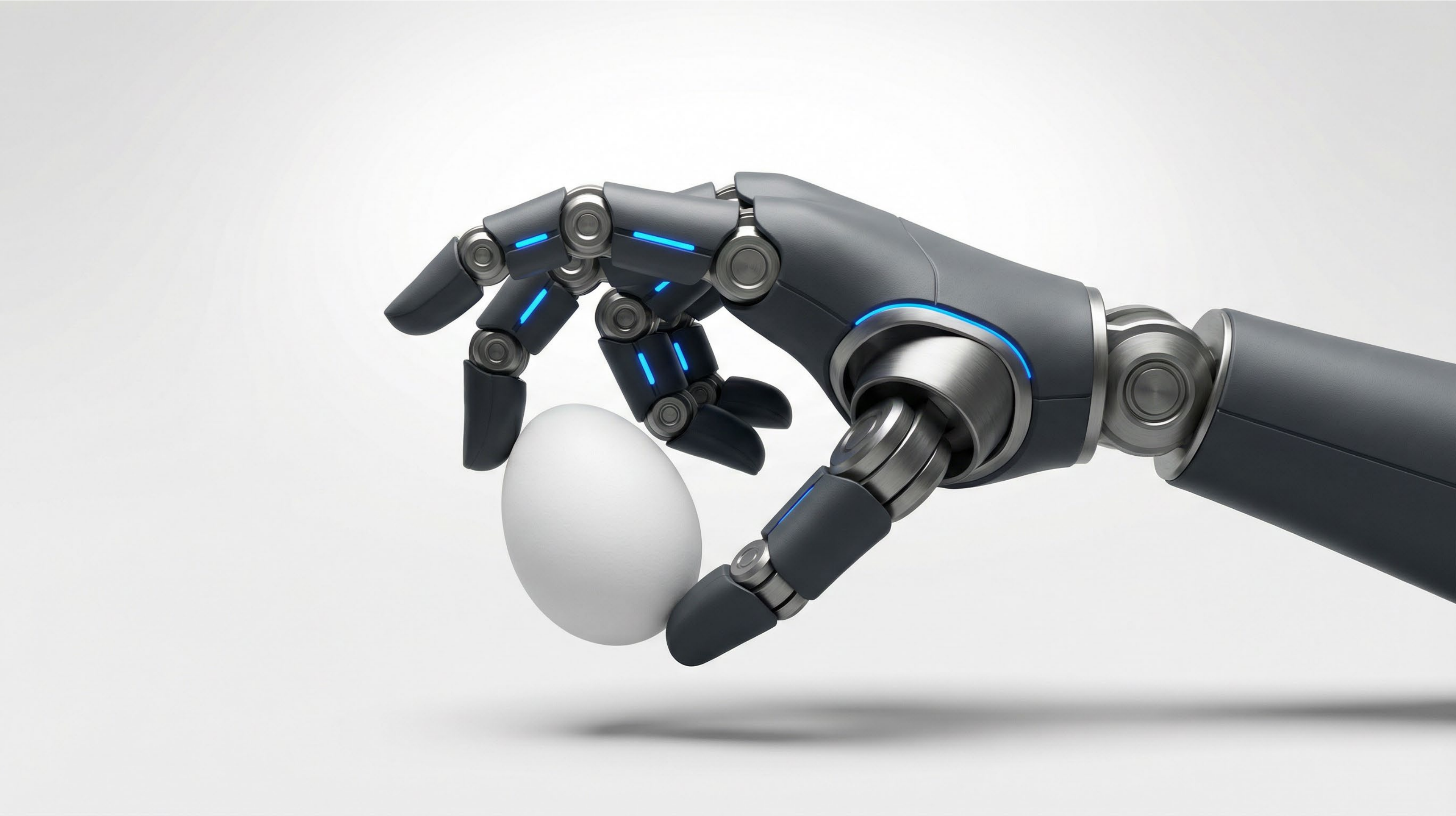
Advanced Joint Architectures for Next-Generation Robotics



Abstract

This white paper explores the intricate world of robotic joint architecture, from the various types of robots and their joint complexities to the crucial role of integrated circuits (ICs) in controlling and driving these joints. We will delve into the key components of a robotic joint, including motor commutation sensors, joint position sensors, motor drivers, and current sensors, and discuss the trade-offs and considerations for each. We will also examine the latest advancements in these technologies and how they are enabling the development of more sophisticated and capable robots.

Introduction

The field of robotics is rapidly evolving, with new and more advanced robots being developed every day. From collaborative robots (co-bots) working alongside humans to complex humanoid robots capable of a wide range of movements, the design of a robot's joints is critical to its performance. This paper will provide a comprehensive overview of the key components that make up a robotic joint and the technologies that are driving the future of robotics.

