AN14547

Four-channel universal input solution with NAFE13388 family of devices

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Document information

Information	Content
Keywords	NAFE13188, NAFE13388, NAFE73388 industrial, multichannel, AI-AFE
Abstract	This application note presents how to configure and design a four-channel, universal-input system using the NAFE13388 family of devices. The design supports 2/3/4-wire RTD, thermocouple, 0 V to 10 V voltage input, 4 ma to 20 mA current input, and load cell. The NAFE13188 variant of the family has been used in this design.

1 Introduction

In this application note, a four-channel, universal-input system using the NAFE13388/NAFE73388 (NAFEx3388) family of devices is presented.

The NAFE13388 products are highly configurable, industrial-grade, multichannel analog input analog front-ends (AI-AFE) that meet high-precision measurement requirements.

The system is able to measure the most common transducer inputs in the industrial environment: voltage, current, RTD, thermocouple and Wheatstone bridges. All four channels can be configured with software to measure any of the above transducers.

2 NAFE13388 family description

The NAFE13388 family of devices are highly configurable, industrial-grade multichannel universal input analog front-ends (NAFE) that meet high-precision measurement requirements. The NAFE13388 family of products is designed to measure any input voltage and current typically used in the industrial market, such as ±10 V, ±0 to 20 mA, RTDs, PTC, NTC, thermocouples, and Wheatstone bridges.

The device integrates low-leakage, high-voltage fast multiplexers (mux), low-offset and low-drift programmable gain amplifier (PGA), high data-rate 16- or 24-bit sigma-delta, analog-to-digital converter (ADC), precise voltage and current excitation source, and low-drift voltage reference. The digital data are read by the host MCU/MPU through the serial peripheral interface (SPI).

The family is composed of different parts, which differs for speed, factory calibration, ADC resolution, and number of channels.

The NAFE13188, which is the part used in this report, is a 288 kSPS, eight-input, 24-bit ADC version. Other version includes NAFE73388, which features a data rate up to 576 kSPS, or the NAFE13144, which is a four-input version.

3 NAFE13188 operation in universal input system

The NAFE13188 has eight analog inputs AI1P…AI4P, AI1N…AI4N and one common input AICOM (see Figure 1), which can measure low voltages, in the range of millivolts, to tens of volts. Table 1 shows the different input voltage ranges according to the PGA gain.

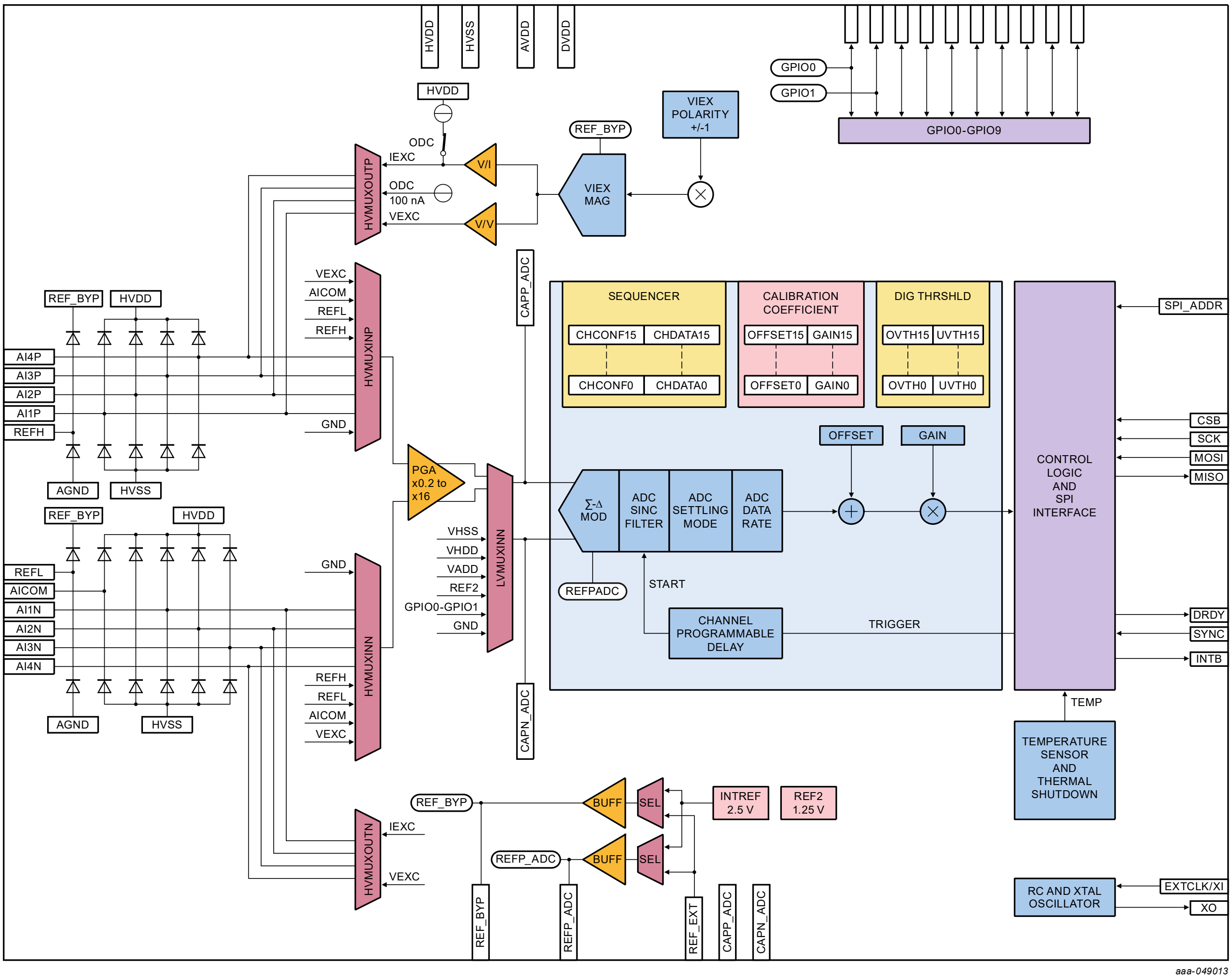

Figure 1. NAFEx33388 block diagram

Even if the AICOM is mostly used as a reference in pseudo-differential measurements, it can also be used as a standard analog input, such as AIxP or AIxN. This pin is used as part of the analog inputs for one of the four channels.

