Precision signal conditioning for safety-enabled AIMs in factory automation

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Precision Amplifiers

Introduction

Industry 4.0 refers to the fourth Industrial Revolution; an Industry 4.0-outfitted smart factory has machines augmented with cloud connectivity. These machines are connected to a system that can visualize the entire production chain and make decisions autonomously. Continued automation and data exchange within the Internet of Things are raising the bar for the performance of factory-automation infrastructure, especially for electronic brains such as programmable-logic controllers (PLCs) inside factory-automation networks.

An analog-input module (AIM) is a key subsystem in a PLC. AIMs vary based on what real-world physical parameters they monitor, such as temperature, pressure, force or strain, and they communicate via command signals in either voltage (±10 V, for example) or current (4 to 20 mA, for example). Figure 1 shows a typical example of a simple industrial process, where proper automation requires the acquisition of different analog signals from various sensors. Each type of signal (voltage, current, temperature) requires a suitable AIM with corresponding performance parameters.

A multichannel AIM offers flexibility, space efficiency and power efficiency when compared to many single-channel, dedicated input modules. Reference 1 discusses different multichannel AIM architectures and their trade-offs.

The focus in this article is solely on multiplexed architectures (both integrated and external multiplexers) and their relevance in high-channel-count and high-density systems with slow-changing process quantities such as temperature or pressure.

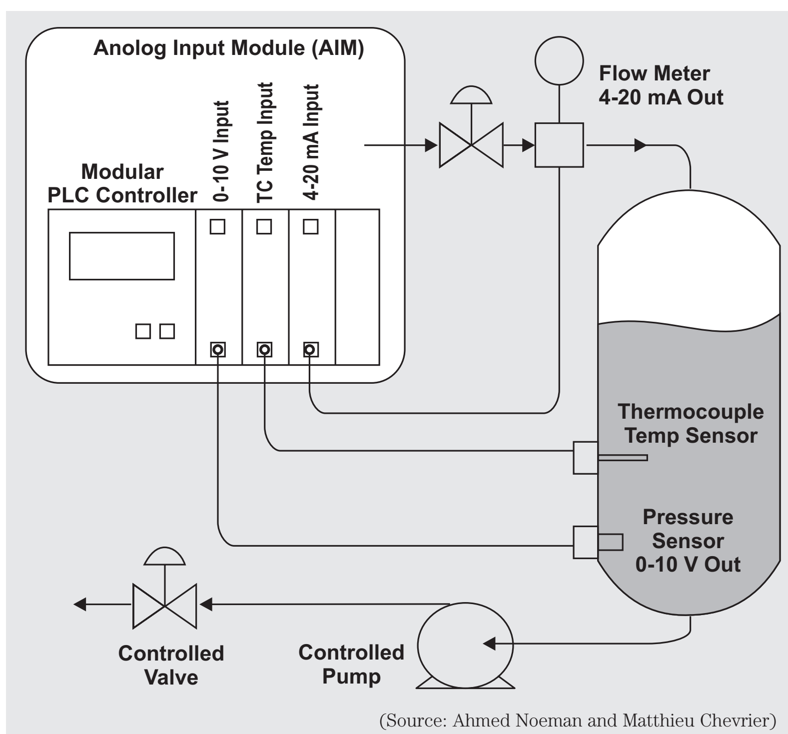
Functional safety considerations of multichannel AIMs

Designing the functional-safety architecture of an AIM requires considering its hardware fault tolerance (HFT), that is, its ability to operate in a safe state even during a hardware failure. HFT also requires the ability to detect and report a hardware failure through monitoring and diagnostics.[2] Multiple channels are often used in parallel, known as a redundant-channel architecture, to make the design robust in terms of HFT. A one-out-of-two (1oo2) architecture uses two identical channels in parallel. If the channel outputs don't match, the system enters into a safe state. However, without further diagnostics on the channels, it is not possible to determine which channel has the fault. Correspondingly, in a two-out-of-four architecture, four identical channels create a system with safe operation of two independent channels.[2]

A clearly defined safety goal for the system is required. For example, if the required target accuracy in normal operation is 0.1%, the safety goal could be defined as being able to still operate with 1% accuracy in failure mode. A well-defined safe state is also needed. For an AIM, this could be as simple as having the analog-to-digital converter (ADC) deliver a code outside the valid code range.[3]

The next section compares three alternative implementations of the signal chain and analyzes their performance and trade-offs in the context of functional safety. The system requirements are defined first and then each implementation is described individually.

