

White Paper

MCU-based High-accuracy Measurement System

Pedro Pachuca, Sr. Manager, Renesas Synergy™ Product Marketing, Renesas Electronics Corp.

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Abstract

Measurement systems play a critical role in industrial, medical, and building automation applications where data collected from sensors can be used to improve efficiency, ensure reliability, or make certain that equipment is operating safely. This document outlines how MCU-based high-accuracy systems can be implemented to reduce the bill of materials, simplify design, and shorten time to market.



Introduction

Sensors such as temperature, force, pressure, pH, and bio-sensors are commonly used in medical, factory, and building automation applications. These sensors produce an electrical analog signal that correlates to a physical property that the sensor is designed to detect or measure. Most of these sensors provide a low-level analog output signal that is susceptible to noise. For highly accurate data acquisition, systems are required to secure the integrity of the signal and amplify and convert the signal to levels that can be interpreted by a digital system.

Sensors are also classified as *Passive or Active*:

- Passive sensors, such as thermocouples, generate output signals without the need for an excitation source.
- Active sensors, such as bio-sensors or thermistors, require an external source of excitation. These sensors also require a current or voltage for excitation to produce an electrical output.

Whether the sensors are passive or active, designers are confronted with the challenges of designing an accurate system while keeping costs down and meeting demanding deadlines. Reducing design complexity is one of the primary options for overcoming these challenges.

The white paper will discuss how MCU-based high-precision data acquisition systems reduce design complexity by eliminating external components due to high integration and flexibility challenges. The Renesas Synergy™ S1JA Group MCU is used as an example due to its highly integrated, high-accuracy analog capabilities. Its novel implementation of analog switches as an interconnect fabric, which is software controllable and strategically implemented as part of the operational amplifier IP, enables the greatest flexibility to develop from basic analog circuits to complex analog blocks with minimum external components.

Measurement Systems

A fundamental measurement system is primarily composed of three stages: sensor, signal conditioning, and signal processing as shown in Figure 1. The sensor stage converts a physical property (e.g., force) into an electrical signal (e.g., voltage, current, resistance, capacitance, etc.). The signal conditioning stage converts the variation of a small signal into a level that is more suitable for additional processing. The signal processing stage converts an analog signal into a digital representation – a digitalized signal enables further analysis that allows the system to implement certain tasks or behaviors.

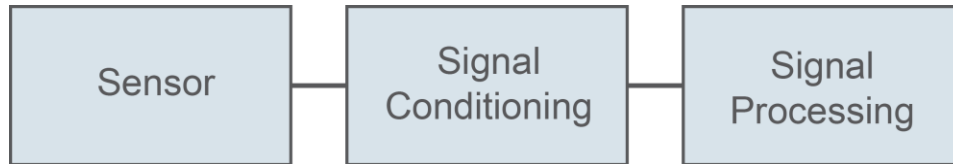


Figure 1: Fundamental Measurement System

The signal conditioning stage is of vital importance to guarantee the success of the measurement system. The sensor's signals are often fairly sensitive and very small in amplitude. The granularity of the output requires special care while being amplified, and noise, whether internally generated or externally induced or conducted, manifests as an error, which tends to distort information from the signal. As part of the signal conditioning stage, active sensors require an excitation signal, which can be constant or dynamic. Bio-sensors are a good example of active sensors that require dynamic excitation. To properly activate the sensor, a range of variable signals should be carefully applied over time to allow for chemical reactions to be completed. The accuracy and granularity of the excitation signal is extremely important to guarantee the reliable output of the sensor signal.

Electronic components used in signal conditioning must be carefully selected as some of the electrical specifications can significantly affect the quality of the signal conditioning stage. A brief explanation of signal conditioning circuits is included in this document, as well as the impact of some of the most important electrical characteristics of the electronic components most commonly used in signal conditioning circuits.

The signal processing stage is commonly implemented with data converters such as analog to digital converters and linearization circuits. The accuracy and precision of the analog to digital converters is of special interest as the impact of these two specifications can have considerable influence on the overall measurement system. We define accuracy as the error between the real and measured value. If this error is too large, our measurement system may lead to an erratic or wrong behavior of our entire system. This document exposes some of the most common elements of signal processing and their electrical specifications.

