# Precision signal-conditioning solutions for motor-control position feedback

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## Introduction

Electric motors are an ever-increasing part of our lives, not only in automated factories and electric vehicles, but inside homes as well—in living rooms and even our children's favorite toys. Picture an automotive factory where robots pick up heavy parts or engines and place them exactly into car assemblies, requiring precise motor control as the robots employ variable amounts of speed and torque. These types of applications are driving advances in electronic technology that enable precision control during real-time operations. As intelligent motor drivers, high-end power supplies and signal processing work together to deliver precise speed and torque,[1] position-sensing feedback is a key subsystem.

More complex and precise motor-control systems require more advanced position-feedback implementations. For example, a modern standard-robot configuration can be six motors per axis, with resolver feedback required for each motor.

## Position-sensing technologies

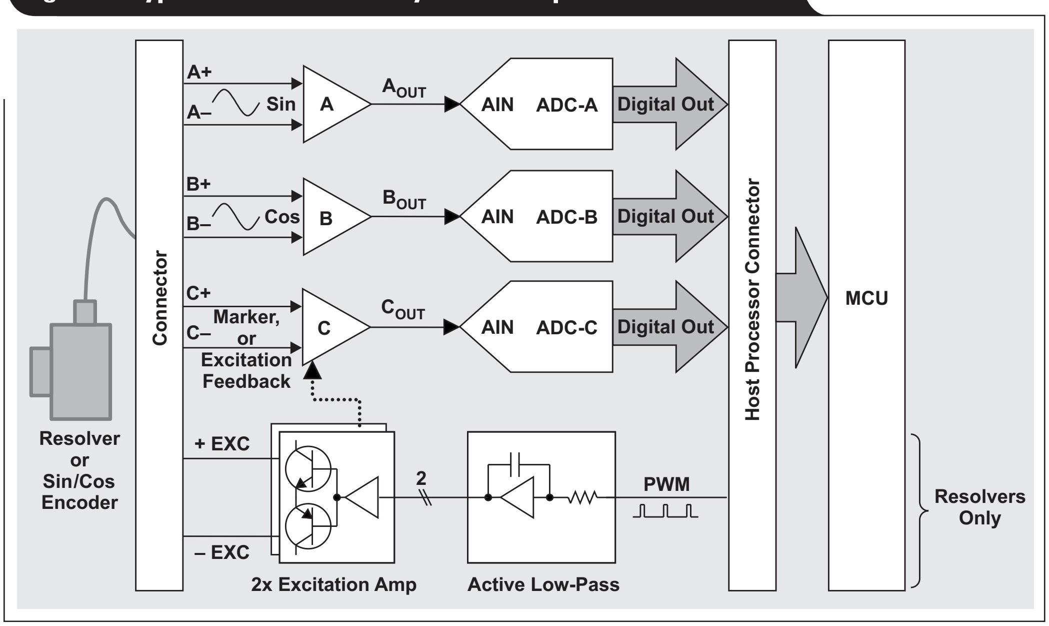
Although magneto-resistive and hall-sensing technologies are starting to get traction in automotive and integrated motor applications, the focus of this article is on angle/position encoders (incremental and absolute) and resolvers. Together, there are as many as 13-million channels per year (about 10 million coming from encoders), reflecting the majority of implementations in the industry.

In the encoder world, analog signal processing is still the dominant approach for decoding incremental position information using sinusoidal signals with a peak-to-peak voltage of 1 $V_{PP}$. This approach requires the lowest amounts of both software implementation effort and cost. For absolute position encoding, serial protocols have been on the rise, but require more effort (and thus cost) in terms of hardware and software. A hybrid implementation of digital and analog is still common. In the resolver world, analog frequency-modulated signals can decode angle and position in harsh environments, which makes them ideal for factories or automotive applications.