Figure 1. AIM application in industrial process control or factory automation



(Source: Ahmed Noeman and Matthieu Chevrier)

System specifications for an AIM signal chain

Table 1 is an example set of system-level requirements for an AIM channel that has only voltage-type inputs. While this article limits analysis to a single-type module for simplicity, the concepts outlined in this article are also applicable to universal AIMs with multiple types of inputs.

The goal is to compare three different implementations of an analog signal chain—named A, B and C—in order to meet the requirements in Table 1.

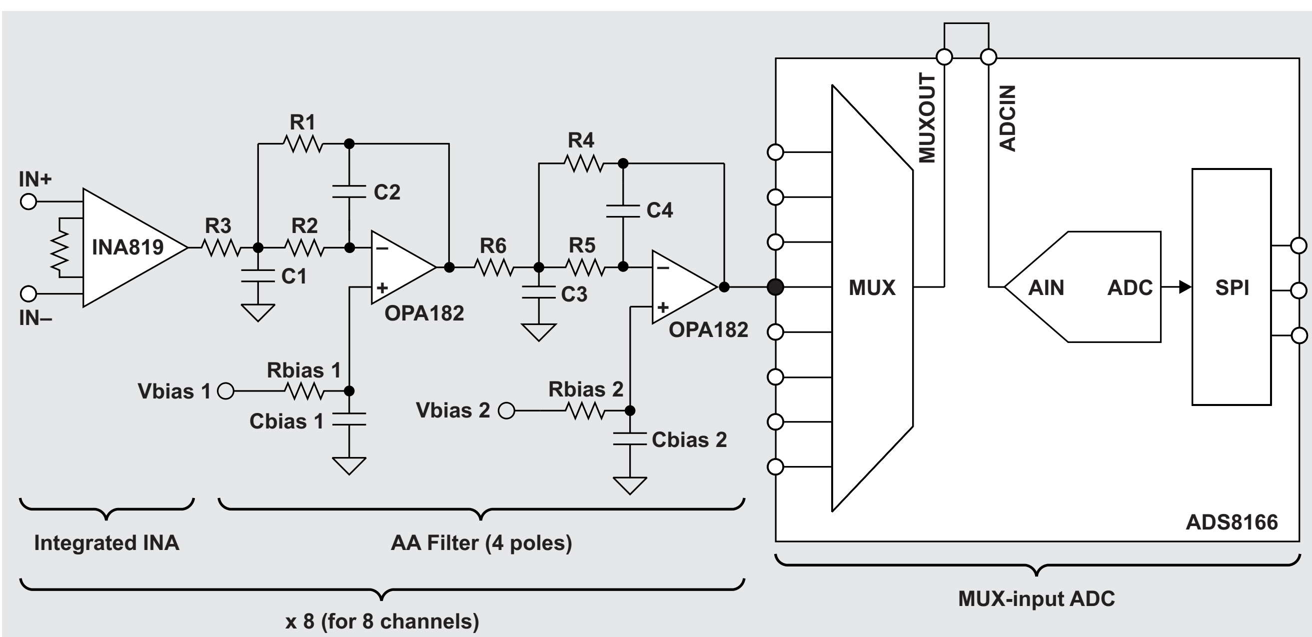
Implementation A: Instrumentation amplifier with filter and multiplexed-input ADC

Figure 2 is the simplified circuit diagram of implementation A. An instrumentation amplifier such as TI's INA819 provides the differential-to-single-ended conversion, followed by a fourth-order antialiasing filter and a multiplexed-input ADC with an integrated multiplexer. The figure shows only one out of eight channels for the signal-conditioning circuit up to the ADC input.

Table 1. System-level requirements for a high-channel-density, functional safety-enabled AIM

System Parameter	Target Value
Operating/storage temperature	–20°C to 60°C/–40°C to 85°C
Input type and range	Voltage input: 0 to 10 V
Number of channels	8
Input impedance	>10 MΩ
Signal type	Differential
Maximum sampling rate and filtering	100 kSPS; ADC sampling speed of 250 kSPS to accommodate a background diagnostics signal that needs fast sampling
Antialiasing filter	Fourth-order antialiasing low-pass filter with 60-kHz bandwidth
Functional diagnostics	Yes
Connection diagnostics	Broken wire/short circuit
Input overvoltage protection	Minimum ±40 V beyond supply rails
Common-mode input voltage range	Signal plus common-mode voltage must be within ±12 V
Common-mode rejection ratio (CMRR)	>80 dB
Maximum total unadjusted error	0.1% at room temperature
Overall design challenge	**High-channel-density, functional safety-capable AIM**