Due to its high integration of analog functions, flexibility, and ease of use, the Renesas Synergy S1JA MCU is used as an example to explain the signal conditioning and signal processing stages, as well as to highlight the key electrical specifications of the analog functions.

Signal Conditioning Circuits

The full-scale output from a sensor is relatively small and, therefore, their output should be properly conditioned before digital processing can be applied. Figure 2 shows the most common signal conditioning circuits such as amplification, filtering, and impedance coupling.

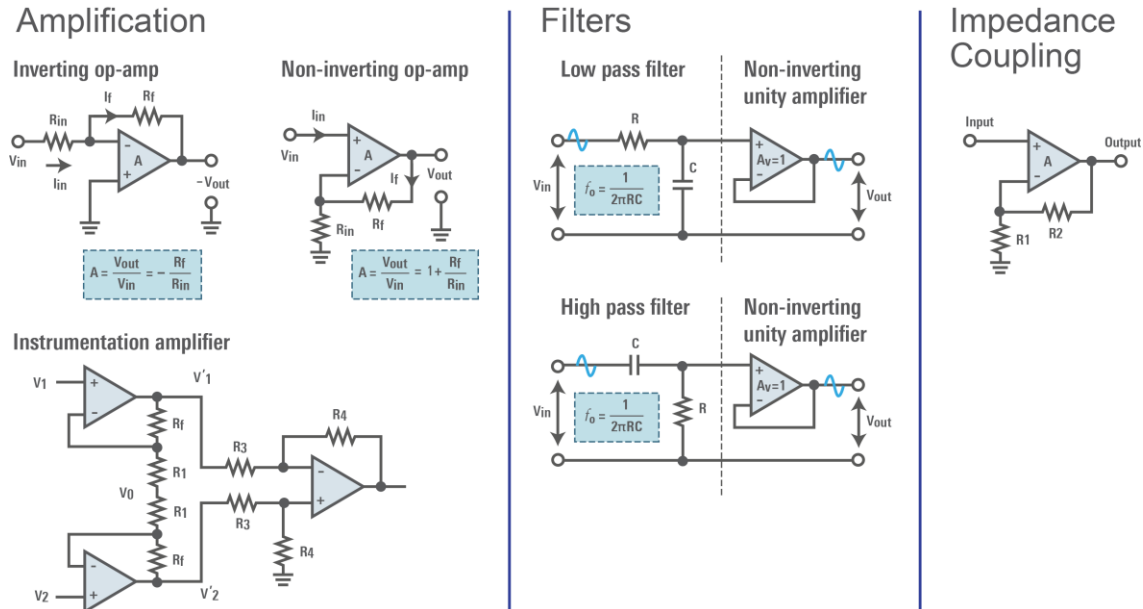


Figure 2: Signal Conditioning Circuits

Traditionally, signal conditioning circuits are implemented using external standalone components (OP-AMPS). Sensitive specifications, such as input offset, rail-to-rail operation, and input noise density were very difficult to achieve in an integrated microcontroller product. However, advances in technology process and design techniques allow implementation of these circuits with very high-quality and reliable specifications.

For example, the Renesas Synergy S1JA MCU offers three different operational amplifiers. In addition, a novel implementation of analog switches as an interconnect fabric is strategically implemented to allow users to design signal conditioning circuits with minimal external components. Figure 3 shows the operational amplifier implementation; a brief description of its flexibility is also included.