## Position-feedback system requirements

Figure 1 shows a typical analog position-feedback architecture. Either a sine/cosine encoder or a resolver's secondary windings can generate the 1-$V_{PP}$ differential input signals (A+, A–, B+ and B–), with the main difference being the signal's frequency range of interest (0 to 400 kHz for optical encoders versus 10 kHz up to 20 kHz for a typical resolver), as well as the amplitude. The idea is to level-shift, amplify and filter the signals of interest while rejecting unwanted common-mode disturbances and converting the differential inputs into single-ended

**Figure 1. Typical motor-control system with position feedback**



outputs ($A_{OUT}$ and $B_{OUT}$), all simultaneously. After conditioning the input signals, the resulting signals can be presented to an analog-to-digital converter (ADC) for accurate digitization and extraction of the position/angle information. References 2, 6 and 7 offer a detailed explanation on how the angle/position of the motor is extracted from the difference between the instantaneous voltage readings on channels A and B. A third channel, C, is frequently used as either a marker (encoder case) or excitation feedback path (resolver case).

Table 1 is an example set of system-level requirements. The specifications given in the table reflect the minimum performance needed in the signal chain to guarantee the accuracy of an angle measurement with the targeted maximum phase error of <0.2%.[2] While this analysis focuses on an angular measurement, the procedure is easily applicable to a linear position measurement as well. The mismatch of both offset and gain between the two channels (sine/cosine) contributes significantly to the overall phase error due to imbalance in the signal propagation.[3]

Drift over temperature is a critical concern as well because calibration at more than one temperature point is typically prohibited due to cost reasons. The common-mode requirement guarantees that disturbances up to ±10 V are suppressed to a level below 0.1% of the full-scale-range (FSR) input signal, which corresponds to a maximum tolerable rejection ratio of $0.1\% \times 1\ V_{PP}/10\ V_{PP}$ = 100 µV/V, or 80 dB. The common-mode disturbance could be created due to shifts in the signal ground level from long cables between the sensor and signal-conditioning circuit's printed-circuit board. Another disturbance source could be due to coupling from power-carrying wiring located close to the signal cables from the encoder to the motor shaft. There might be additional requirements such as noise and slew rate, however, those are omitted for sake of simplicity.

**Table 1. System-level requirements for a position-feedback signal path**

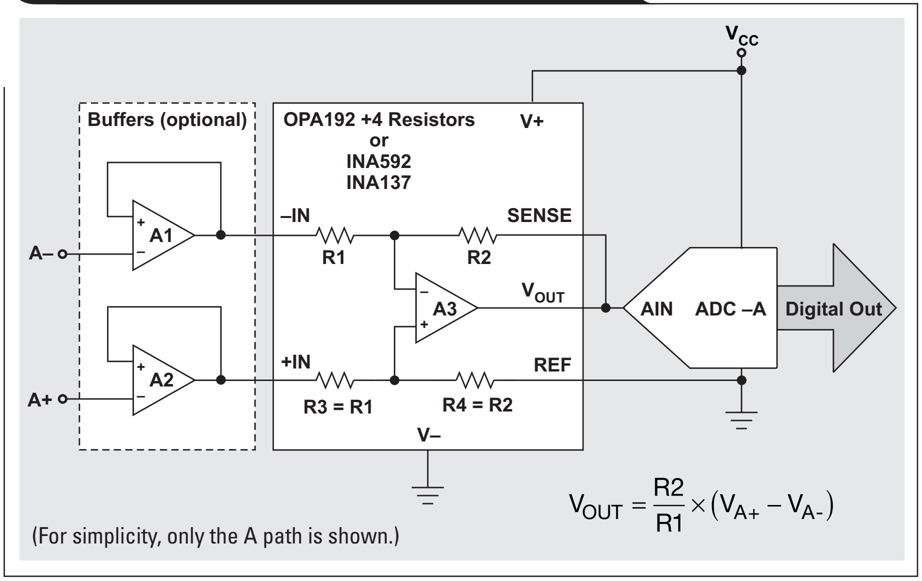
| System Parameter | Target Value | Impact on Phase Error |
|---|---|---|
| Ambient temperature | –40°C to 125°C | — |
| Signal frequency | 0 to 500 kHz (encoder)<br>10 kHz ±1 kHz (resolver) | — |
| Input signal amplitude/offset | 1 $V_{PP}$ at 2.5-V offset or 0-V offset (encoder), 4 to 7 $V_{RMS}$ (resolver) | — |
| Offset error of A and B (across temperature) | <0.1% | 0.05% (0.18°) |
| Gain error of A and B (across temperature) | <0.1% | 0.05% (0.18°) |
| Phase shift between A and B | 90° + 0.36'' (<0.1%) | 0.1% (0.36°) |
| Common-mode rejection (assuming up to ±10-V perturbation) | >80 dB | 0.1% (0.36°) |
| **Total root-mean-square phase error** | — | **0.16% (0.57°)** |