The analog input signals are routed to the PGA through two multiplexers.

The excitation (VIEX) is able to inject current or voltage to any of the inputs except AICOM.

In a four-channel universal input system, the input multiplexer performances play an important role. To obtain good performance, one input channel must not influence the other channels. The NAFE13388 has a low DC crosstalk of 1 µV/V, which corresponds to 120 dB.

Table 1. Nominal and min/max input voltage ranges

Nominal range values (V)								
PGA gain	**0.2**	**0.4**	**0.8**	**1**	**2**	**4**	**8**	**16**
Bipolar differential	±20	±10	±5	±4	±2	±1	±0.5	±0.25
Bipolar single-ended	±10	±5	±2.5	±2	±1	±0.5	±0.25	±0.125
Unipolar differential	±10	±5	±2.5	±2	±1	±0.5	±0.25	±0.125
Unipolar single-ended	±10	±5	±2.5	±2	±1	±0.5	±0.25	±0.125
Min and max values (V)								
PGA gain	**0.2**	**0.4**	**0.8**	**1**	**2**	**4**	**8**	**16**
Bipolar differential	±25	±12.5	±6.25	±5	±2.5	±1.25	±0.6.25	±0.3125
Bipolar single-ended	±12.5	±6.25	±3.125	±2.5	±1.25	±0.625	±0.3125	±0.1562
Unipolar differential	±12.5	±6.25	±3.125	±2.5	±1.25	±0.625	±0.3125	±0.1562
Unipolar single-ended	±12.5	±6.25	±3.125	±2.5	±1.25	±0.625	±0.3125	±0.1562

The low-noise sigma-delta ADC samples the PGA output and filters the signal with configurable SINC filters. In the digital domain, the gain, and offset calibration coefficients are used to compensate the measurements.

The NAFE13388 can store 16 different measurement configurations. Each of them applies different settings to the input multiplexer, PGA gain, calibration coefficients, data rate, SINC filter, and IEXC. In this way, 16 logical channels (LCH0 to LCH15) are available to the user. With the channel-based configurations, the user is able to switch among the configured channels seamlessly, and without the need to perform multiple SPI transactions to set up various configurations before each ADC conversion. The sequencer steps through the activated channels to execute the conversion and transfers the results on the data register. The sequencer gives a high degree of flexibility to implement the universal input capability.

The NAFE13388 also integrates ten GPIOs that drive the switches used in the system. In galvanic isolated systems, using the integrated GPIOs allows the host to drive the switches on the isolated side through the SPI, thus saving additional digital isolators. GPIO0 and GPIO1 can also be used as auxiliary inputs of the ADC.

4 Application schematic description

Figure 2 shows the implementation of the four-channel, software-compatible, universal-input solution with the NAFE13388.

J1 to J4 are the connectors to the transducers. Each connector has four terminals, which are all used in the case of 4-wire RTDs. Other transducers require fewer terminals.

The AI4P pin of the NAFE13388 is used as current excitation to measure the RTD resistance. To support multiple channels, the current is routed to the Jx connectors through the multiplexer U2.

Referring to J1 connector, for example, the current is supplied to the J1-1 terminal for 4-wire RTDs, to J1-2 for 3-wire RTDs, and to J1-3 for 2-wire RTDs. The multiplexer is driven by three NAFE13388 GPIOs (GPIO2 to GPIO4). A detailed description of the system operation for RTD transducers is described in the dedicated sections.

To support 4-20 mA or 0-20 mA current input, each channel has a sense resistor RSx and a switch. The switch is needed to disconnect the sense resistor from AIxN when other types of transducer are measured. The switches are driven by the NAFE13388 GPIOs (GPIO5 to GPIO8).

For the ±0-10 V inputs, no additional components, such as a resistor divider, are needed because the NAFE13388 inputs can directly measure these voltage ranges.

