Data acquisition systems and SoCs—A guide

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Data acquisition systems (abbreviated with the acronym DAS or DAQ) measure real world signals (temperature, pressure, humidity etc.) by performing appropriate signal conditioning on a raw signal (amplification, level shifting, etc.), and then digitizing and storing these signals. This digital signals can then be transmit to another digital system for further processing, usually on a periodic basis.

Examples of data acquisition systems include such applications as weather monitoring, recording a seismograph, pressure, temperature and wind strength and direction. This information is fed to computers, which then predict natural events like rain and calamities like earthquakes and destructive winds. An example of a DAS in the medical field is a patient monitoring system that tracks signals like an ECG (Electro-cardiogram) or EEG (Electro-encephalogram).

A typical DAS consists of the following components:

- Sensors that convert real world phenomenon to equivalent electrical analog signals
- Signal conditioning circuitry that alters signals from the sensor to a form, which can be digitized
- Analog to digital converters that convert conditioned analog signals to a digital representation
- Store and forward memory, which is used to store digital signal streams for forwarding to another system at a later time
- A communication interface over which the digital streams are transferred to the other system
- A microprocessor system or a microcontroller to sequence and control all of the other components.

Figure 1 shows a block diagram of a basic data acquisition system. The details of these internal blocks are explained in the next section.
Subsystems of a Data Acquisition System

Sensors:

As discussed in the previous section, Data Acquisition Systems track physical parameters such as temperature, pressure, humidity, flow rate, etc. Since processing is flexible to be done in the electrical domain, these parameters are converted into an electrically measurable quantity such as change in resistance or current or voltage by using appropriate sensors. For instance, transducers like thermistors, RTDs (Resistance Temperature detectors) etc. change their resistance with respect to temperature and pressure transducers like strain gauge provide change in resistance with respect to the applied pressure. These can be converted to an electrical quantity like voltage using a wheatstone’s bridge [1].

Table-I lists some of the common physical parameters, which are being monitored in DAQs and also the appropriate sensors/ transducers used.

<table>
<thead>
<tr>
<th>Physical parameter</th>
<th>Corresponding electrical transducer</th>
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<tbody>
<tr>
<td>Temperature</td>
<td>Thermistor, Resistance Temperature Detector (RTD)</td>
</tr>
<tr>
<td>Pressure</td>
<td>Strain gauge, piezo-electric transducer</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>Magneto-resistor</td>
</tr>
<tr>
<td>Light intensity</td>
<td>Photo-diode, Photo-transistor</td>
</tr>
<tr>
<td>Position/ Displacement</td>
<td>Linear Variable Differential Transformer (LVDT), rotary encoder</td>
</tr>
</tbody>
</table>

Table-1: Commonly used Electrical Transducers
**Isolation**

Applications that involve signal acquisition can damage the system in cases where very high voltage signals are being processed. Stepping down these high voltages using a transformer or providing other protection circuitry like optical isolation are highly recommended [2].

**Signal conditioning**

**Signal conditioning:**

Though sensors are valuable assets which provide electrical interpretation of the signals to be monitored, the available electrical signals are of minute amplitude levels, usually smaller by a factor of $10^{-6}$ or $10^{-3}$ than the signals which are actually quantifiable.

Apart from the measured electrical signals, certain external disturbances, that are irrelevant, are also picked up by the sensor as added noise. If there is prior knowledge of these signals’ frequency range, suitable filters can be designed so as to remove the noise. In applications such as temperature monitoring at a particular location, there would not be a significant change in temperature over time (i.e., most of these are slowly varying, low frequencies). Hence it would be necessary to feed the input to an LPF (Low Pass Filter) before providing it to a high gain amplifier.

A data acquisition system typically tracks many signals from an environment in parallel, and separate sensors for measuring each of these quantities are utilized. If a separate data acquisition system as shown in Figure-1 is designed for measuring each such parameter, then the overall system would turn out to be bulky. Also, since these signals do not require constant monitoring because of very slow variation in the quantity being measured, we have the flexibility to multiplex different signal conditioned outputs through a single path for further processing. This is shown in Figure 2.
ADC:

The multiplexed signal inputs arriving out of the analog multiplexer are then fed to an ADC (Analog to Digital converter), as digital signals are easy to be processed. The required resolution of ADC purely depends on the application’s requirements. However, the sampling rate of ADC depends on the bandwidth of the input signals. Assuming the bandwidth of channel1 is $f_1$, channel2 is $f_2$, ..., Channel N is $f_n$. And the n-channel multiplexed analog input is fed to ADC, the sampling frequency should be

$$FS \geq 2\times\max(f_1, f_2, \ldots, f_n).$$
$$FS=k\times\max(f_1, f_2, \ldots, f_n), \quad k \geq 2$$

A higher value of k is recommended so that the digitally decoded signal closely tracks the analog signal and doesn’t miss any significant data.