Figure 2. Implementation A: Simplified circuit diagram of AIM signal chain



The external resistor sets the gain (G) for the INA819 or will not be populated for a G = 1. The system-level error budgeting is fairly complex for an instrumentation amplifier: Reference 4 provides a comprehensive analysis. The fourth-order filter is constructed using two stages of the multiple-feedback active filter type. Multiple feedback filters:

- Are efficient in realizing higher-order filters (two poles per amplifier).[5, 6]
- Have better stopband rejection compared to Sallen-Key filters.
- Have zero gain for the noninverting current noise and/or DC bias current.
- Offer a very straightforward implementation of non-zero gain given by the ratio of resistors expressed in Equation 1:

$$\text{Gain} = \frac{-R3}{R1} \quad (1)$$

Equation 2 calculates the cut-off frequency for the multiple-feedback filter:

$$f_C = \frac{1}{2\pi \times \sqrt[2]{R1 \times R2 \times C1 \times C2}} \quad (2)$$

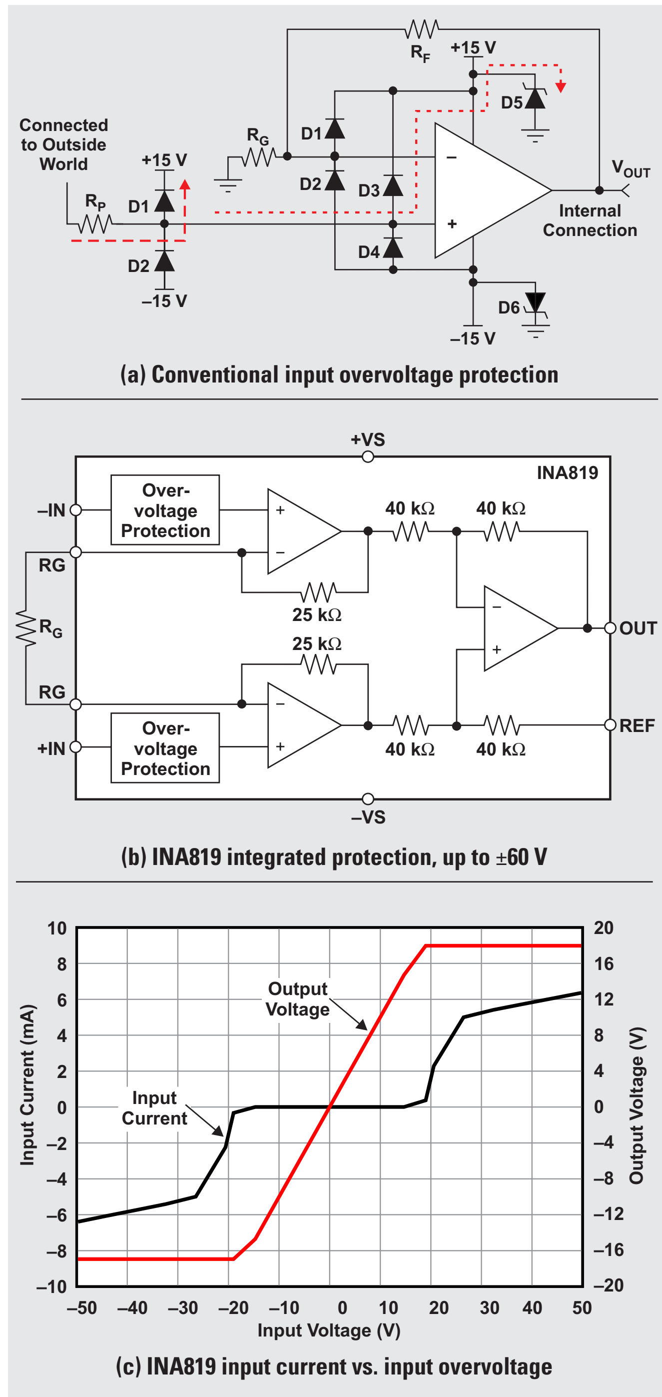
The OPA182 serves as both the filter's operational amplifier as well as the ADC's input/multiplexer driver due to its excellent DC precision, sufficient bandwidth (5 MHz) and high-voltage operation. The ADS8166 provides excellent DC precision, a sampling rate as high as 1 MSPS and an eight-channel input multiplexer.

If higher throughput requirements are required, consider placing a mux-friendly operational amplifier such as the OPA192 or a device from the OPA189 family between the multiplexer output and the ADC input; see Reference 7 for a detailed explanation of this technique.

