How Highly Integrated ADCs Can Simplify Convertering Real-World Signals

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Introduction

Data converters are tiny marvels that translate real-world signals into digital representations, which can then be transmitted, processed, and stored in an efficient and noise-resistant way. These converters are highly diverse and are utilized in a wide range of applications, from audio processing, to scientific instruments, to image scanning machines.

This article will briefly introduce analog-to-digital converters (ADCs), and discuss how a highly integrated solution such as the MDC91128 can be used to improve a scanning x-ray application that depends on fast, high-resolution imaging.

Analog-to-Digital Converter (ADC)

An analog-to-digital converter (ADC) is a device that converts a continuous analog input signal into a discrete digital signal that can be conveyed as a series of 1s and 0s. By quantizing these input signals into a digital format, they become less susceptible to noise when further processed or transmitted.

ADCs come in a wide range of architectures including delta-sigma, successive approximation register (SAR), and pipelined ADCs. Regardless of architecture, all ADCs provide the same basic function, in that the ADC compares an input voltage signal to a fixed, full-scale (100%) reference voltage (V_{REF}), and assigns a digital code proportional to the signal level's size in comparison to the reference voltage. For example, consider a case where V_{REF} is 10V. If the input signal is only 3V, the ADC will use a specific series of 1s and 0s to convey that the input voltage is at 30% of V_{REF}. If this were an 8-bit converter, the binary output would be 010 (see Figure 1).

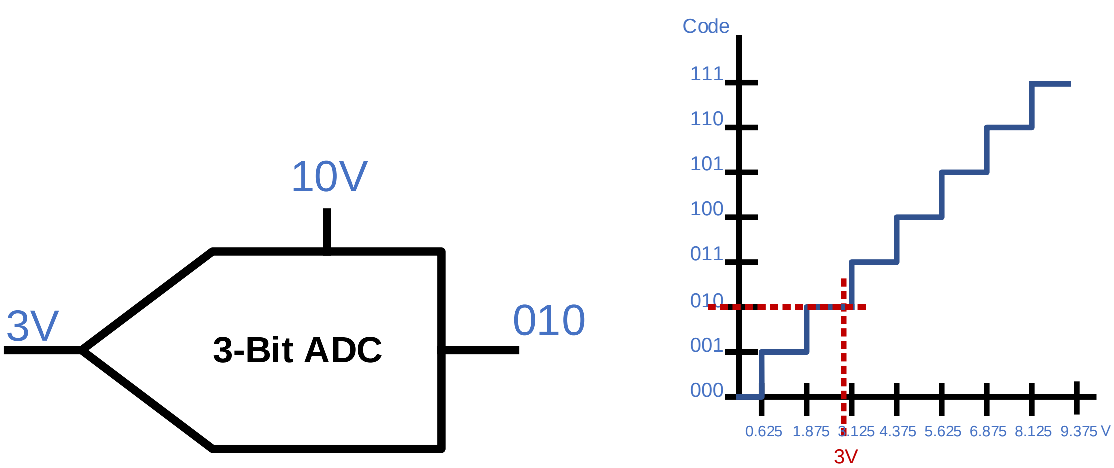

Figure 1: Analog-to-Digital Conversion

However, many signals that a designer may want to convert (e.g. temperature, light level, or pressure) are physical quantities which cannot be directly processed by an ADC. Transducers such as thermocouples, photodiodes, and strain gauges convert these physical quantities to electrical quantities such as voltage, current, and resistance. Signal conditioning circuitry processes these electrical signals to make them compatible with the ADC inputs. This includes further signal transformation, say from a current to a voltage, scaling and shifting to match the ADC input range (as defined by V_{REF}), buffering to be able to appropriately drive the ADC's input impedance, and filtering to reduce noise and aliasing (in which the higher frequency signals may fold back to a lower frequency, which can distort accuracy) (see Figure 2).

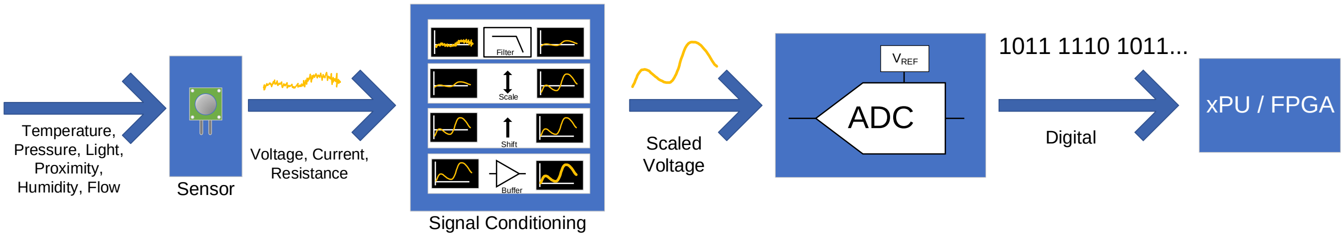

Figure 2: Converting Physical Quantities to Digital Signals

This shifting, scaling, buffering, and filtering is accomplished by signal conditioning circuits, placed between the sensor that supplies the input signal and the ADC. It may be built from discrete components including operational amplifiers and passive components, or it may be integrated with the ADC.