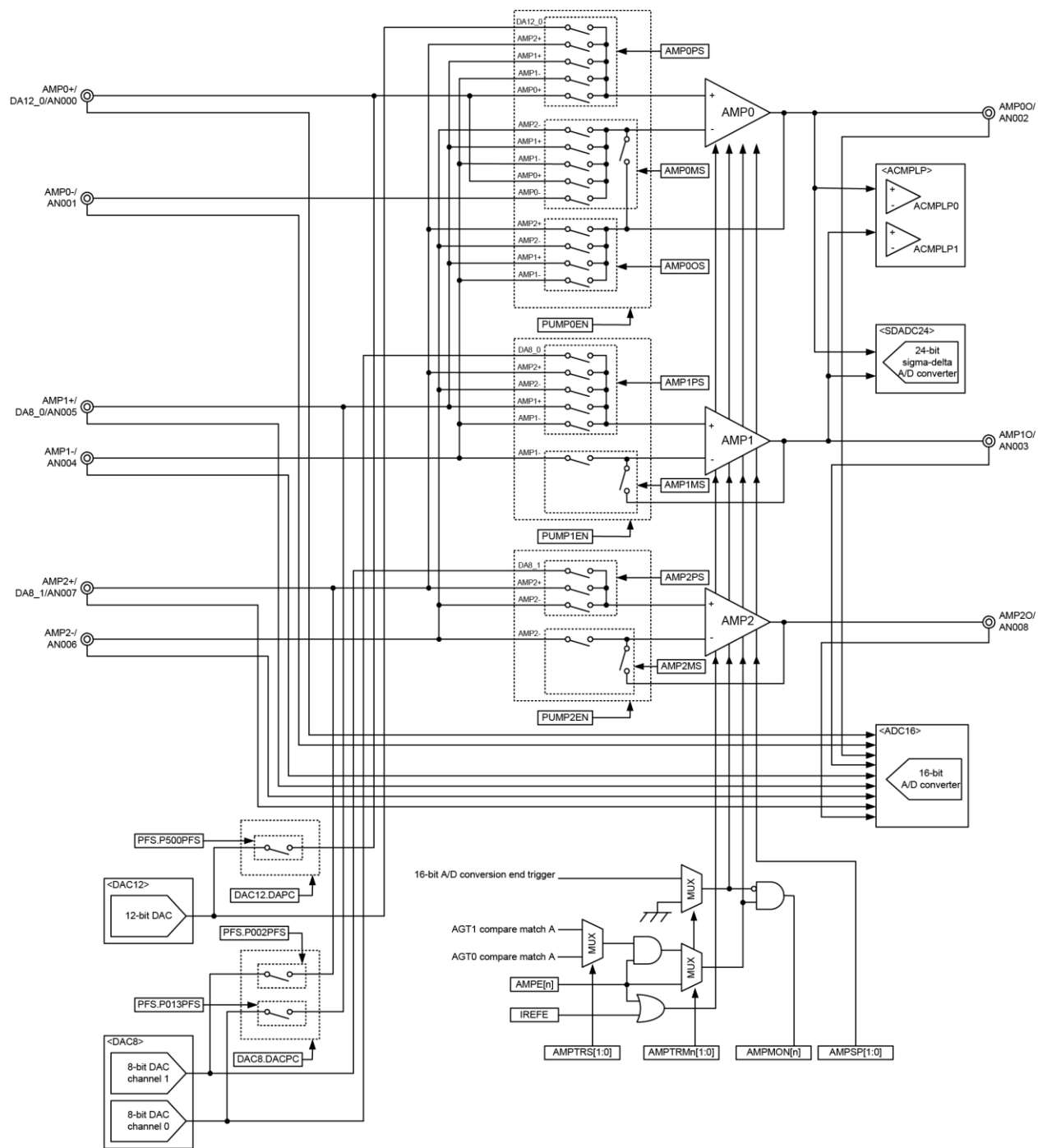


Figure 3: Renesas Synergy S1JA operational amplifier implementation for signal conditioning

S1JA Integrated OPAMP Configuration Capabilities

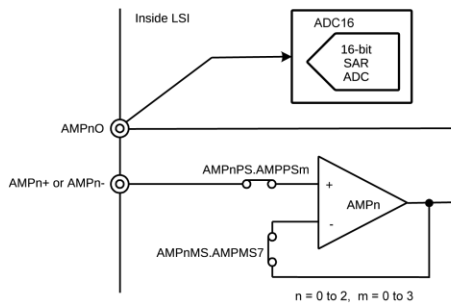
The S1JA MCU's integrated operation amplifier provides the following capabilities and functional modes, which enhances the number of configurations that can be implemented. The internal connections reduce the PCB complexity by eliminating the need to use external PCB traces.