Functional safety consideration No. 1: Protection features such as overvoltage

Protection against surges is an important consideration of every AIM used in factory automation and process control because the input terminals will interface to the outside world. This type of protection may or may not be considered a functional safety feature, as the problem is caused by operation outside recommended conditions. Designers often use transient-voltage suppressor (TVS) diodes as shown in Reference 2 to meet requirements in the International Electrotechnical Commission (IEC) 61000-4-5 standard, but these devices exhibit inherent leakage current, which causes systemic offset errors and degraded precision. The inputs of the INA819 are individually protected for voltages up to ±60 V through internal circuitry, as shown in Figure 3.[8]

Figure 3. Conventional vs. integrated overvoltage protection



Functional safety consideration No. 2: Fault detection and diagnostics

The designs presented in References 9 and 10 demonstrate how the introduction of redundant channels and/or components facilitates the detection of system faults. For example, a redundant external reference could be used in addition to the internal (ADC) reference, or the use of a parallel signal path with a discrete instrumentation amplifier to compare multiple measurements and detect an error.

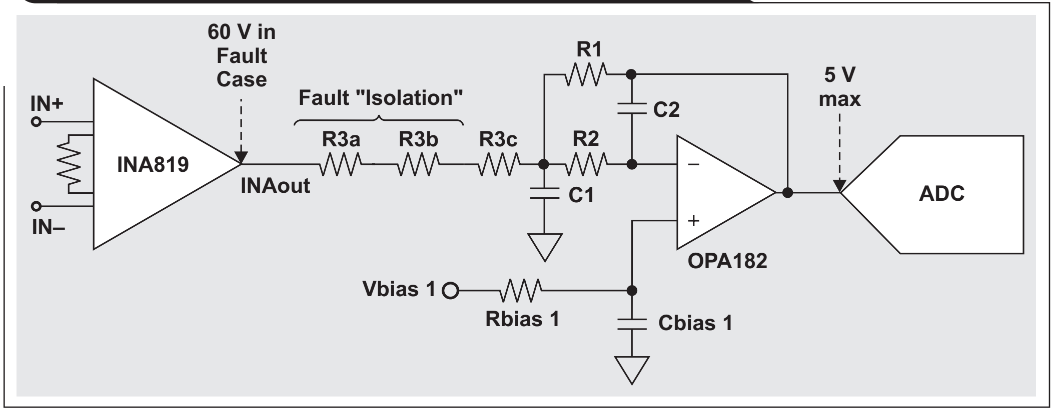
Also, the higher the number of channels needed for redundancy (in a 1oo2, or even a 1oo3 architecture), the higher the need for small size and lowest overall cost. Internal diagnostic features such as window comparators, alerts and digital error checks such as cyclic-redundancy check (CRC), some of which are available in the ADS8166, are useful but cannot usually support a higher safety-level certification by themselves.

Additional device requirements may have to be taken into account, such as the 250-kSPS capability listed previously in Table 1. This requirement is meant to accommodate a sine-wave-shaped, higher-frequency diagnostic signal processed to test the signal chain by sending a known high-frequency test pattern and verifying the output versus an expected result.

Functional safety consideration No. 3: Pin-to-pin short and fault tolerance of the ADC

During failure-mode-effects and diagnostics analysis (FMEDA) of any functional safety module, it is important to consider the possibility of a pin-to-pin short as well as a stuck-high on the INA819 output pin. In this situation, the ADC must be protected from damage so that it can still transmit a valid diagnostic signal to the controller. For a multistage (and thus discrete) signal chain, the implementation of fault isolation is fairly straightforward. As shown in Figure 4, expanding the feedback resistor network by using multiple high-impedance components in series provides a simple but effective way to limit push-through currents, and decouples the ADC from a potentially damaged input device.

Figure 4. Isolation technique to enable failure tolerance against pin-to-pin shorts or an output stuck high



TINA-TI™ software: DC and transient simulations

Figure 5 is a more detailed schematic of implementation A and Figures 6 and 7 show TINA-TI software simulation results.

Note the DC-transfer characteristics in Figure 6 where the differential input signal is swept from 0 V to 10 V and the output of the filter stage (ADC input) is monitored. The simulation shows that the 0- to 10-V input voltage is scaled correctly to the desired 0.1- to 4-V range.