Depending on the application, the ADC front-end can require designer input to optimize for a compact, fast, and accurate system. The scenario below will discuss the optimization of the front end for an x-ray application.

Improving the ADC Front-End

Consider an x-ray signal. This signal is converted to visible light by a layer of scintillator material, and then the visible light is converted to a very small current (picoamps to nanoamps) by a photodiode. Because each pixel is represented by a tiny current in an array of photodiodes, numerous tiny currents must be converted to a voltage, scaled, and buffered to drive the ADC. How is it possible to compare all of these small currents to a reference voltage? This is where effective signal conditioning comes in.

Using a Resistor in an ADC Front-End

Designers may initially be tempted to use a resistor, taking advantage of Ohm's law. This fundamental electrical equation describes the relationship between current (I_{IN}), voltage (V), and resistance (R), calculated with Equation (1):

$$V = I_{IN} \text{ x } R \tag{1}$$

Figure 3 shows this relationship within a circuit. Note that in photovoltaic mode, current flow is in the opposite direction of the arrow, which would make the voltage (V) in Figure 3 negative.

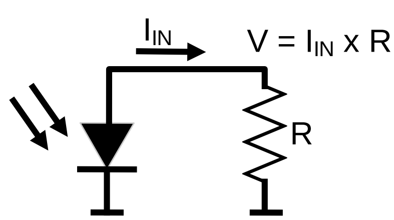

Figure 3: Relationship between Voltage, Current, and Resistance

Applying Ohm's law to this x-ray example, if the full-scale signal is 1nA, and the ADC's V_{REF} is 4.096V, the resistor should be 4.096V / 1nA = 4.096GΩ. This would mean that each channel would require a 4.096GΩ resistor.

Although using a resistor of this size could theoretically convert the current into an output voltage that can be scaled to an ADC, one major problem is speed. Designers should consider that because real-world photodiodes have junction capacitance, the resistor-capacitor (RC) circuit will have an incredibly long time constant (τ or tau), calculated with Equation (2):

$$\tau = R \times C_{JUNCTION} \quad (2)$$

Figure 4 shows this relationship in an actual circuit.

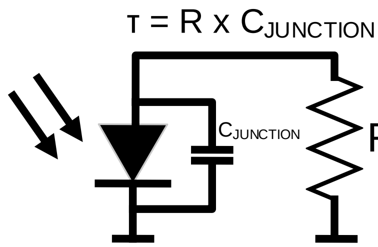

Figure 4: Relationship between Current, Resistance, and τ

For example, if the capacitance of the photodiode and the trace connecting it to the data converter (also known as input capacitance) is 20pF, then the time constant of this RC circuit is (4.096GΩ x 20pF) = 82ms. Mathematically, a single time constant only reaches about 63.2% (e^{-1}) of the full voltage. It would take a total of 5 time constants (e^{-5}) to settle to 99% of the voltage, or almost half a second.

With this in mind, an 82ms tau is too slow for kHz speed applications. In addition, adding a resistor to each current source can reduce system reliability, increase costs, and result in a larger layout.

Using a Transimpedance Amplifier in an ADC Front-End

Alternatively, a transimpedance amplifier (TIA) can be used to buffer the signal, while converting the current to a voltage (see Figure 5). For Figure 6 and Figure 6, keep in mind that since the current flow is in the opposite direction of the arrow, the negative sign cancels out, so the voltage at the amplifier's output is positive.

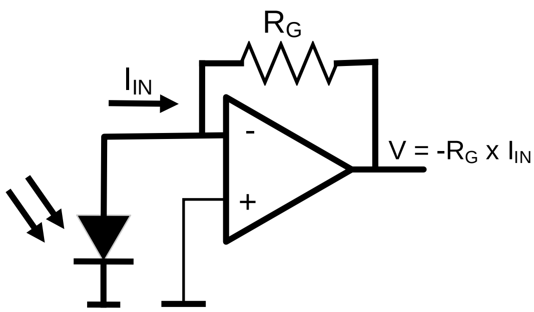

Figure 5: Transimpedance Amplifier

A TIA places a gain resistor (R_G) in its feedback, resulting in an output voltage that can be calculated with Equation (3):

$$V = -R_G \times I_{IN} \quad (3)$$

The result of using an amplifier is a buffered, time-varying voltage signal that is proportional to the current flowing from the photodiode. This is a great choice for many applications, where an instantaneous current is desired and the data converter is fast enough to capture the signal.

Using an Integrator Amplifier in an ADC Front-End

For many x-ray applications though, the total charge or integrated current is of interest, as this is proportional to the dose of radiation that passes through the target during a fixed interval (integration period or t_{INT}). In such applications, an integrator front end is more suitable than a TIA (see Figure 6).