- OPAMP0 and OPAMP1 of the three units can be used to input signals to the Low-Power Analog Comparator (ACMPLP) and the 24-bit Sigma-Delta A/D Converter (SDADC24)
- High-speed mode (high current consumption), middle-speed mode (medium current consumption), and low-power mode (slow speed response) are supported, and any mode is selectable based on trade-offs between the response speed and current consumption
- Operation can be started by a trigger from the Asynchronous General-Purpose Timer (AGT)
- Operation can be stopped by a 16-bit A/D conversion end trigger
- All units have switches that can select input signals. Additionally, OPAMP0 has a switch that can select the output pin
- The output of the OPAMP can be output from the AMP0O to AMP2O pins without passing through the switch
- The I/O signals of all OPAMP units can be used for the input signals to the ADC16
- The signal output from the DAC8 and DAC12 can be used as the positive input signal for each OPAMP
- A voltage follower circuit can be configured by feeding back its own OPAMP output signal as the negative input signal of OPAMP.

Figure 4 shows how common signal conditioning circuits can be easily implemented using the interconnect switch fabric, which is software controllable (detailed information can be found in the S1JA user manual at renesas.com).

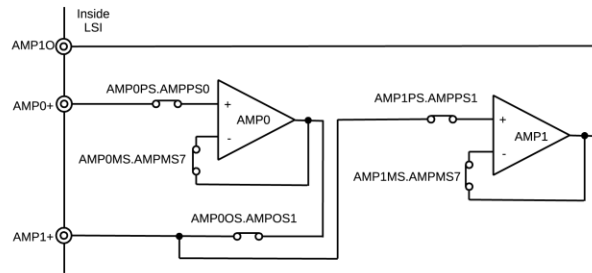
Voltage Follower

Use general operational amplifier can configure a voltage follower by feeding back its own output signal as its own negative input signal.



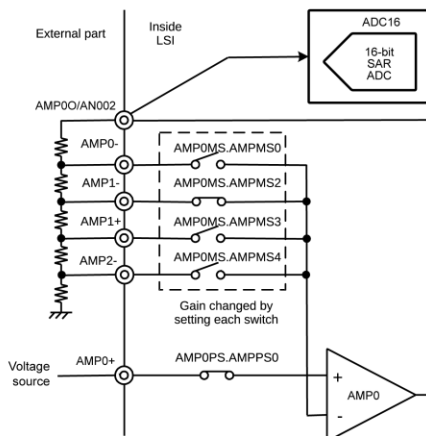
Cascade Voltage Follower

Use general-purpose analog port n (AMP1+, AMP1-, AMP2+ or AMP2-) to input the pre-amplifier output signal to the post amplifier. To connect the signal output from the voltage follower of operational amplifier 0 to the positive input of operational amplifier 1.



Programmable Non-inverter Amplifier

A programmable non-inverting amplifier can be configured using a combination of configurable switches and external resistors connected to general-purpose analog ports.



Programmable Trans-impedance Amplifier

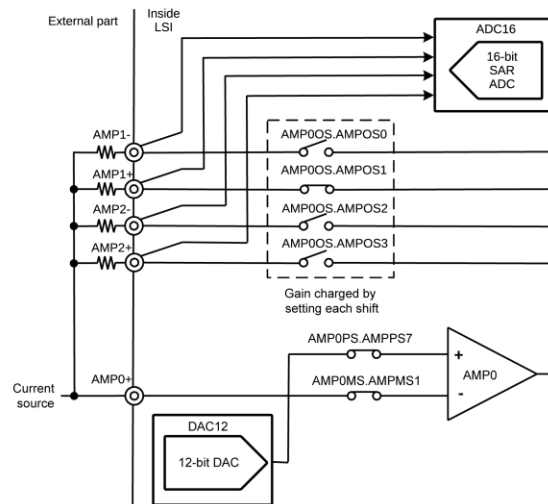


Figure 4: Signal conditioning circuit implementation using the Renesas S1JA MCU

Additional configurations such as the instrumentation amplifier and digital-to-analog buffer amplifier can be easily implemented using the interconnect switch fabric. As a software configurable interconnect fabric, some configurations can be done on the fly, opening the door to a new level of applications. In addition to flexible configurability, the S1JA's operational amplifiers offer user trimming capability to adjust offset to suit the user's requirements.

Signal Processing Circuits

One of the elemental analog functions in the signal processing chain is the analog-to-digital converter (ADC) whose basic function is to take an analog system and create a digital representation. ADCs are at the front end of any digital circuit that needs to process signals coming from the exterior world.