Figure 5. TINA-TI™ simulation schematic

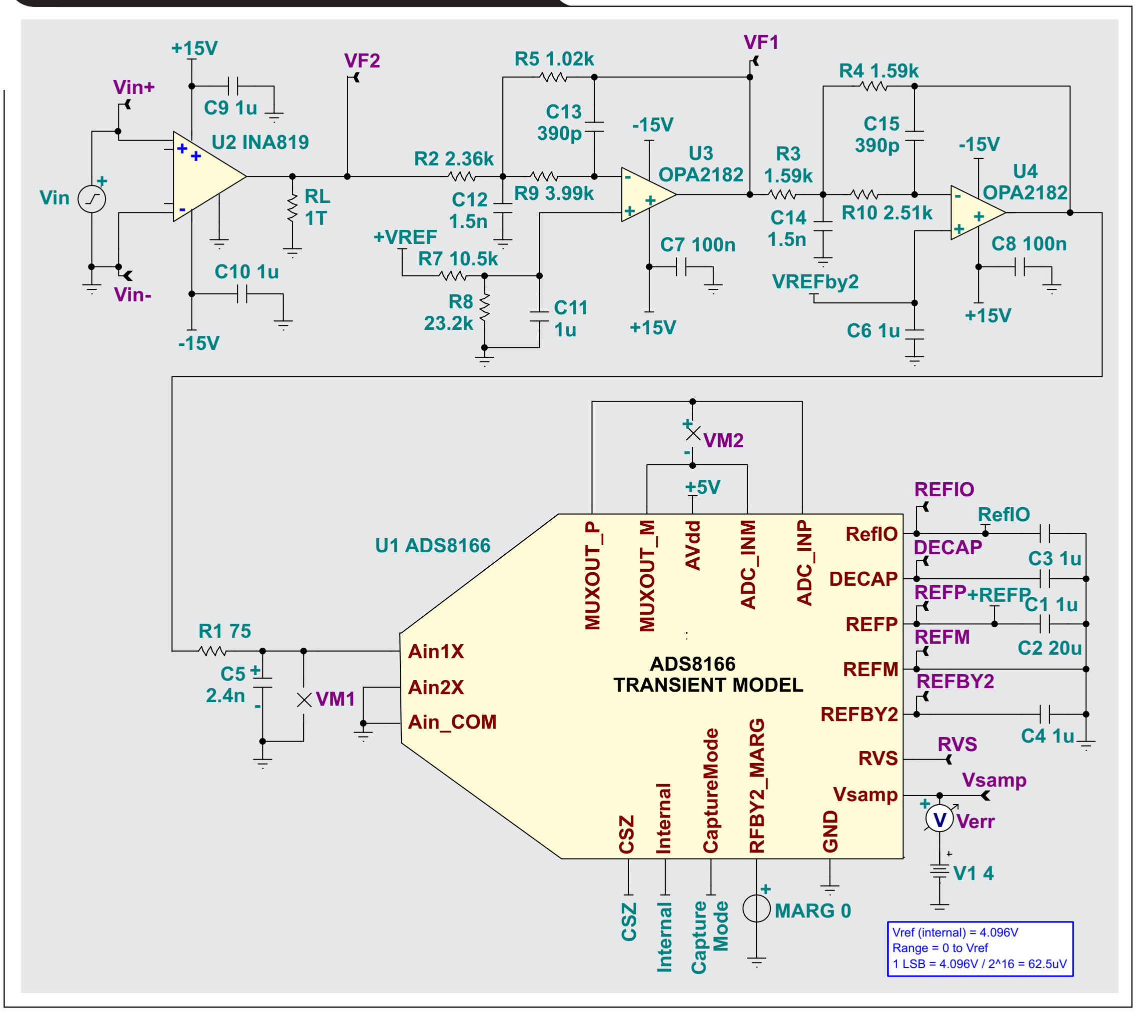
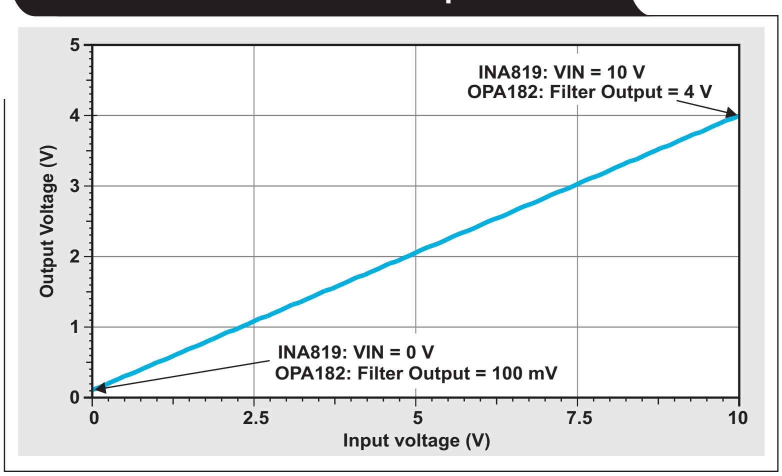


Figure 6. TINA-TI software simulation results: INA819 and OPA182 filter DC sweep



The transient simulation in Figure 7 includes the ADC input stage of the TINA-TI model and shows the settling behavior at the ADC input (signal Vsamp). The error signal, Verr, is the deviation from the expected input voltage, and must be within one least-significant-bit (LSB) magnitude based on the ADC full-scale range to guarantee the recommended signal-to-noise ratio and total harmonic-distortion performance of the overall circuit solution.[11] As shown in Figure 7, the error signal settles within 1 LSB inside the acquisition time period.