## Signal-chain device requirements: DC

The first step is to break down the system-level requirements into detailed device specifications for the individual analog signal-path components. For the signal-path implementation shown in Figure 2, input buffers A1 and A2 are optional, and are frequently omitted in case the signal source has low output impedance. In applications requiring high input impedance, an instrumentation amplifier such as the INA821 or INA819 from Texas Instruments might be a better choice (also see Table 3 on next page).

In a practical implementation, additional filtering and/or voltage limitation/clamping could be added to the circuit shown in Figure 2.[2] Scaling the input signal amplitude of

**Figure 2. Precision signal-path implementation**




$$V_{OUT} = \frac{R2}{R1} \times (V_{A+} - V_{A-})$$

1 to 2 $V_{PP}$ into a full-scale input signal that maximizes the ADC dynamic range typically requires a gain in the range of 1 to 4 V/V, depending on the ADC chosen. In the resolver case, depending on the loss factor from the primary to the secondary coil and the resulting output amplitude, it is sometimes necessary to scale down the 4- to 7-$V_{RMS}$ input signal to accommodate the ADC input range.

In order to present the differential input signal to the ADC in a single-ended fashion, amplifier A3 is connected in a well-known "difference-amplifier" configuration that could be either integrated into one integrated circuit or implemented with a stand-alone operational amplifier and discrete, well-matched resistors. In both cases, the gain is set by the resistor ratios and the offset- and gain-error requirements translate directly into an offset and gain specification for difference amplifier A3 in combination with resistors R1, R2, R3 and R4 (shown in Table 2). Equation 1 translates the percentage offset error into an absolute offset-error voltage based on the 1-$V_{PP}$ FSR:

$$V_{OS\_max}(A,B) = 0.1\% \quad 1\text{ V} = \frac{1\text{ V}}{1000} = 1\text{ mV} \qquad (1)$$

Equation 2 obtains the temperature drift specification for A3, also shown in Table 2. It becomes clear from the farthest right column in Table 2 that the INA592 difference amplifier from Texas Instruments is an excellent choice for this solution, as it meets or exceeds all specifications needed.

$$\text{Drift}_{OS\_max} < \frac{1\text{ mV} \times 0.5}{\left[125-(-40)\right]°\text{C}} = 3\ \mu\text{V}/°\text{C} \qquad (2)$$

As an alternative to the INA592, a discrete implementation of the difference-amplifier stage could be tried. This means using a stand-alone operational amplifier such as the OPA192 in combination with fully discrete resistors, or even a matched resistor array. The common-mode rejection ratio (CMRR) is dominated by a mismatch tolerance of resistors R1, R2, R3 and R4 (assume R3 = R1 and R4 = R2). Equation 3 gives the CMRR, according to Reference 4.

**Table 2. Device-level requirements for difference-amplifier stage with position feedback**

| Device parameter | Maximum Specification | INA592 | Meets Spec.? |
|---|---|---|---|
| Ambient temperature | –40°C to 125°C | –40°C to 125°C | Yes |
| Gain | Typically in the 0.5 to 4 range | 0.5 or 2 | Yes |
| Gain error (A3, B3) | <0.1% | 0.03% | Yes |
| Offset error (A3, B3) | <1 mV | 40 µV max | Yes |
| Offset drift (A3, B3) | <3 µV/°C | 1.5 µV/°C max | Yes |
| Bandwidth (3 dB) | >500 kHz | 2.5 MHz | Yes |
| Common-mode rejection ratio (CMRR) | >80 dB | >80 dB across temperatures | Yes |

$$\text{CMRR}(\text{dB}) = 20\ \log\left(\frac{1+\text{R2}/\text{R1}}{4\text{T}/100}\right) \qquad (3)$$