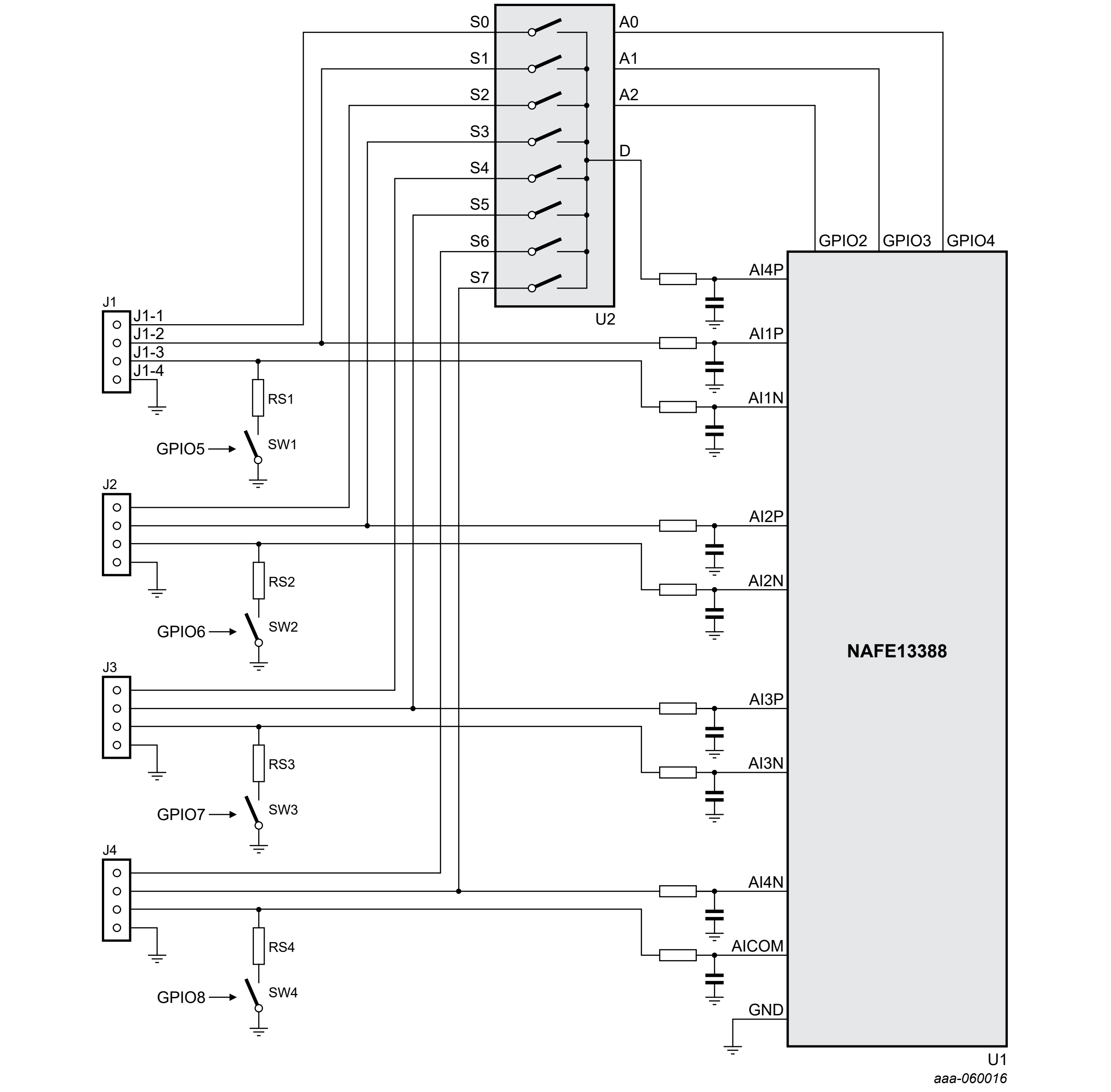

Figure 2. Application schematic

Table 2. Transducers configuration summary

	Voltage input	Current input	4-wire RTD	3-Wire RTD	2-wire RTD	Thermocouple	Wheatstone
J1	AIP-AIN	AI1N-GND	Force: S0-GND Sense: AI1P-AI1N	Force: S1-GND Sense: AI1P-AI1N	Force/Sense: AI1P-AI1N	AIP-AIN CJC: GPIO0-1	Force: S0-GND Sense: AI1P-AI1N
J2	AI2P-AI2N	AI2N-GND	Force: S2-GND Sense: AI2P-AI2N	Force: S3-GND Sense: AI2P-AI2N	AI2P-AI2N	AI2P-AI2N CJC: GPIO0-1	Force: S2-GND Sense: AI2P-AI2N
J3	AI3P-AI3N	AI3N-GND	Force: S4-GND Sense: AI3P-AI3N	Force: S5-GND Sense: AI3P-AI3N	AI3P-AI3N	AI3P-AI3N CJC: GPIO0-1	Force: S4-GND Sense: AI3P-AI3N

Table 2. Transducers configuration summary*...continued*

	Voltage input	Current input	4-wire RTD	3-Wire RTD	2-wire RTD	Thermocouple	Wheatstone
J4	AI4N-AICOM	AICOM-GND	Force: S6-GND Sense: AI4N-AICOM	Force: S7-GND Sense: AI4N-AICOM	AI4N-AICOM	AI4N-AICOM CJC: GPIO0-1	Force: S6-GND Sense: AI4N-AICOM

Note: *CJC: cold junction compensation*

5 Detailed operation

In this section the operation for the supported transducers is described:

- Voltage Input
- Current Input
- 4-wire RTD
- 3-wire RTD
- 2-wire RTD/PTC/NTC
- Thermocouple with cold junction compensations
- Wheatstone bridge

Table 3 summarizes the supported sensors. The min/max values refer to the nominal signal range inside which the NAFE13388 accuracy specifications are guaranteed. An extended range is also supported.

Table 3. Supported transducer nominal signal range

Sensor	Linear range		Extended range
	Min	Max	
Voltage input	-10 V	0 V	±12.5 V
Current input [Rs = 250 Ω]	-40 mA	40 mA	±50 mA
4/3/2-wire RTD	All types		For example, Pt100, Pt1000
NTC, PTC	1 mΩ	1 MΩ	
Thermocouple	All types		
Wheatstone Bridge (impedance)	2.5 kΩ		Lower impedance values supported with additional current buffer.

In the following sections, the examples are all referred to J1 connector. All the cases can be applied, as well, to the other connectors according to Table 3

5.1 Voltage input

The NAFE13388 measures the most common industrial voltage sensors without any need of external components. The linearity range is guaranteed between -10 V and 10 V. However, the NAFE13388 is able to measure the voltage up to ±12.5 V. The S0 and S1 switches of U2 are open.