Contents

Robotic Joint Architecture

There are many different types of robot architectures, each with its own unique set of challenges and requirements. Co-bots and robotic arms, for example, typically have six joints, while humanoid robots can have 24 or more. The simplest humanoid architecture might have four joints per arm and five per leg, while more complex architectures can integrate hip, torso, head, and hand movements.

At the heart of each robotic joint is a complex system of ICs that control and drive the joint's movement. A typical robotic joint block diagram includes the following components:

Motor Commutation Sensor: Senses the rotor position of the motor.

Joint Position Sensor: Senses the position of the joint.

Motor Driver: Drives the motor.

Motor Phase Current Sensors: Sense the current in the motor phases.

Power Supply: Provides power to the system.

Joint Brake Driver: Controls the joint brake.

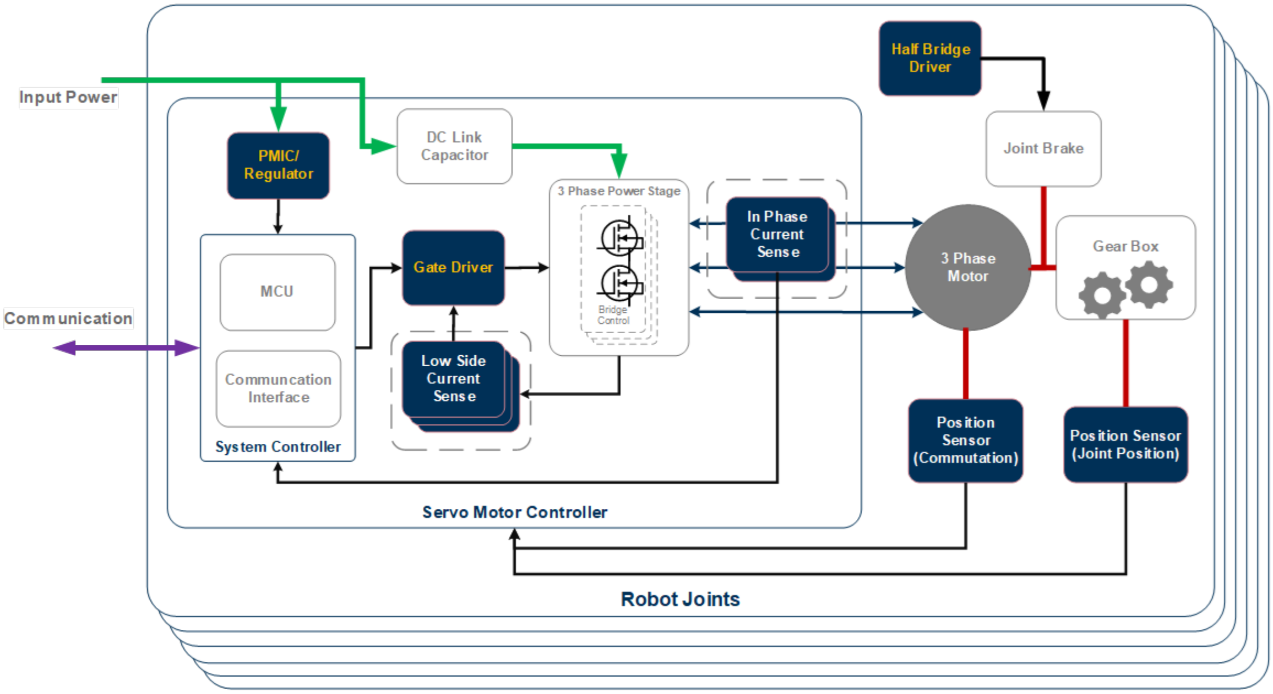


Figure 1. Robotic joint block diagram

This block diagram illustrates the basic architecture of a robotic joint, including the motor commutation sensor, joint position sensor, motor driver, motor phase current sensors, power supply, and joint brake driver.

Motor Commutation Sensor

The motor commutation sensor is a critical component of the field-oriented control (FOC) loop, which is used to control the speed and torque of the motor. The sensor's primary function is to sense the rotor position of the motor, which is then used to calculate the electrical angle of the motor. This is done by multiplying the angle by the number of pole pairs in the motor. [Better transition here]

Size Requirements

The physical integration of this sensor heavily influences its design. Motor commutation sensors are typically packaged with the motor and driver assembly, so smaller implementations are always preferred. For motors with a shaft, the sensor can be placed on one side of the shaft, with the other side having a mechanical connection to the gear box or joint. For hollow shaft motors, which are used to route cables through the middle of the motor, the sensing requires side shaft or through-shaft sensing. This can be achieved with magnetic or inductive sensors.