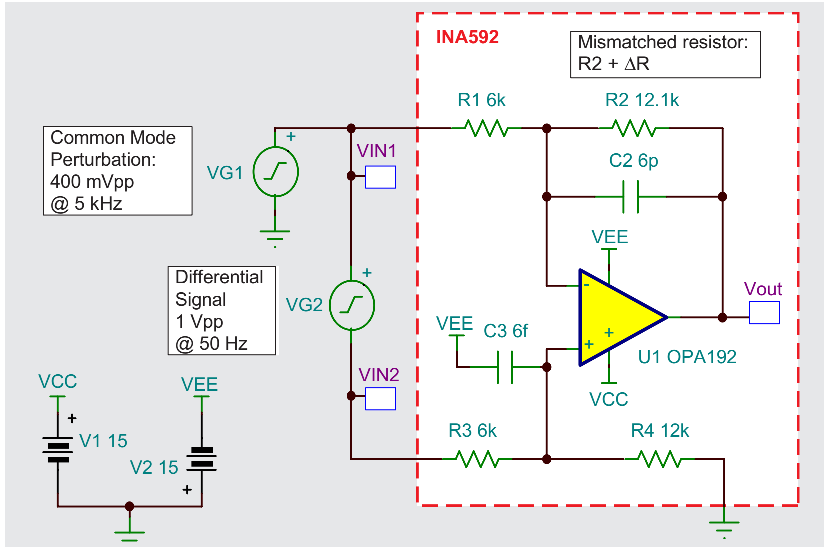
where T is the resistor tolerance in percent (%).

As shown in Reference 4, even for an external resistor tolerance of 0.01%, the CMRR performance will be limited to 74 dB due to resistor mismatch. This would make an implementation with discrete resistors achieving the target specification of >80-dB CMRR extremely costly. At the time of this writing, an array containing two matched 10-kΩ resistors with a tolerance of 0.01% is (US) $11.55.

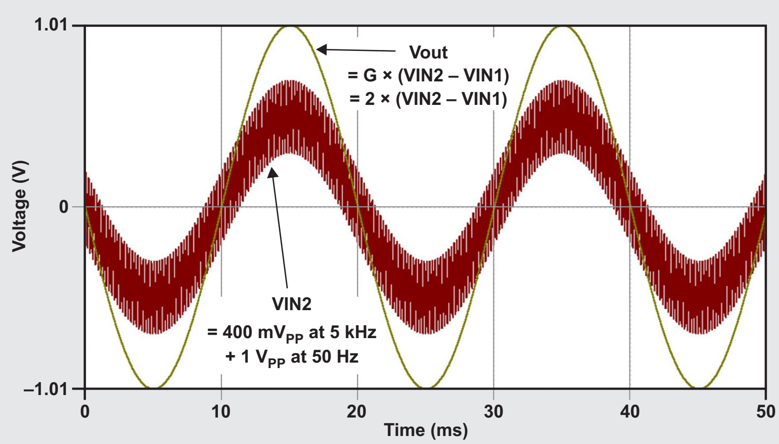
On the other side, a modern monolithic difference amplifier such as the INA592 provides a CMRR of >80 dB across all process variations and temperatures by using thin-film resistor technologies, which enable on-chip resistor matching at the 0.001% level.