Implementation B: Discrete amplifier front end with an external multiplexer and ADC

Implementation B uses operational amplifiers to realize both high input impedance and the common-mode rejection needed to extract the differential input signal (a discrete INA implementation), and an external multiplexer in front of an ADC, as shown in Figure 8.

Figure 7. TINA-TI software simulation results: INA819, OPA182 and ADS8166 transient simulations

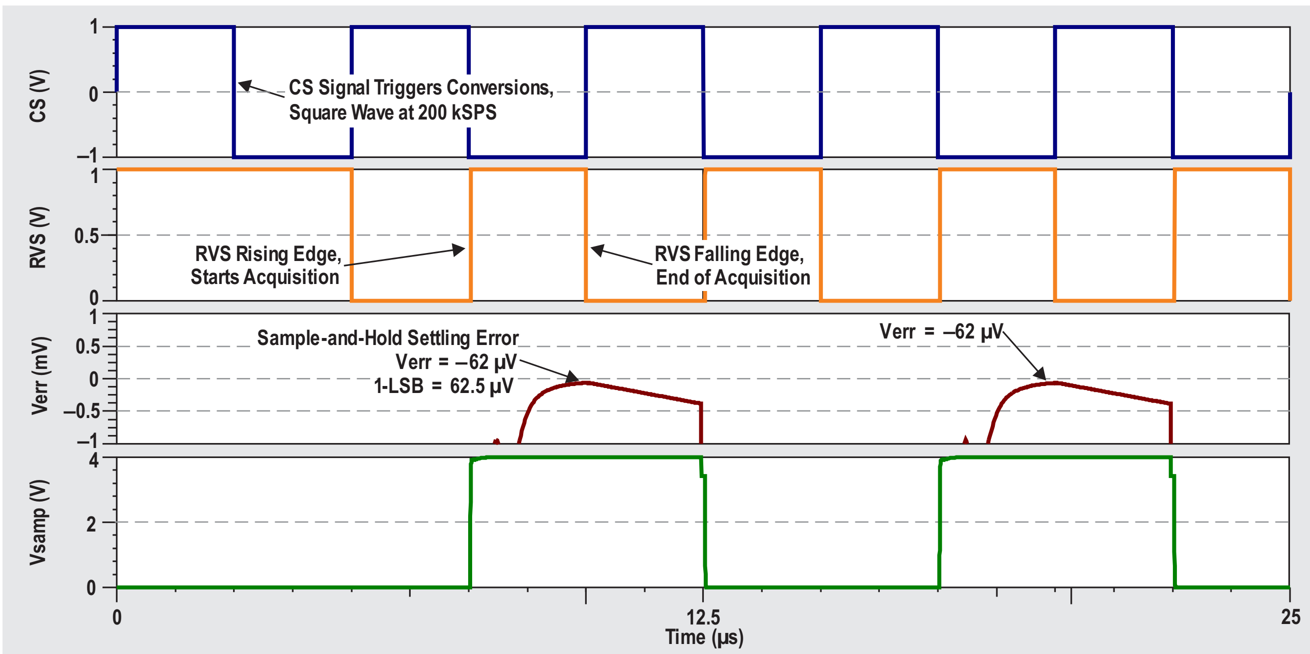
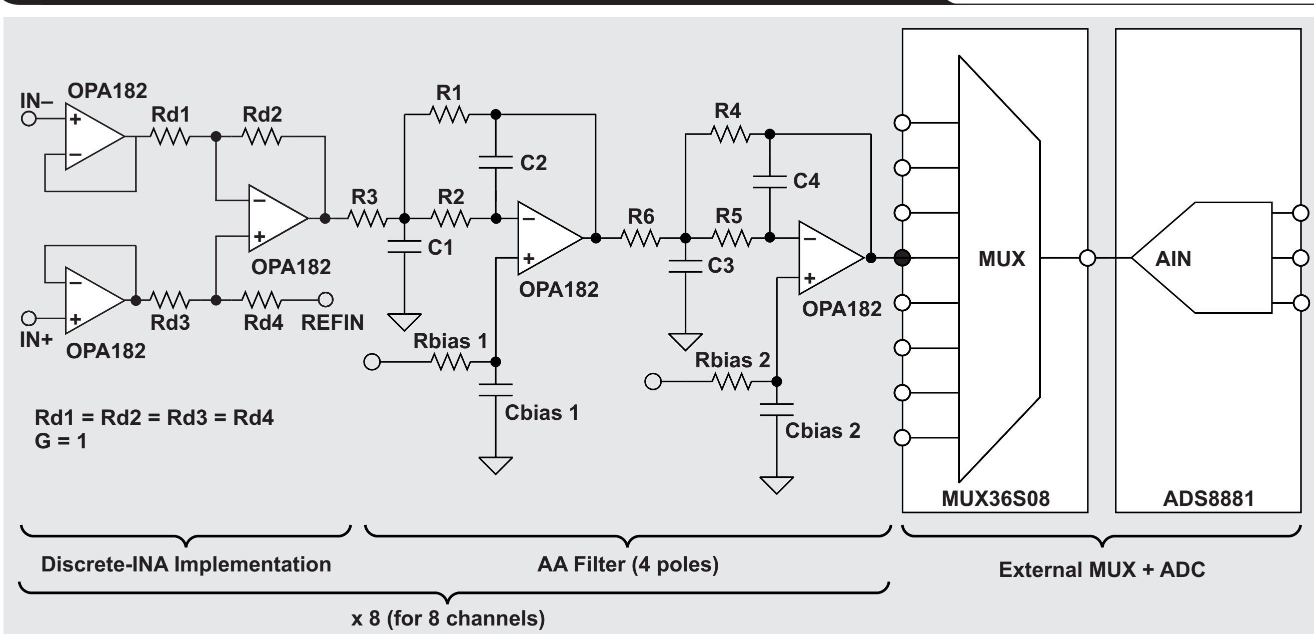