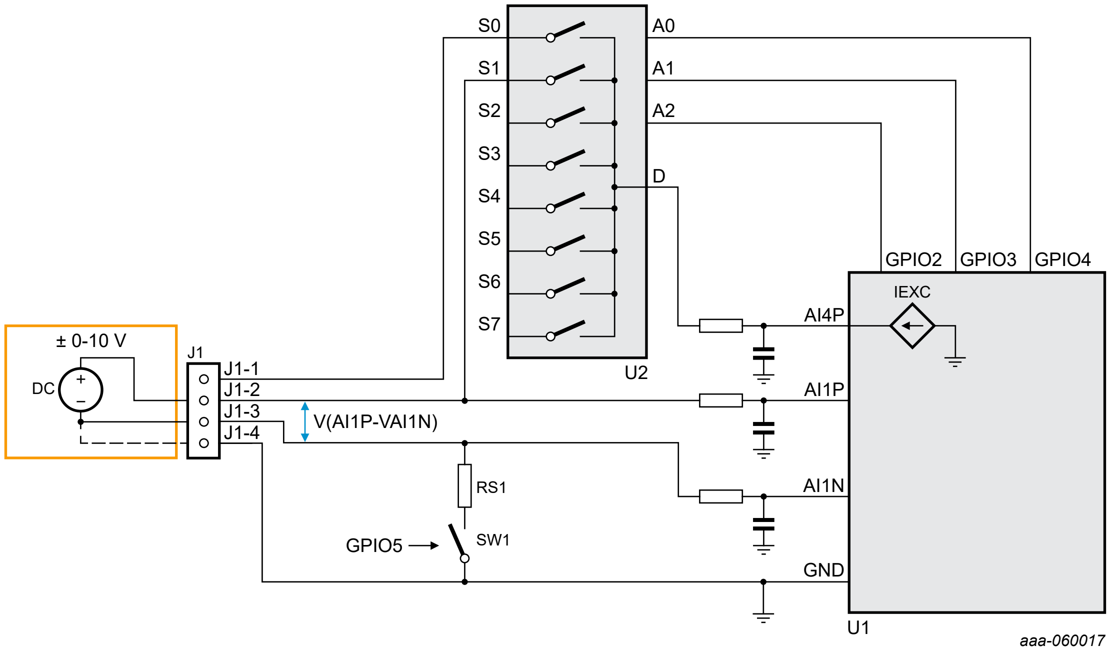

Figure 3. Voltage input configuration

The voltage is measured between J1-2 and J1-3 in differential mode, a single-ended configuration is also possible by connecting the transducer between J1-2 and J1-4.

5.2 Current input

The NAFE13388 measures the typical 4-20 mA or 0-20mA current loop transducers by sensing the voltage across the sense resistor RS1.

To close the current path, the SW1 switch is closed. In Figure 4, the equivalent series resistor of SW1 is also shown. The sum of RS1 and RSW1 translates the current into voltage, which is measured between AI1N and GND pins.

The S0 and S1 switches of U2 are open.

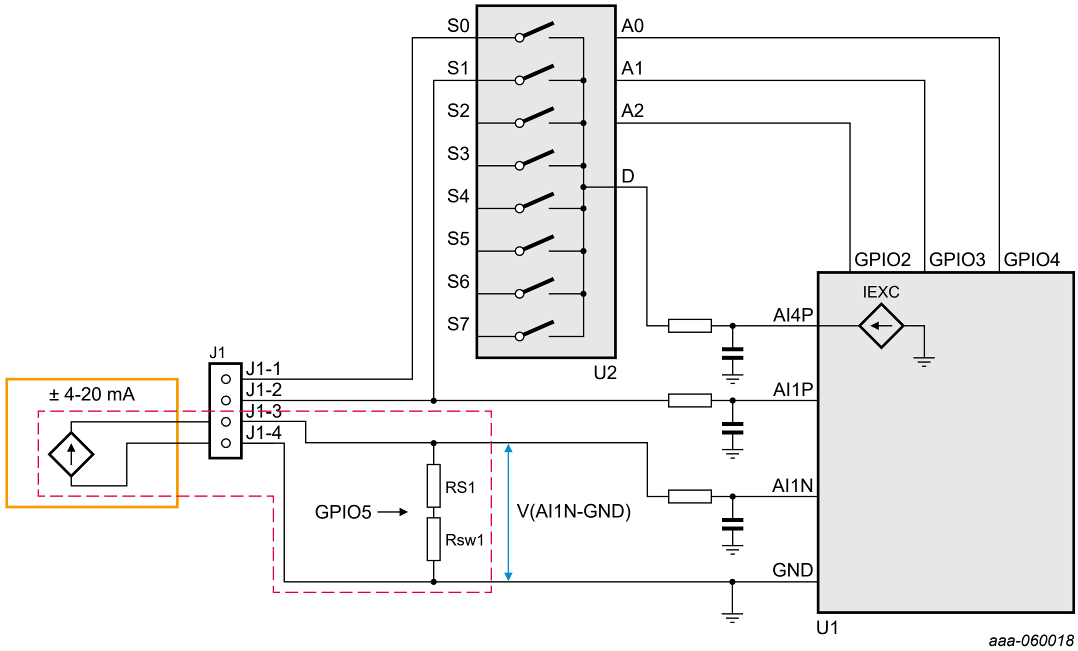

Figure 4. Current input configuration

5.3 4-wire RTD

The 4-wire RTD measurement is implemented by injecting the current using the integrated current source in the NAFE13388. The current is routed to J1-1 by closing the S0 switch of U2. It goes through the RTD and returns to ground. Figure 5 shows the resulting current flow. The equivalent series resistances, RL1 to RL4, of the RTD wires are also shown. As the current does not flow through the sensing wires, the resulting voltage of VAI1P-VA1N provides the measurement with good accuracy.