To illustrate the performance differences between the discrete and the monolithic difference-amplifier solutions, Figure 3a is a schematic of TINA-TI™ Spice simulations. The circuit is essentially the same as that shown in Figure 2, but without a buffer, and the resistors are configured to achieve a gain of 2. The resistors are intentionally mismatched by modifying the value of R2, which results in various levels of mismatch ranging from 10% to 0.01%. In a practical application, a 1% or 0.1% mismatch corresponds to a discrete implementation versus a mismatch of only 0.001%, as in a modern monolithic difference amplifier like the INA592. The input signal is a differential signal of 1 $V_{PP}$ at 50 Hz, which "rides" on a common-mode perturbation of 400 $mV_{PP}$ at a 5-kHz frequency. Figure 3b shows a full-scale plot of the input signal VIN2 and the output voltage, while Figure 3c shows a zoomed-in version of the output voltage for four different simulations with varying mismatch. Clearly, the common-mode perturbation is significantly suppressed for the cases with tighter matching of the resistors.

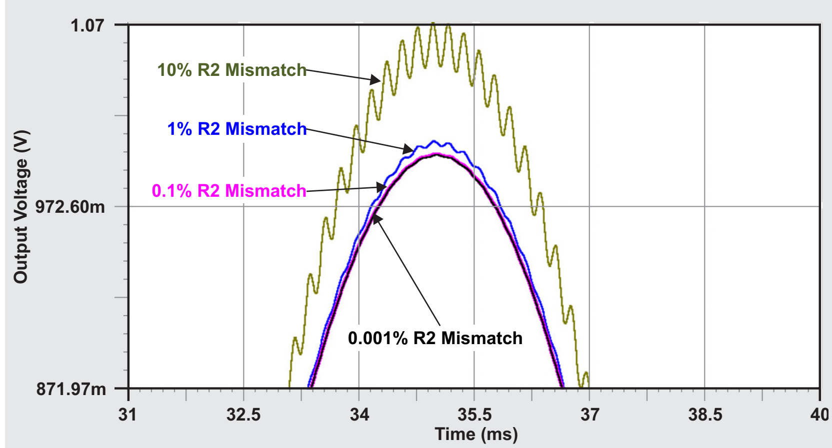
**Figure 3. Spice simulation circuit and results**




(a) TINA-TI™ simulation schematic

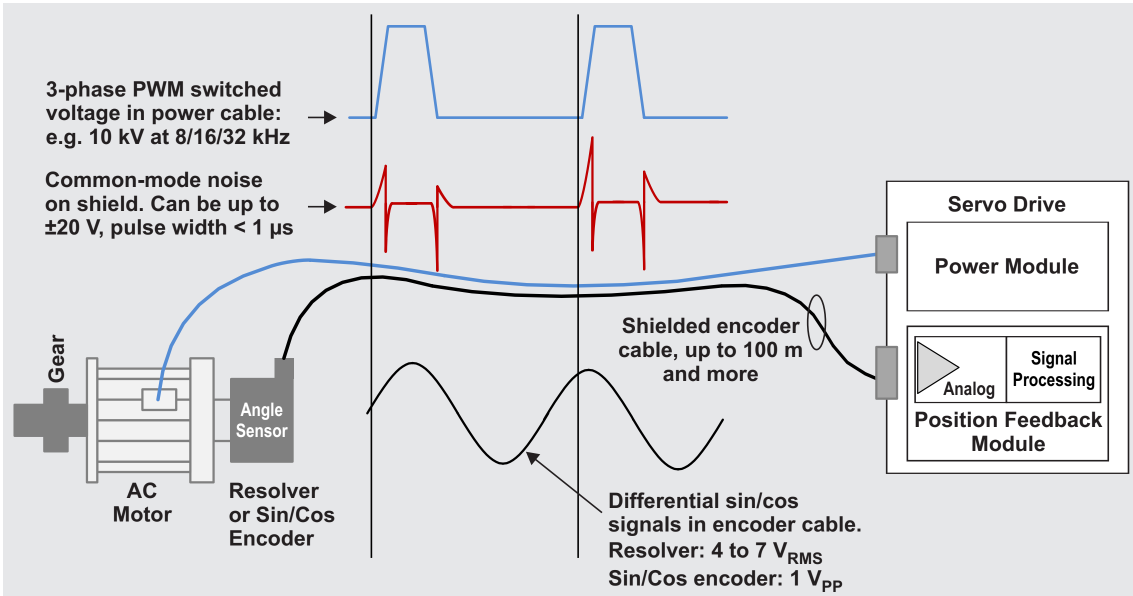



(b) Input/Output simulation results




(c) Zoomed-in simulation results

Figure 4. AC coupling mechanism in motor systems that results in high-frequency common-mode perturbations




## Signal-chain device requirements: AC

One important aspect that could be easily overlooked in the design of the precision signal path is the immunity against high-frequency perturbations.