Output Requirements

The output protocol of the motor commutation sensor must be fast enough to have a response within the FOC control update rate, which is typically around 20kHz. Diagnostics are also a nice-to-have feature for safety and for comparison with the joint sensor. While there are many different output types, two common output types among many devices are SPI or Analog Outputs.

The SPI protocol, requiring four pins, can be set for high speed (10MHz) and can provide additional status information on the IC itself. In addition, multiple devices can operate on a single bus. However, at high speeds, poor board layout and noise can corrupt the signal. This can be caught with safety diagnostics in the protocol. Some devices also allow the sampling time for the angle to be set to ensure that it is aligned with the current measurements.

Analog SIN/COS output can be single-ended or differential. The output of the device two orthogonal signals that represent the trigonometric functions of the sensed angle. The differential output mitigates the effect of common-mode noise on the signal path. The sampling speed is determined by the bandwidth of the sensor and the sampling speed of an external ADC. The configuration of the microcontroller can determine how to sample efficiently. This may also require signal compensation/calibration. This allows the customer flexibility in how they want to compensate the signal. For FOC control, the sin/cos of the signal are naturally present, which reduces the need for trigonometric functions to be implemented, reducing computation time.

Resolution vs. Accuracy

Beyond speed, it's crucial to distinguish between resolution and accuracy, two often-confused parameters. Higher resolution does not mean higher accuracy. High accuracy increases system efficiency due to the use of position in the transformation of the phase currents into the axis currents used in FOC control. An error in this results in a current ripple. Low resolution can have a similar effect, as the rotor might be in an unknown state between different measurements, but interpolation can be used if the accuracy is high. If you have low accuracy, you must use external compensation or look-up tables to account for the error. In terms of resolution from a sensor transducer level, Hall-based magnetic sensing has high accuracy but lower resolution. TMR-based magnetic sensing has lower noise and therefore a higher resolution, and inductive position sensors can achieve the highest resolution comparatively. The accuracy of each sensor depends on the internal/external signal processing used for each sensing type. For all sensing types, there are a variety of offerings with different levels of processing to achieve the required accuracy.

Stray Field Immunity

Motor commutation sensors are often tightly integrated near the motor and on a board with high-current traces for motor power. Immunity to stray fields generated by the motor or the current can provide a more robust solution. Immunity can be achieved by choosing the right sensor type. Optical encoders and inductive sensors are naturally stray-field-immune due to their sensing type. Otherwise, smart processing and layout of magnetic sensors can employ differential sensing types to be immune to common-mode stray magnetic fields.

Joint Position Sensor

The joint position sensor is another critical component of the robotic joint. It is used to sense the position of the joint, which is then used by the robot's control system to plan and execute movements.

Stray Field Immunity

Like the commutation sensor, the joint position sensor's placement dictates its need for stray field immunity. If located near the motor assembly, it faces the same challenges from motor-generated fields. However, if placed further down the kinematic chain, such as after a gearbox, it becomes susceptible to unpredictable external magnetic fields. For example, a humanoid robot handling a power tool with a large magnet could experience sensor interference. In such unpredictable environments, the inherent immunity of optical or inductive sensors provides a significant advantage.

Small Joints

For the smallest joints on a robotic system, there might only be room for one sensor to handle both motor commutation and joint position. Inductive technology has a high resolution, which can be beneficial when having to account for any gear reduction and motor pole pairs, but it has a limit to the implementation size. Magnetic current sensors are able to be integrated in very small spaces, making them perfect for the most tightly constrained applications. There will always be a trade-off in the sensor cost vs. the performance needed for the joints.

Large Joints

For large joints, the resolution of the sensor directly relates to the repeatability of the movements. If the resolution of the system was 0.1 degrees and the arm was 80mm long, then your end position might only have a resolution of 8mm, disregarding other kinematic constraints.

The joint position sensor is part of a control loop that is updated at a slower frequency than the commutation sensors. Typically, the position control loop might run at about 1kHz-5kHz. Therefore, standard digital communication protocols can easily meet the data transfer needs. SPI is a standard protocol, but if the sensor is farther away from the controller, a high-speed differential communication type might be preferred.