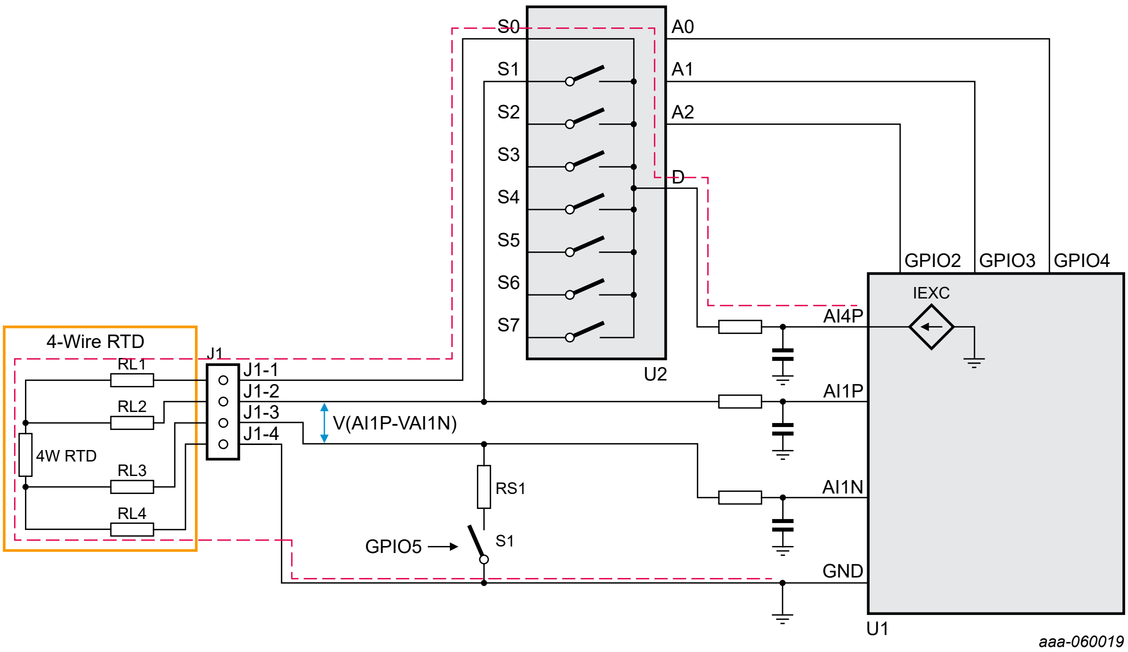

Figure 5. 4-wire RTD configuration

5.4 3-wire RTD

For the 3-wire RTD measurement, the current is injected by the integrated current source of the NAFE13388. The current is routed to J1-2 by closing the S1 switch of U2. It goes through the RTD and returns to ground. Figure 6 shows the resulting current flow. The equivalent series resistances, RL1 to RL3, of the RTD wires are also shown. The resulting voltage (V1) is measured between J1-2 and GND. As the wire resistances RL1 and RL3 are also part of the current flow, the measured voltage also includes the wire resistances contribution. The NAFE13388 reduces the error caused by this wire resistance by also measuring the voltage (V2) between J1-3 and GND, which measures the voltage drop caused by RL3 only.

The RTD resistance is calculated as:

$$R_{RTD} = (V1 - 2 \times V2) / \text{IEXC}$$

A detailed description and test results of a 3-wire RTD system with NAFE13388 can be found in Reference [3].

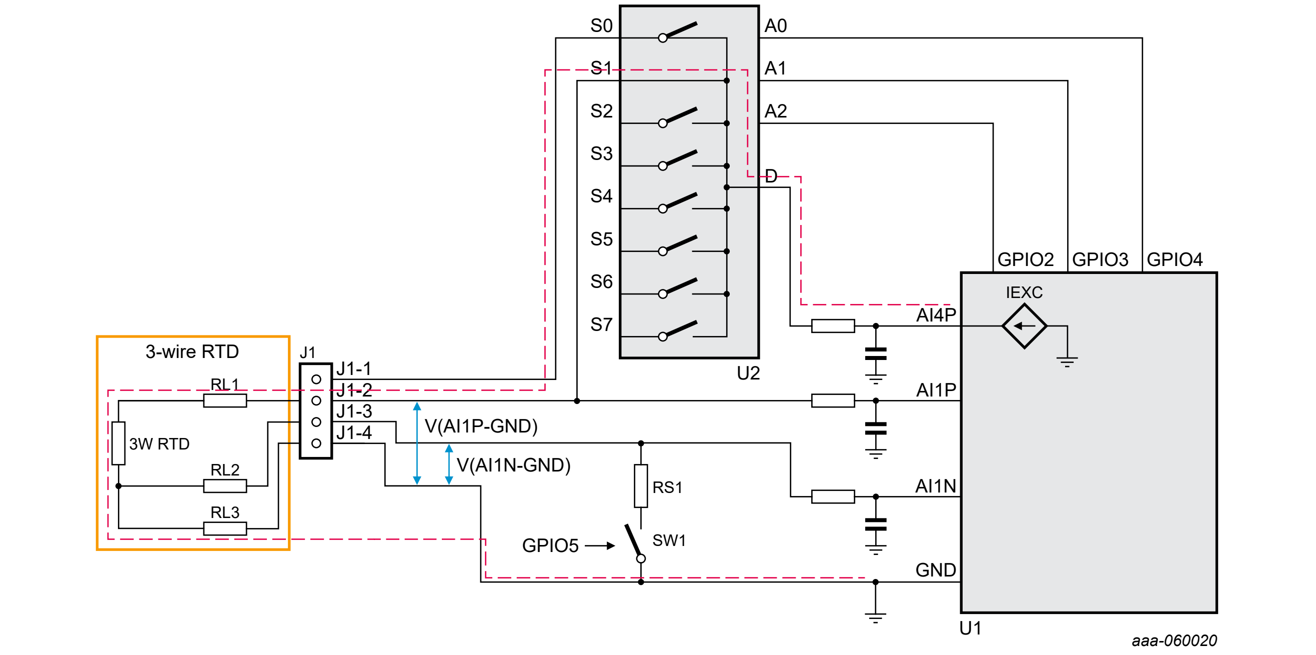

Figure 6. 3-wire RTD configuration

5.5 2-wire RTD/PTC/NTC

The 2-wire RTD measurement is the simplest one, but also the least accurate. As seen in the 3-wire RTD configuration, the current is injected through S1, goes to the J1-2 pin, and returns to ground. This time there is no way to estimate or measure the wire resistance RL1 or RL2. The resulting voltage measurement contains the error given by those resistances. To minimize the impact of these resistances, it is recommended to have R_{RTD} >> RL1 and RL2. A Pt1000 RTD with short-wire connection is a configuration where the error can be acceptable.

The same configuration can measure NTC and PTC. These transducers typically have a high value of resistance so the 2-wire configuration achieves good accuracy.