Depending on the specific application requirements, a type of ADC is chosen. However, although there are many types of ADCs, their primary function is the same -- convert a certain signal to a certain number of bits. For illustration purposes, below is an example that explains the basic functionality of an ADC using the staircase ramp technique.

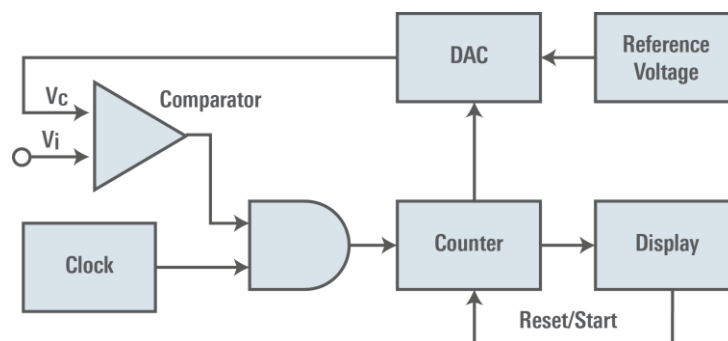


Figure 5: ADC basic functionality

Basic Principle: V_i input is compared with an internal staircase voltage. At the start of a measurement, $V_c = 0$ and the counter is set to 0. The comparator output is set that when $V_i > V_c$, the comparator output opens the gate and the counter starts counting based on clock input. The counter feeds the DAC, which starts generating an output voltage, increasing the V_c . When V_c is equal or slightly greater than V_i , the comparator output changes polarity and closes the gate, stopping the counter. The number of counts is proportional to V_c and, hence, to V_i , and the counter holds the digital representation of the signal value.

As mentioned before, there are many types of ADCs. In this document, we will focus on Successive-Approximation Register and Sigma Delta ADCs and how these ADCs are implemented in the Renesas Synergy S1JA MCU to provide a complete measurement system.

Renesas Synergy S1JA Successive-Approximation Register (SAR) ADC

The S1JA MCU provides a 16-bit successive approximation analog-to-digital converter. The implementation of this ADC enables users to reduce the bill of materials and simplify the design by working in conjunction with the operational amplifier and the interconnect fabric of analog switches, as well as by using the internal resources of the MCU, such as precision voltage references, and eliminating the dedicated external crystal, which is an external ADC component. Figure 6 shows the S1JA's SAR ADC implementation details.