One may wonder why we are not opting for digitizing each channel separately before multiplexing them. Consider an application where we are monitoring 10 or channels. If we digitize the signals before multiplexing them, we might have to use 10 separate ADCs, one for each channel, which would require 10 separate ADC ICs.

One important point to be considered in the above mentioned usage of ADCs is when the various
parameters like temperature, pressure, etc. are sampled at different instances; i.e., temperature at time ‘t’, pressure at ‘t+Dt’ where $Dt = 1/ F_{\text{switch}}$, where $F_{\text{switch}}$ = Switching frequency of multiplexer = $Fs/N$). If there is a sudden change in environmental conditions between ‘t’ and ‘t+Dt’, the temperature reading measured initially would not indicate this change, while the pressure reading measured at ‘t+Dt’ would indicate a sudden change. Under situations where a measurement of all physical parameters at the same instance is needed, a separate sample and hold circuit must be used in each channel before feeding it to analog multiplexer. The trigger is fed to the sample and hold circuit of all channels at the same time and the frequency at which the trigger is given should be $F_{\text{switch}}/N$ where $N$ is the number of channels. Such a system is specially called a time-synchronized system.

The switching frequency of analog multiplexer is governed by the number of channels used and requires sample rate. However, the switching frequency is also limited by the conversion time parameter of ADC.

**Example:** If the ADC is operated at a clock frequency $F_{\text{ADC}}$ and if each conversion takes ‘L’ clock cycles for sampling and ‘M’ clock cycles for conversion, then

$$\frac{L+M}{F_{\text{ADC}}}$$
is the overall AD conversion time.

$$\frac{1}{F_{\text{switch}}} < \frac{L+M}{F_{\text{ADC}}}$$

(switching interval of multiplexer should be greater than the AD conversion time)

$$F_{\text{switch}} < \frac{F_{\text{ADC}}}{L+M}$$

$F_{\text{ADC}} > (M + L) \times F_{\text{switch}}$

The above condition can be interpreted in two ways:

- If ‘M’ and ‘L’ are large, higher would be the requirement of the clock to the ADC.
- A fixed clock fed to ADC with large ‘L’ and ‘M’ restricts $F_{\text{switch}}$ which in turn restricts the bandwidth of the signals which are being monitored.

**Data acquisition using PSoC**

This condition is not mandatory as we can switch the mux to the next channel when the previous channel has crossed the sampling stage and is going through the conversion stage (provided ADCs have this feature. In this case

$$F_{\text{switch}} < \frac{F_{\text{ADC}}}{M}$$

(In this case the sampling period “L” disappears)

$F_{\text{ADC}} > M \times F_{\text{switch}}$ which is reasonable.
Data Acquisition Systems using PSoC (Programmable System On Chip):

Excluding the external sensors, isolators, and the storage PC, the above system typically needs 'N' low pass filters, 'N' high gain amplifiers, 'N' sample and hold circuits, 1 external N:1 analog mux, 1 ADC chip (with external reference voltages), and 1 dedicated MCU to read the digital data and communicate the readings to the PC via RS-232. Overall, it comes to '3N+2' chips; if we are monitoring signals from 10 channels, we would in fact require 32 chips, which makes the system too bulky and expensive.

We can replace these 32 chips with a single Programmable System on Chip to reduce the BOM by a factor of '3N+1'. The list of components used by a data acquisition system implementable using a programmable SoC and its significant features are available in Table-2.