Figure 8. Implementation B: Simplified circuit diagram of AIM signal-chain



Functional-safety consideration No. 4: Component count and failure-in-time (FIT) rate for type-A vs. type-B elements

IEC 61508 categorizes type-A (simple) and type-B (complex) elements.[12] Failure modes of type-A elements are well defined, and it is possible to completely determine their behavior under fault conditions. Passive components, discrete transistors and switches, as well as low pin count (such as 6- or 8-pin amplifiers) and low-transistor-count integrated circuits (ICs), are typically considered type-A elements.

Not all failure modes are well defined for type-B elements, and it is not possible to completely determine their behavior under fault conditions. High-pin-count and high-transistor-count ICs such as DC/DC converters, microcontrollers and highly-integrated data converters are typically considered type-B elements.

For a targeted HFT, a specific safe-failure fraction (SFF) of an element can support a higher safety-integrity-level (SIL) performance for a type-A versus a type-B element. For example, if HFT = 1 and the SFF is between 60% and 90%, SIL 3 can be supported for a type-A element, but only SIL 2 for a type-B element.[12] This difference between type-A and type-B elements suggests that the decision to build a more discrete solution from simple components, such as operational amplifiers, could be favorable for systems with higher functional-safety targets.[13]

Considerations for precision performance

As far as accuracy is concerned, the fully-discrete implementation has a major disadvantage due to the dependence of the CMRR on resistor matching from discrete components. The CMRR is dominated by a mismatch tolerance of resistors R_{d1}, R_{d2}, R_{d3} and R_{d4} (assuming that $R_{d3} = R_{d1}$ and $R_{d4} = R_{d2}$). Equation 3 gives the CMRR, according to Reference 14, as:

$$\mathrm{CMRR}(\mathrm{dB}) = 20\log\left(\frac{1 + R_{d2}/R_{d1}}{4T/100}\right) \quad (3)$$

where T is the resistor tolerance in percent.

As shown in Reference 15, even for an external resistor tolerance of 0.01%, the CMRR performance will be limited to 74 dB due to resistor mismatch, which does not meet the target specification of >80 dB (shown in Table 1).

A modern monolithic device such as the INA819 provides a CMRR of >90 dB across all process variations and temperatures by using thin-film resistor technologies, which enable on-chip resistor matching at the 0.001% level. See Reference 15 for an in-depth analysis of the impact of resistor matching on CMRR performance.

Implementation C: A fully integrated ADC with an internal multiplexer and programmable gain stage

Figure 9 shows a fully integrated and compact solution using the ADS125H02. Due to the oversampling architecture and availability of various filter options, the external anti-aliasing filter can be omitted.[16, 17]

On the following page, Table 2 summarizes the four functional-safety considerations covered in this article and how they apply to implementation C. One limitation of implementation C is that the system throughput is lower compared to implementations A and B, and will not cover the 250-kSPS requirement previously shown in Table 1 that is necessary for background diagnostics.