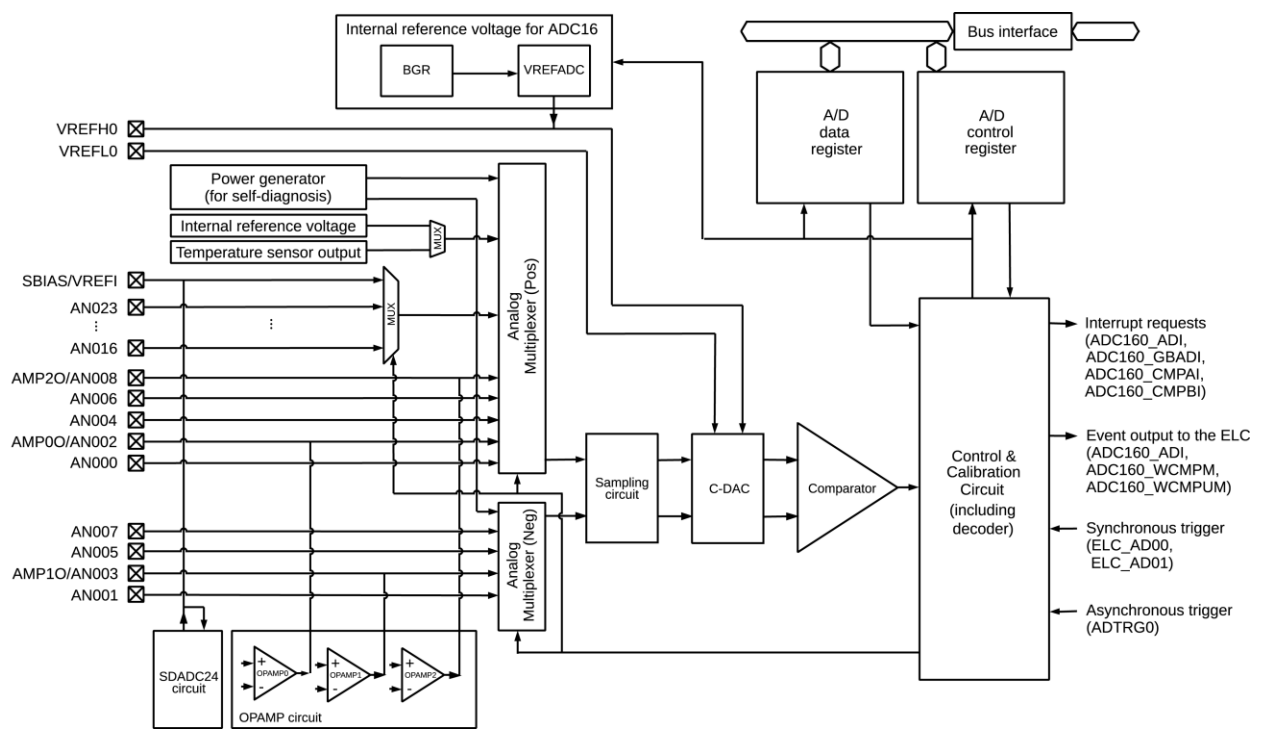


Figure 6: S1JA's SAR ADC implementation

The S1JA SAR ADC provides up to 17 analog input channels and an internal reference voltage that can be selected for conversion, which is one of the significant options for reducing the bill of materials. The internal reference voltage is programmable for 1.5 V, 2 V and 2.5 V typical values. With this wide range of options, users can eliminate external voltage references.

The S1JA internal operational amplifiers that can be used for signal conditioning can be internally connected to the SAR ADC inputs, eliminating external routing that can compromise the signal integrity. Additionally, safety functions such as self-diagnosis and analog input disconnection detection eliminate the need for an external component to monitor proper ADC functionality.

Table 1 provides a quick overview of the electrical specifications of S1JA's SAR ADC.

Table 1: S1JA's SAR ADC technical specifications

Parameter	Typical value	Unit	See user manual for specific conditions
Resolution	16	bit	
Integral non-linearity	± 4	LSB	
Differential non-linearity	-1 to +2	LSB	
ENOB	13.2	bit	
Conversion time	0.82	μS (per channel)	

The S1JA SAR ADC also provides calibration capabilities to allow high-precision measurements by obtaining the linearity error correction and gain (offset) error correction values from the internally generated analog input under usage conditions in the C-DAC stage. This enables users to calibrate the ADC at the beginning of each measurement to obtain the best results. Calibration is performed based on the following three steps:

- Step 1 – When ADC conversion starts, the correction values for C-DAC linearity error and gain are calculated
- Step 2 – When calculation of all values is completed, the ADC interrupt calibration is generated
- Step 3 – Calibration is completed and the user can start a scanning procedure

Calibration time is estimated to be completed in approximately 24.22ms when the ADC clock is equal to 32MHz.

Renesas Synergy S1JA 24-bit Sigma-Delta A/D Converter

Sigma-Delta ADCs basically consist of an oversampling modulator and a digital/decimation filter working together to produce high-resolution data-stream output. These ADCs are widely used in industrial applications ranging from temperature sensors and industrial weight scales to process control sensors. Typical standalone Sigma-Delta ADCs require an external precision voltage reference and external clock; these external components add design complexity and cost to the overall design.

The Renesas Synergy S1JA MCU provides an integrated solution that supports single-ended and differential measurement capability. A selectable voltage reference can use an internal voltage reference over a range of 0.8 V to 2.4 V, in increments of 0.2 V, which allows an extensive and flexible selection to accommodate a large range of application requirements. In addition, the 24-bit Sigma-Delta A/D converter clock is generated from the MCU peripheral clock, eliminating the need for an external clock, thus, reducing costs and design complexity while increasing system reliability.

Power-sensitive designs require low power operation, and the S1JA integrated Sigma-Delta ADC offers a low power conversion mode using a reference clock from 125 KHz to 500 KHz. This is achieved by using an internal frequency divider in the MCU, eliminating the need for an external low frequency clock.

In a typical measurement system, the output of the signal conditioning system is connected to the Sigma-Delta ADC to convert the analog signal into a digital representation. This connection can be easily accomplished using the analog switch “interconnect-fabric” of the integrated OPAMPs, eliminating the need for external connections and simplifying the PCB design, as shown in Figure 7. The OPAMP0 output and OPAMP1 output can be selected as input to the Sigma-Delta ADC.