Motor Driver

The main goal of the motor driver is to efficiently and safely switch the FETs to drive the motor. Safety is provided by ensuring that both FETs of a half-bridge don’t turn on at the same time, creating a shoot-through current, and by withstanding transient voltages that may appear on the three phases due to the inductance of the motor. Efficiency comes from a trade-off of the FET switching frequency and turn-on/off times. A faster switching frequency creates smoother motion but results in higher switching losses. Fast turn-on/off times reduce switching losses but can result in poor EMI performance. Well-controlled and configurable turn-on/off times allow the designer to find their perfect balance of all these attributes.

The operating voltage of the system is a primary driver of the motor driver's architecture. The power density of these systems is a key performance parameter. The best performance will be achieved with higher voltage batteries. However, there is a risk of harm to humans and animals in systems above 60V. Therefore, systems with 48V batteries have become common due to their intersection of safety and power density.

To maximize power density in these systems, designers must choose between a highly integrated three-phase driver and a more distributed architecture using three separate half-bridge drivers. Power density is also achieved through small implementation size. 48V-capable motor drivers eliminate the need to step down the voltage level with external regulators/converters. Depending on the implementation size, it might be better to have all three gate drivers integrated into a single package with diagnostics. This is the smallest implementation size. Opposingly, three separate half-bridges can distribute the design across the board and potentially be more space optimized. It also allows the driver to be closer to each FET, reducing switching losses due to parasitic inductance.

When applications demand even greater power, high-voltage systems are required, which introduces the critical need for isolation. Typically, this is provided through isolated gate drivers. The standard approach is to have an IC that has two isolated sides, which have optical coupling of data lines. An external transformer provides isolated power between the two sides. This can be a bulky solution. Allegro provides an innovative technology where the external transformer is integrated into the package. PWM signal and power are both transmitted through the transformer, allowing for a space-optimized solution and reduced design time needed for the external DCDC matching. The integrated components also reduce the parasitic inductance and capacitance of the system, greatly increasing system efficiency.

Current Sensing

Current sensing is an integral part of joint control. It is required for efficient commutation using the FOC algorithm. It is also used for joint torque estimation. There are two competing technologies commonly used for robot joints in low-voltage systems: magnetic-based sensing and shunt resistor sensing, which can be implemented in two main locations.

Low Side

One common placement is low-side sensing, where the sensor measures current on the low-side path to ground. This legacy approach has the advantage of operating near zero volts, avoiding the need for high common-mode voltage rejection. The signal is only available when the low-side FET of the half-bridge is conducting. The system must have good timing to ensure the signal is measured properly. It also limits high and low duty cycle operation based on the bandwidth of the current sense amplifiers.

When using a shunt resistor for low-side sensing, the resistor's value creates a trade-off between signal strength and power loss. While many motor drivers integrate current sense amplifiers (CSAs) to improve matching, the inherent power loss remains. Magnetic sensing can also work in this application, but the lower typical bandwidth of these sensors makes them less applicable. Magnetic sensing shines for in-phase applications.

In Phase

A more advanced and flexible approach is in-phase sensing, where current is measured directly on each motor phase. This allows the current to be measured at any time, regardless of the switching state, which relaxes the bandwidth requirements for the sensor. However, using a shunt resistor for in-phase sensing is complex and expensive, as it requires specialized amplifiers with high common-mode rejection and often full isolation. This is where magnetic current sensors truly shine. Magnetic current sensors are inherently isolated from the voltage. They are offered in a variety of bandwidths to fit system requirements. The integrated conductor current sensors have a low-resistance path, which reduces the system losses compared to the shunt-based method. For high-voltage/high-current systems, field current sensors are fully isolated from the system voltage. The cost vs. accuracy of the implementation is dependent on whether C-core, U-core, or coreless technology is used.

Power Supply

As stated earlier, 48V battery-based systems are the most common. Voltage conversion is still required to power sensors, the microcontroller, and other circuitry. 48V-capable regulators and PMICs allow for power conversion and monitoring of power draw to turn the system off if there are fault states in the normal circuitry.

Joint Brake

Some systems have an electromagnetically controlled brake on the joints. This ensures no movement when the robot is powered off or if it needs to go into a fault state. These brakes are often powered by half-bridges that can energize or de-energize when needed. This is an important but often overlooked function. A small, robust solution size is key to allowing this to be easily integrated into the system.

Conclusion

The design of a robotic joint is a complex process that requires careful consideration of a wide range of factors. From the choice of sensors and motor drivers to the overall architecture of the system, every decision has an impact on the robot's performance, efficiency, and safety. As the field of robotics continues to advance, so too will the technologies that power these amazing machines. By understanding the trade-offs and considerations for each component of the robotic joint, engineers can design and build robots that are more capable, reliable, and efficient than ever before.

Find out more.
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