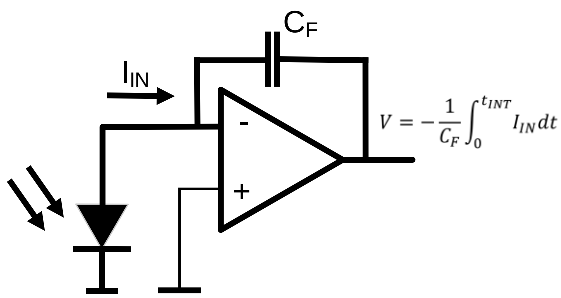

Figure 6: Integrator Amplifier

When using an integrator amplifier, the output of the amplifier and input to the ADC (V) can be estimated with Equation (4):

$$-V = -\frac{1}{C_F}\int_0^{t_{INT}} I_{IN} dt \quad (4)$$

Where C_F is the feedback capacitance, t_{INT} is the integration time, and I_{IN} is the input current from the photodiode.

The MDC91128 and X-Ray Systems

X-rays are used in many applications with a range of energy levels. Some industries may have a system looking over small parcels (e.g. airport or post office), which can use a smaller x-ray source. However, other industries may need to scan a pallet full of parcels, which would require a larger x-ray machine with higher energy. An even larger x-ray system would be used to scan ship containers and the numerous layers in each container. Designing with an ADC that can convert low power and high power signals using different feedback capacitors in the front end integrators would allow x-ray system manufacturers to scale the same data converter across different applications.

MPS offers the MDC91128, which uses an internal capacitor as the feedback element for the integrator amplifier. The MDC91128 is a delta-sigma ADC with 128 channels, which allow it to support 128 photodiode sensors (see Figure 7). Each channel includes a selectable gain integrator and ADC to provide an easy-to-use, small, cost-effective solution.

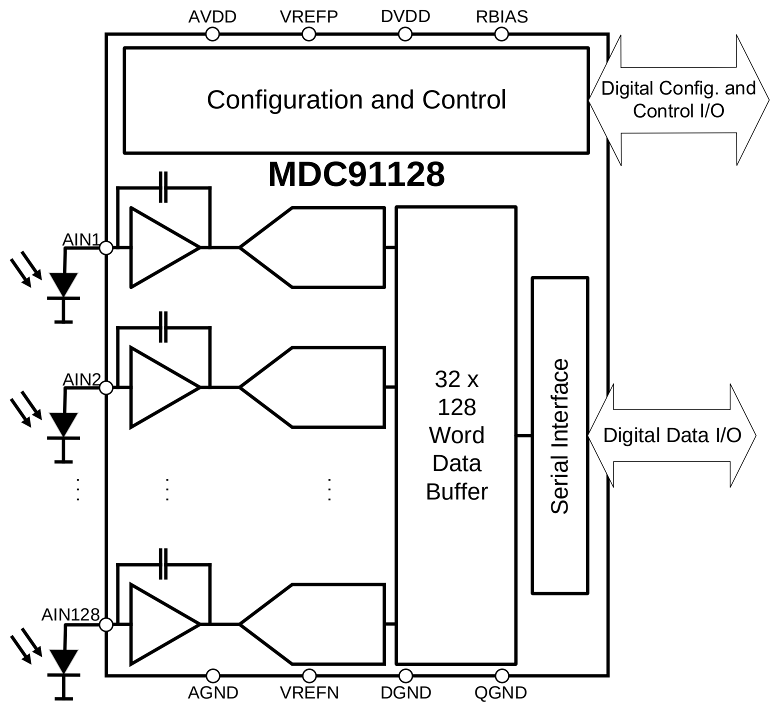

Figure 7: The MDC91128

By including multiple selectable feedback capacitors, an integrated ADC such as the MDC91128 can be used in systems of varying energy levels from smaller x-rays in a medical office to large-scale x-rays meant to provide high-resolution images of different layers in a shipping container. In addition, by dividing the 128 channels of the MDC91128 into two banks of 64 channels each, two separate gain settings can be configured, supporting dual-energy systems, in which low and high energy images are combined to improve material density resolution.

As mentioned before, it is vital in x-ray applications to ensure that radiation is not wasted, which creates a drive to continuously integrate the photodiode signals. The MDC91128 accomplishes this process by allowing a new integration period to start while the ADC converts the value of the just-completed integration.

The architecture used by the MDC91128 can be useful for many small-signal current to digital applications. In addition to scanning x-ray, it is well-suited for measuring and converting small currents in laboratory settings, biochemical reactions, biomedical imaging, other photodiode sensors, dosimetry and radiation therapy systems, optical fiber power monitoring, instrumentation, in-vitro diagnostic applications, and any other applications with large numbers of photodiodes or a large parallel number of voltage measurements.

Conclusion

Data converters are powerful devices that can take real-world information and convert it into digital signals that can be understood and stored by computers, but they must also be optimized to bridge the gap between time-varying parameters and discrete signals. In particular, the front end of an analog-to-digital converter (ADC) must have conditioning circuitry that can scale the input signal to a digital signal that the ADC can understand and quantize.

This article discussed the benefits of using on-chip integrator amplifiers to convert incredibly tiny currents to voltages to match the ADC's range. It also discussed the MDC91128, a scalable delta-sigma ADC that can be used in a wide range of applications, including x-ray scanning.