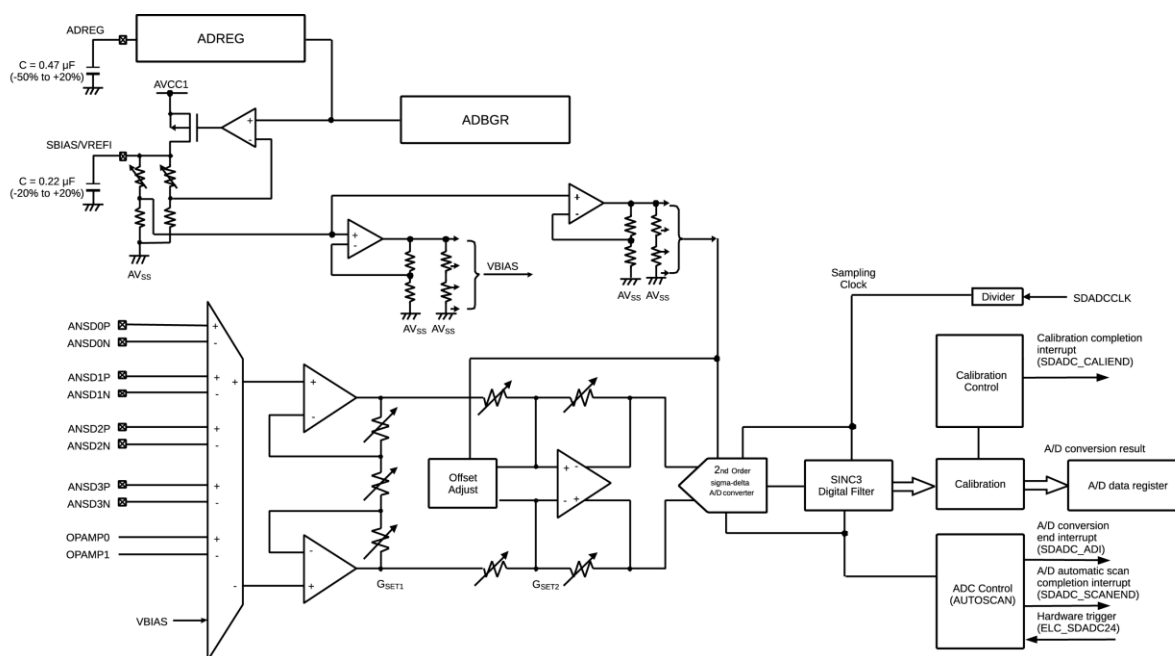


Figure 7: Sigma-Delta ADC implementation for the Renesas S1JA MCU

A unique capability integrated in the S1JA Sigma-Delta ADC is the SBIAS, which can be used to power up an external sensor. The output voltage range varies from 0.8 V to 2.2 V and can be set in units of 0.2 V. The output current is 10 mA (max). SBIAS has an over-current (the current exceeding the maximum) protection circuit. If an overcurrent state occurs, the protection circuit protects the internal circuit. The SBIAS circuit enables users to eliminate external power supplies to bias sensors.

In addition to the benefits presented in this document, the S1JA Sigma-Delta ADC's start-conversion can be controlled via the event-link controller module, which can use the event requests generated by various peripheral modules as source signals to connect them to different modules, allowing a direct link between the modules without CPU intervention. Designers can use this capability to implement different capabilities to enhance their products, such as precise-timed measurements or dynamic-biasing systems. For more details, see the S1JA event-link controller chapter in the user manual.

Conclusion

Fully-integrated microcontrollers, such as the S1JA, that provide high-precision analog functions such as operational amplifiers, Sigma-Delta ADC, successive approximation ADCs, and digital-to-analog converters allow designers to simplify their design by eliminating external components. Additionally, they reduce cost and increase system reliability. Advances in technological processes and design techniques allow the implementation of high-quality specification analog functions that were previously only possible on external dedicated components. The integration of analog functions in a microcontroller offers interesting ways to create combined analog and digital functions that work together under full user control. The designer's imagination is the only limitation to designing new applications.

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