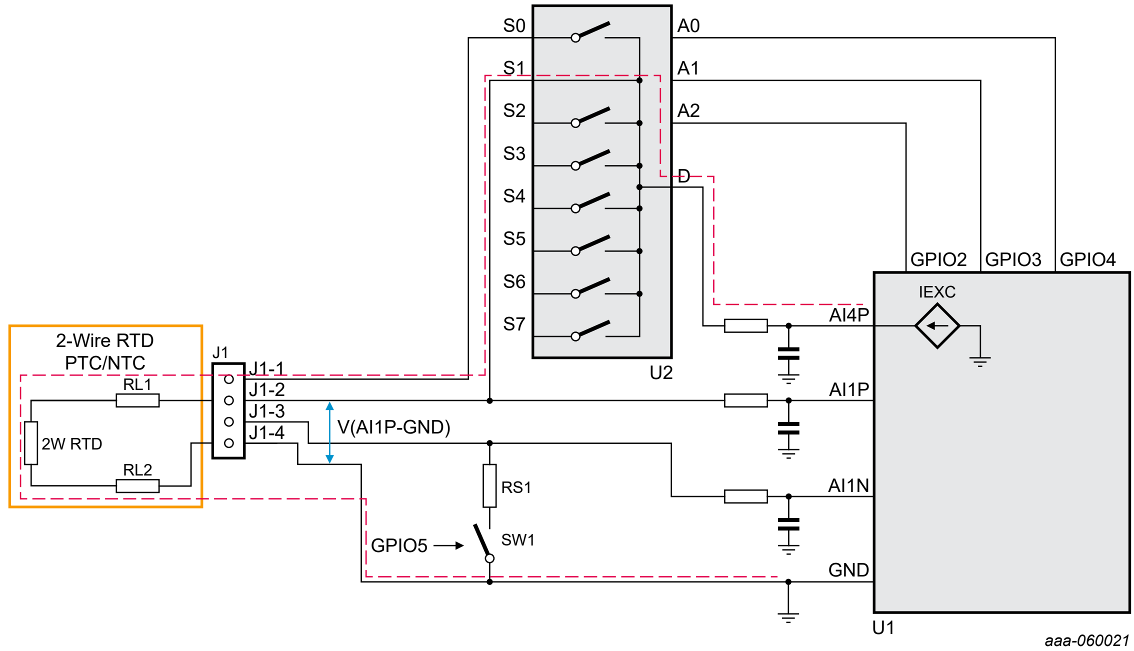

Figure 7. 2-wire RTD/PTC/NTC configuration

5.6 Thermocouple with cold junction compensation

Thanks to the bipolar input range, the NAFE13388 measures thermocouple voltages without the need of bias resistors. This allows implementing the universal input capability without additional switches that typically disconnect the bias resistors in case of other transducers (RTD for example).

In the typical case when a Common mode voltage has to be fixed for the thermocouple, the excitation (VIEXC) can be configured as voltage output on either the AI1P or the AI1N pin. A VIEXC value of some millivolts (DAC code 1-3) allows to fix the Common mode voltage without exceeding the full-scale input.

In addition, the NAFE13388 supports cold junction compensation measurement by using the low-voltage auxiliary inputs of the ADC available at the GPIO0 and GPIO1 pins.

Figure 8 shows the implemented configuration. The thermocouple voltage is measured differentially between J1-2 and J1-3. An onboard Pt100 is used to measure the cold junction temperature. The Pt100 current is set by using the precise voltage reference output REF_BYP and the two low-temperature coefficient resistors R1 and R2. The Pt100 voltage is measured by the auxiliary inputs GPIO0/GPIO1.

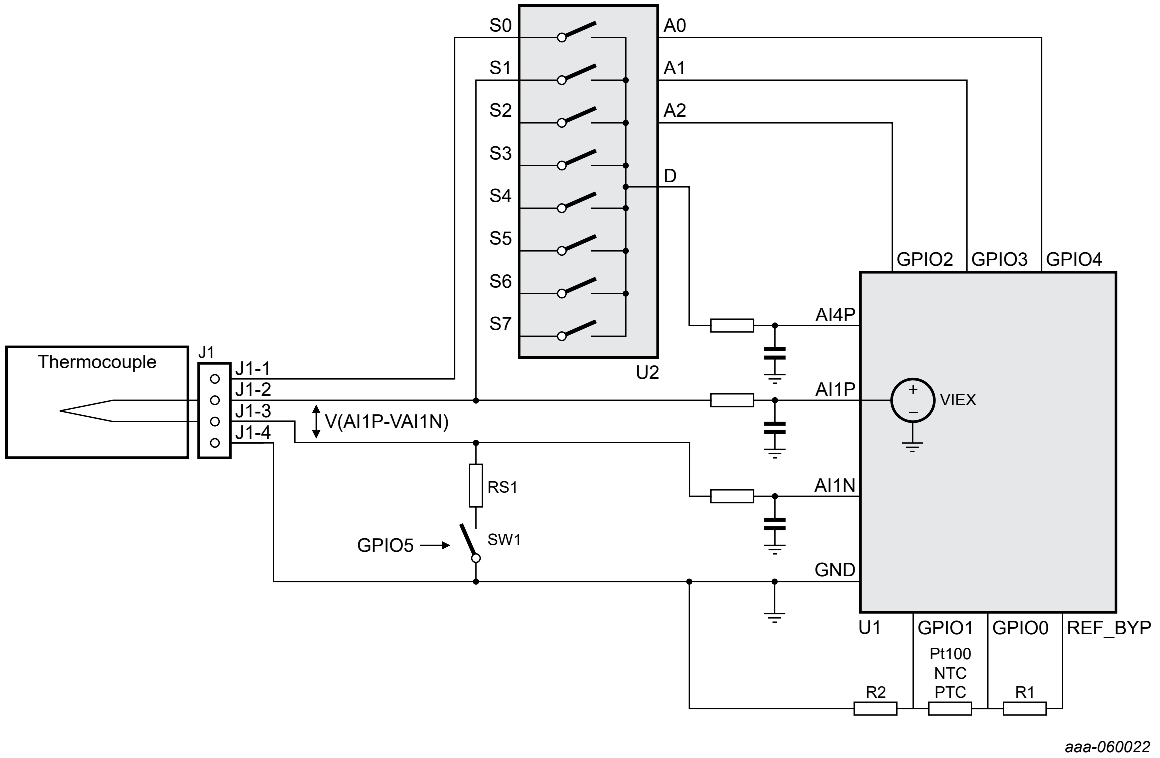

Figure 8. Thermocouple with cold junction compensation configuration

5.7 Wheatstone bridge

The NAFE13388 excitation source can also be configured as voltage output. In this way, it is possible to support a Wheatstone bridge measurement without additional components.

When configured as voltage output, the excitation source has an output impedance of 500 Ω. The applied voltage at J1-1 is the result of the excitation impedance and bridge impedance that work as a resistor divider. In case the measured Wheatstone bridge has low impedance, a voltage buffer might be needed.

The bridge output is measured differentially between AI1P and AI1N.