<table>
<thead>
<tr>
<th>Blocks</th>
<th>PSoC1</th>
<th>PSoC3/5</th>
<th>Other units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inputs and Outputs</td>
<td>Any number of GPIOs can be connected to the AMUX bus, which in turn can be routed to any of the analog blocks. PSoC1 provides the flexibility of using any GPIO pins required for the digital blocks.</td>
<td>PSoC3/5 provides the flexibility of using any GPIO pins to any of the analog and digital blocks.</td>
<td>I/O pins in MCUs are not as flexible as in PSoCs. There will be certain restrictions.</td>
</tr>
<tr>
<td>Analog Mux</td>
<td>The analog mux bus available in PSoC1 can be used to switch the required GPIO to the input. Its operation can be controlled by the CPU.</td>
<td>The AMUX (Analog Multiplexer) component available in PSoC3/5 can support up to a maximum of 32 channels.</td>
<td>We require an external N:1 analog multiplexer IC or a list of N switches.</td>
</tr>
<tr>
<td>Low Pass filter(Anti-aliasing)</td>
<td>PSoC1 has powerful analog SC blocks to implement the low pass filter of required cutoff frequency. The cutoff frequency is controlled by firmware for each of the channels.</td>
<td>PSoC3/5 has four in-built Op-Amps which can be used to build up to 8th order Low-pass filter. The resistors and capacitors are to be used externally depending on the required cutoff frequency which is fixed for all the channels. Since it is not possible to build separate LPF for each of the channels, a single LPF can be used whose cutoff frequency should be set to the highest among the N channels.</td>
<td>One separate Op-Amp is required for first order/second order filter. If such filters are used for each of the 'N' channels, then 'N' Op-Amps are needed. Else a single Op-Amp can be used with suitable resistors and capacitors such that this single filter's cutoff frequency is the highest among the cutoff frequencies of N channels.</td>
</tr>
<tr>
<td>High Gain Amplifier</td>
<td>PSoC1 has PGA (Programmable Gain Amplifier) with maximum gain of 48 and instrumentation amplifier (IA) with maximum differential gain of 93. Gain control of the above for each of the channels can be done by firmware. Higher gains can be achieved through cascading.</td>
<td>PSoC3/5 have separate PGAs and TIAs (Trans-impedance Amplifiers). If the sensor gives current output, TIA can convert it to an equivalent voltage for further processing by ADC. Gain control of PGA for each of the channels can be achieved by firmware.</td>
<td>Each and every sensor’s output requires a separate a separate amplifier circuit. So, ‘N’ such amplifier circuits are needed. It is not possible to have a single amplifier whose gain can be configured through instructions or through firmware.</td>
</tr>
<tr>
<td>Sample and hold</td>
<td>PSoC1 does not have an S/H (Sample and Hold) circuit. So the switching frequency of AMUX is limited as ( f_{\text{switch}} &lt; \frac{f_{\text{ADC}}}{L} \times \frac{1}{T_{\text{conv}}(N)} ). The switching to the successive channels is initiated only after the AD conversion of previous channel and the switching is done through firmware.</td>
<td>PSoC3/5 has dedicated S/H component to sample and hold the signal, which is useful for Delta-Sigma ADC. SAR (Successive Approximation Register) ADC has an internal S/H circuit inside it. Hence ( f_{\text{switch}} ) in PSoC 5’s SAR ADC would be higher when compared to PSoC 1.</td>
<td>‘N’ sample and hold circuits are needed if they are built using external Op-Amps and FETs. In this case, we need ‘2N’ Op-Amps and ‘N’ FETs.</td>
</tr>
<tr>
<td>ADC</td>
<td>PSoC1 has Delta-Sigma ADC, SAR ADC, Incremental ADC and Single slope ADC. The resolution and sample rate of ADCs are configurable.</td>
<td>PSoC3/5 has a Delta-Sigma ADC known for its accuracy. PSoC5 has SAR ADC famous for its higher conversion rate. The resolution and sampling rate of ADCs are flexible.</td>
<td>A separate ADC chip is required which provides a fixed resolution and have restrictions on sampling frequency. Also an external reference voltage might be required for ADC.</td>
</tr>
</tbody>
</table>

Table-2: Comparison between use of PSoC and other MCUs in Data Acquisition Systems
Figure-3 shows the internal schematic of a system built using the Cypress PSoC 3/5 along with an explanation of each block. The tool used is known as PSoC Creator.

Figure-4: Second order Low Pass Filter using built-in opamp and external resistors and capacitors (Refer to Figure-3 for connections)
References:

[1] Wheatstone’s Bridge

[2] Isolators

Also See:

Build a DAQ system for about $30

Data Acquisition

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Design MOSFET characteristic variation and reliability degradation issues

Motion Sensors Demystified