Figure 9. Implementation C: Simplified circuit diagram of AIM signal-chain

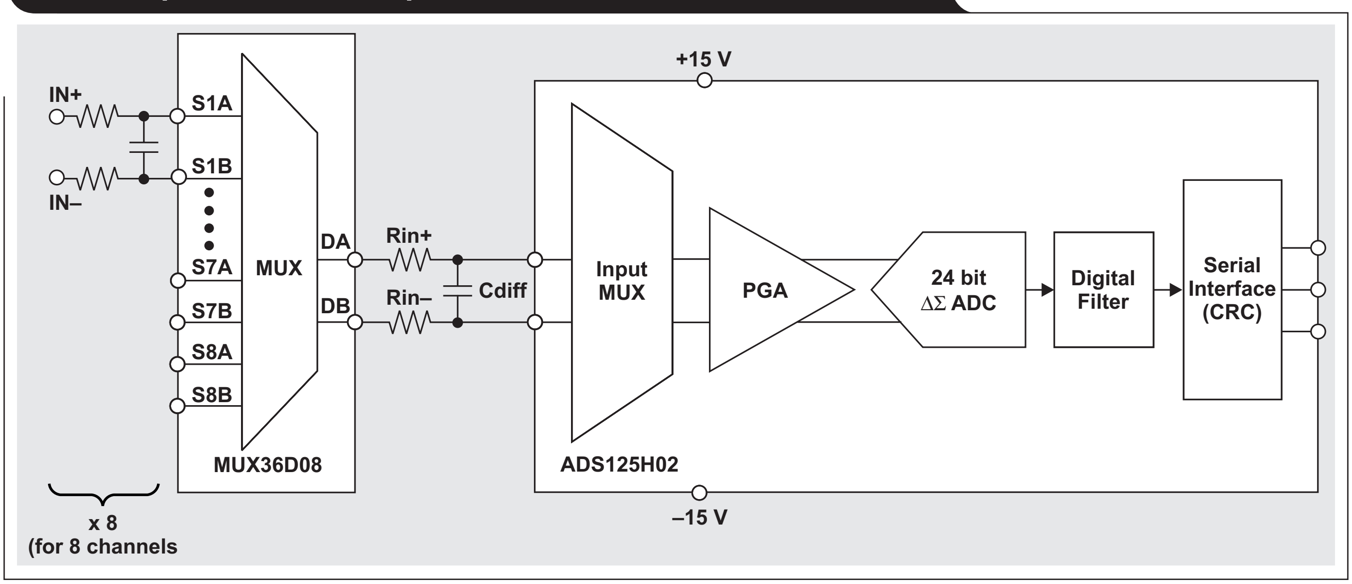


Table 2. Solution performance comparison using different choices of architecture and/or components

Performance Parameter or Feature	Implementation A: INA plus filter plus multiplexed-input ADC	Implementation B: Discrete amplifier plus external multiplexer plus ADC	Implementation C: Fully-integrated ADC	Other Recommended Devices
Recommended TI devices	INA819, OPA182 (2), ADS8166	OPA182 (5), MUX36S08, ADS8881	MUX36D08, ADS125H02	
Active component count	Medium	High	Low	OPA189, OPA182, PGA280/281, INA821, INA819, ADS1261, ADS127L01
CMRR (minimum)	>90 dB	<74 dB	>90 dB	
Input overvoltage protection	Included in the IC (up to ±60 V with the INA819)	Not included in the IC, but can be implemented discretely	Not included in the IC, but can be implemented discretely	
Fault isolation	Implement in antialiasing filter (series R technique)	Implement in antialiasing filter (series R technique)	Implement in input RC filter[17]	
Diagnostic capabilities	Window comparators, alerts and hysteresis	Not included (requires separate implementation)	CRC, signal and reference voltage monitors; not fast enough for 250-kSPS diagnostics	
Board size	Medium	Large	Small	

Conclusion

Table 2 compares all three implementations, summarizing the findings, and how each implementation addresses concerns related to functional safety.

Table 2 also shows that each one of the architectures is a valid solution in terms of functional safety; the main difference is in performance, as well as component count or cost. Economic aspects might also play a role during the decision process that make the fully-discrete circuit the most attractive solution—such as the ability to reuse simple, generic-function building blocks like operational amplifiers, multiplexers and passives across multiple projects.

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