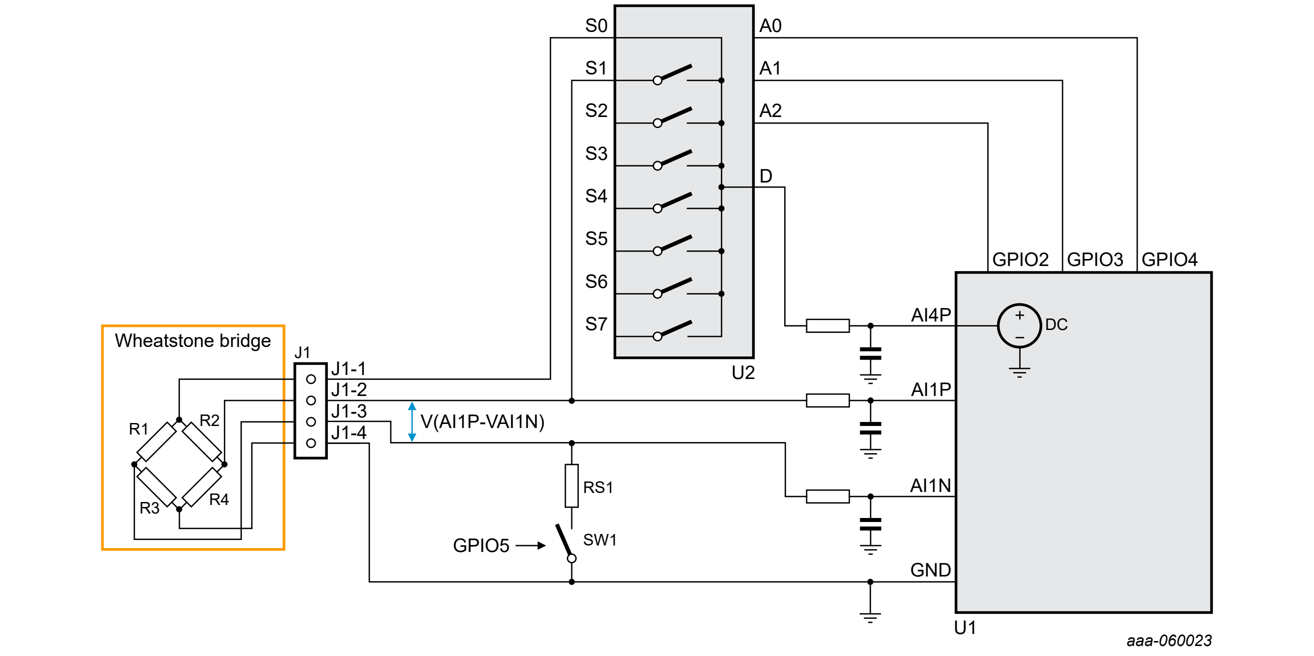

Figure 9. Wheatstone Bridge configuration

6 Universal input solution test results

The performance tests for a specific transducer input can be found in dedicated documents (References [1], [4].

In this document, the scenario in which different types of transducers are connected to the inputs has been considered. This determines a challenge on the AI-AFE signal chain, which must avoid interactions among the various transducers.

Table 4 shows the configuration used in the test. Each connector has a different type of sensor. Six logical channels LCH0 to LCH5 are used and activated to store the various settings and to allow the sequencer to perform the conversions.

Table 4. Transducers input connections and AFE settings

	Input type	Logical channel	IN+	IN-	Excitation	PGA	Data rate	Digital filter
J1	Voltage input	LCH0	AI1P	AI1N	OFF	0.2x	1 kSPS	SINC4+2
J2	Current input	LCH1	GND	AI2N	OFF	0.4x	1 kSPS	SINC4+2
J3	RTD: 3-wire Pt100	LCH2	AI3P	AI3N	S5	16x	50 SPS	SINC4+3
		LCH3	GND	AI3N	S5			
J4	Thermocouple with CJC	LCH4	AICOM	AI4N	OFF	16x	50SPS	SINC4+3
	Pt100 fo CJC	LCH5	GPIO0	GPIO1	OFF	-	50 SPS	SINC4+3