High-frequency impulse, common-mode noise is typically coupled from the motor wires that carry switched pulse-width modulation signals into the resolver cables, or directly into the motor housing; see Figure 4.[5] To connect the wires to the motor, such as inside a robot, the shield of the motor cable might be open for up to 20 cm. The common-mode disturbance therefore is typically AC; pulses are ≈1-µs wide and have an amplitude of ±20 V. In this case, the common-mode rejection at higher frequencies between ≈400 kHz up to 1 MHz is critical.

Figure 5 compares the CMRR-versus-frequency performance of the INA592 (small-signal bandwidth = 2.5 MHz) and INA137 (small-signal bandwidth = 4 MHz). The INA137, which is based on the higher-bandwidth amplifier core, has an improved CMRR in the 400-kHz to 1-MHz signal range and therefore will perform better in suppressing unwanted high-frequency impulses, but at the cost of a worse DC precision from offset and offset drift; see Table 3 on the next page.

Figure 5. AC common-mode rejection: the INA592 vs. the INA137

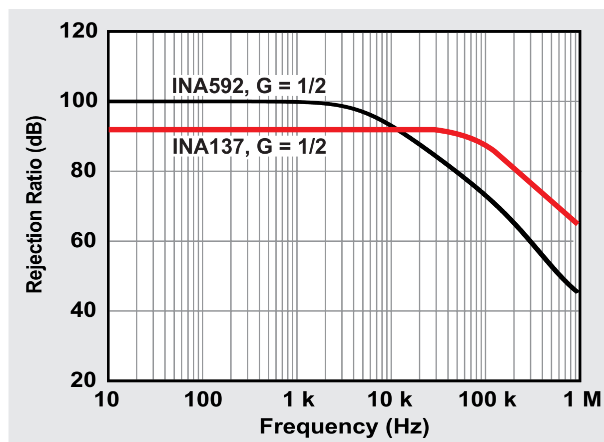


**Table 3. Solution performance comparison using different component choices**

| Parameter | OPA192 Plus Four Resistors (matched 0.01%) | INA592 | INA137 | Other Recomended Devices |
|---|---|---|---|---|
| Output-referred offset $V_{OS}$ (max) | 80 µV | 80 µV | 2 mV | THS4551<br>THS3531A<br>OPA365<br>OPA322<br>PGA411<br>INA821<br>INA819 |
| CMRR at 1 kHz | <74 dB | >80 dB | >74 dB | |
| CMRR at 500 kHz | <50 dB | <50 dB | 70 dB | |
| Board size | Large | Small | Small | |
| Price (1,000-unit quantities) | >$5/channel | $1.30/channel | $1.27/channel | |

## Conclusion

Table 3 compares three different options for implementing the precision signal path: discrete (the OPA192 plus four resistors) and two alternatives using the INA592 and INA137 difference amplifiers. Table 3 summarizes the trade-offs discussed in this article. As outlined earlier, the INA592 is the best option whenever offset, offset drift and CMRR are important. For those cases where CMRR at 500 kHz and beyond is the major concern, consider the INA137. There are other options like using higher bandwidth amplifiers if an extremely fast response is required (see other device recommendations in Table 3), or even using a fully-differential amplifier when interfacing with differential-input ADCs.

In the analysis for this article, the focus was solely on the example of a differential-to-single-ended signal chain. By starting from the system-level requirements, a systematic approach has been presented on how to evaluate the component-level requirements, while considering trade-offs in terms of performance, size and cost.

## References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## Related Web sites

TINA-TI™ SPICE-based analog simulation program

Product information:
**INA821, INA819, INA592, INA137, OPA192**
**THS4551, THA3531A, OPA365, OPA322, PGA411**

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