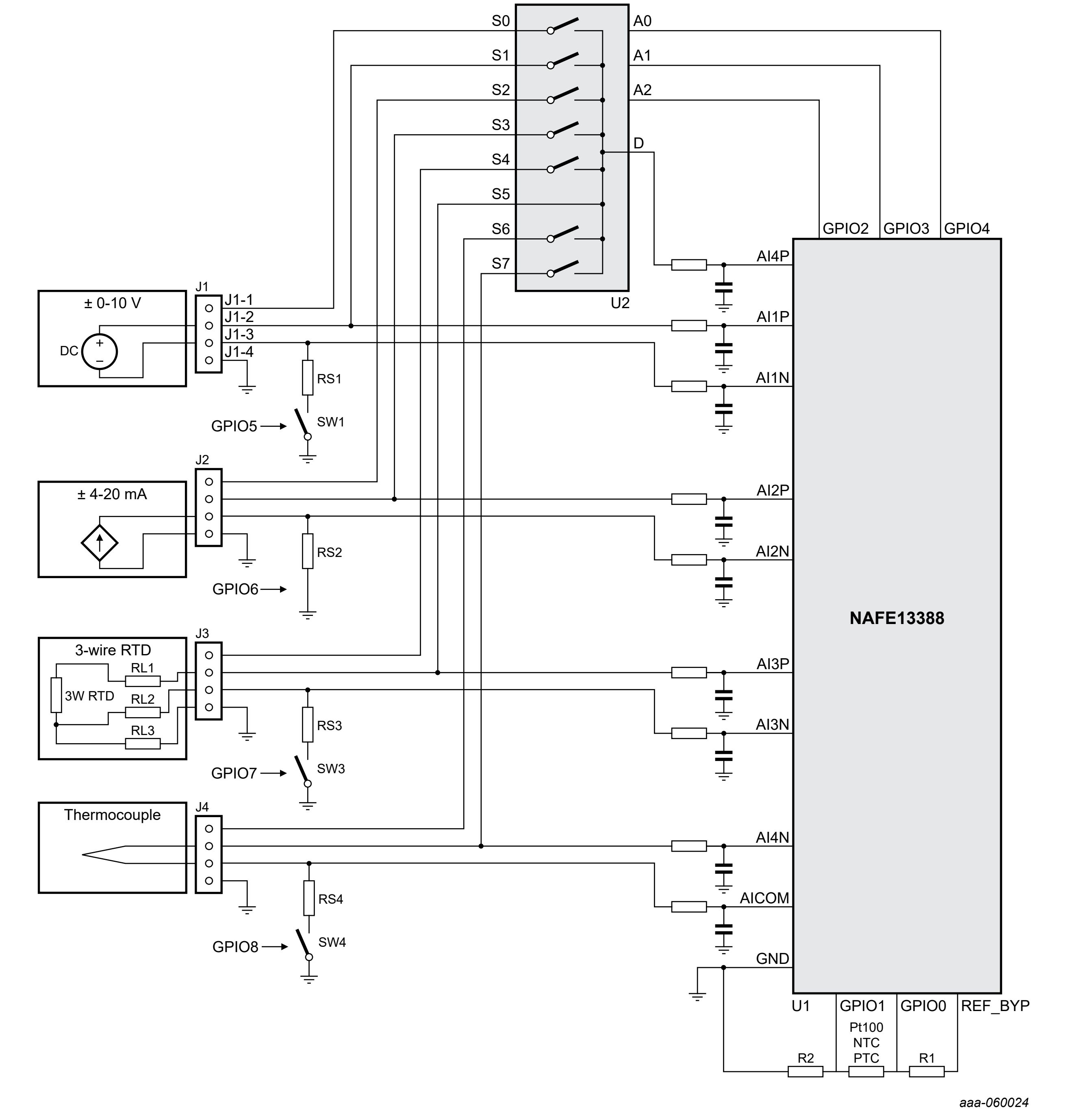

Figure 10. Schematic of the configuration under test

For the voltage input on J1, a gain of 0.2x has been used. This gain setting allows measuring voltages up to ±10 V in Unipolar mode and ±20 V differentially. See Table 1 for detailed values of nominal and min/max ranges according to different PGA gains.

For the current input (J2), a 250 Ω sense resistor has been used in all channels. A normally open MOSFET relay SPST activates the current input path. The SPST has a series resistance of around 7 Ω. This additional resistance is also part of the voltage-to-current conversion during the onboard calibration. The resulting voltage is around 5 V, so a gain of 0.4x has been used for the PGA.

The Pt100 RTD is emulated with a 100 Ω resistor connected as a 3-wire RTD. The wires are 10-meter AWG25 cables. The resistance of each wire is around 1 Ω.

The thermocouple signal is emulated with a voltage source of around 5 mV, and the CJC is implemented with a Pt100 RTD as described in Section 5.6.

Table 5 summarizes the test results. All the channels have been calibrated with the two-points calibration method described in Reference [1]. All the measurements have been verified using a digital multimeter (DMM), and calculating the errors as percentage.

Table 5. Measurement results

Function	Logical channel	IN+	IN-	PGA	Data rate	SINC filter	VIEXC	DMM	MEAS	Error [%]
Voltage input	0	AI1P	AI1N	0.2	1k	SINC4+2	OFF	6.995 V	6.996 V	0.017 %
Current input	1	AI2P	GND	0.4	1k	SINC4+2	OFF	14.211 mA	14.216 mA	0.036 %
3-wire RTD	2	AI3P	GND	16	50	SINC4+3	S5	—	0.050836 V	—
	3	AI3N	GND	16	50	SINC4+3	S5	—	0.000504 V	—
	—	$(V_{LCH2}$-2*$V_{LCH3})$/IEXC		—	—	—	—	99.690 Ω	99.656 Ω	-0.034 %
Thermocouple	4	AI4N	AICOM	16	50	SINC4+3	OFF	0.005160 V	0.005156 V	-0.078 %
CJC	5	GPIO0	GPIO1	x	50	SINC4+3	OFF	0.04541 V	0.04540 V	-0.010 %

The 3-wire RTD measurement needs a detailed explanation to describe the implemented wire cancelation technique, see Reference [3].

Logical channel 2 (LCH2) and logical channel 3 (LCH3) has been configured to measure AI3P vs GND and AI3N vs GND.

The system has been previously calibrated by measuring two precise test resistors on LCH2 to perform the two points calibration. After the onboard calibration, the emulated Pt100 resistor with 10-meter cable is tested.

As anticipated in Section 5.4, in LCH2 measurement, the result is the composition of the voltage drop in RL1, RTD and RL3, while in LCH3 only the RL3 contribution creates the voltage drop. As usual, in 3-wire RTD systems, assuming RL1 = RL2 = RL3, the measurement of RTD is obtained as:

$$R_{RTD} = \left(V_{LCH2} - 2 \times V_{LCH3}\right) / \mathrm{IEXC} = \left(0.050836 - 0.001008\right) / 500^{-6} = 99.656\Omega$$

The test resistor was measured with DMM to be 99.960 Ω , so the error corresponds to 0.09 °C.

For CJC, the following formula provides the relationship between the voltage measured V_{MEAS} on GPIO0-1 and the resistance value:

$$\mathrm{R}(Pt100) = \frac{V_{MEAS}(R1+R2)}{VREF-V_{MEAS}} = 109.215\ \Omega$$

Where:

$$R1 = R2 = 2.94\ k\Omega$$

$$VREF = 2.49\ V$$

$$V_{MEAS} = 0.0450\ V$$

(per Table 5)

The measured resistance corresponds to a cold junction temperature of 23.93 °C.

7 Summary

The proposed solution implements a four-channel, fully configurable universal-input system. All the channels are exchangeable and each channel supports all the most common transducers used in industrial applications.

The logical channels feature of the NAFE13388 allows implementation of the universal input thanks to the possibility to configure different settings for analog inputs, gain, data rate, and excitation source on each logical channel.

The test results show good performance, even when high-amplitude signals and small signals are applied on different channels at the same time.

8 References

[1] AN14102 - Industrial application measurements using NXP AFE

[2] NAFE13388 NAFE13388/NAFE73388 data sheets

[3] AN14127 - RTD measurement system with NAFE13388/73388 family of devices

[4] AN14539 - 3-wire RTD with NAFE13388

9 Revision history

Table 6. Revision history

Document ID	Release date	Description
AN14547 v.1.0	28 March 2025	Initial version

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