Introduction to Data Acquisition Systems

A Data Acquisition System (DAQ) collects data from a wide variety of sensors and instruments. It makes the sensory information available to the monitoring or control system in the most convenient form. It must do this in a manner that is transparent to the sensor information.

An ideal DAQ should also provide certain specific facilities. These include
- Reading the sensors and doing some signal processing (e.g. cold junction for thermocouples.)
- Transmit, via bus, network or standard signal, the information to a central control point
- Provide distributed control and monitoring facilities.
- Convert the sensor signal to an appropriate form for the monitoring or control system (e.g. to a binary number)
- Provide calibration sub-systems to calibrate sensors and instruments
- Provide real-time handling facilities.

There are also several things a DAQ should not do or should minimize. These include
- Corrupt signal information e.g. add noise to the signal
- Compromise signal accuracy e.g. add non-linearities or other distortions
- Reduce system resolution i.e. have less resolution than the sensor
- Slow the response of the system

Practical DAQ systems usually fall short of these ideals in one or more areas. Selecting and designing DAQ based systems becomes the usual engineering task of optimizing a particular set of desired outcomes in the presence of conflicting constraints.

Each of the above features of DAQ will be discussed.

*Provide data in the most convenient form.* Since our most powerful and available processing units are all digital computer based, the sensor information needs to be converted from an electrical signal to a digital number. This requires Analog to Digital (A/D) converters or related technology. Similarly the output control signal must be converted from digital numbers to analog electrical, mechanical or other signals for plant control. This requires Digital to Analog (D/A) converters or related technology.

The phrase “transparent data transmission” needs to be clarified. The DAQ will probably convert the sensor signal from some electrical signal (such as a mA current) to a signal, such as a binary number for the controlling computer. The conversion function will be “transparent” if all the useful information in the original signal appears in the converted signal. This is a pragmatic definition of transparent. Inevitably some information in the original signal is lost in the sensor and some more is lost converting into a form suitable for the DAQ system. The amount lost must be insignificant relative to the application.

There are several ways that DAQ systems can avoid corrupting sensor signals. This is illustrated by the following examples.
e.g. 1. Thermocouples are terminated at an “isothermal block”
- Excellent heat conductor - no temperature difference between terminals.
- Correct metals for terminals
- “Cold junction” temperature sensing
- Close proximity signal conditioning amplifier.

e.g. 2. Amplifier input impedance for photovoltaic sensor. The output impedance of the sensor is
the input impedance of the amplifier. The sensor performance (load line) depends on the
impedance on its output. If the impedance is too low the response of the sensor becomes non-
linear. Therefore the amplifier of the DAQ system must have a very high input impedance.
Figure 16-9 in the Carstens text shows a family of (diode) curves and a load line dependent on
impedance.

e.g. 3. Transmission cables from sensors to the DAQ system pick up noise. Long lengths of
instrumentation cable act as antennas to electromagnetic noise. This can be avoided by using
“twisted pair” cable, shielded cable and other related techniques.

**Analog to Digital (A/D) Conversion and Digital to Analog conversion (D/A or DAC)**

A key technology in DAQ systems is A/D conversion. A/D converters take a continuously
variable electrical signal and convert it into a digital (binary) number. As with many other
instrumentation topics we are concerned with speed, accuracy and cost. There are a number of
techniques, all designed to enhance the accuracy and speed of this operation while keeping costs
low. There are several important topics or specifications that must be considered when selecting
A/D converters. These are

- **Resolution**
- **Scaling**
- **Conversion Time**
- **Sampling frequency, sampling theorem and aliasing**
- **Digitizing errors**
- **Sample and hold**

**Resolution:** The analog signal is converted to a binary signal with a definite number of bits. For
example, a ten bit converter can represent the incoming signal a one of \(2^{10} = 1024\) digital numbers
(usually 0 to 1023). This can have a significant effect on the resolution. The best resolution we
can have is \(1/(2^n-1)\) or 1/1023 or approximately 0.1% of the range.

Example: A DAQ system has a 0-5V, 8 bit A/D converter measuring the temperature from a
sensor. The sensor outputs a 0 to 2V signal representing a temperature range of 0-200° F. We
wish to use this as a thermostat control signal for house temperature.

Here the 0-2V signal from the sensor can safely be connected to the 0 to 5 v A/D input. The
range of the A/D is \(2^8 = 256\) counts. i.e. 0V = 0, 5V = 255. Therefore, 0V from the sensor = 0°
F; 2V from the sensor = 2/5 x 255 = 102.0. This would be read by the A/D as 102. A
temperature change of 5°F would become 5/200 x 2.0V = 0.05V which becomes 0.05/5.0V x 255
= 2.55 which would be rounded to 2 or 3 counts. This means that the temperature has to change
by 2°F or more for the DAQ system to notice it i.e. to change one digit. This is poor
performance for many applications but may be acceptable for simple residential temperature
control. There are design techniques that can significantly improve the performance in the
example cited above. One of the simplest is to scale the signal.

**Scaling:** In any instrumentation application we want the sensor to give us a signal that matches
the display or DAQ system. While it is possible to display a zero to one volt signal on a zero to
100 volt display, it does not make best use of the display system. In fact, in this case, not only
will the resolution be poor but we are probably operating the display in its most inaccurate region.

Example. Consider the previous example. We can improve the resolution of the controller by
amplifying the 0-2V from the sensor to 0-5V before putting the signal into the A/D. This would
effectively more than double the resolution. This concept can be taken further. If we are only
interested in temperatures in the range 30°F-130°F, we can amplify and offset the signal going into
the A/D converter so that 30°F = 0V = 0 count and 130°F = 5V = 255 count. This give a
resolution of 0.4°F/count. Obviously there is a trade-off. The instrument is no longer capable of
working with temperatures outside the range 30°F-130°F.

Resolution can be expressed in several ways. If the sensor is known, as it is in the above example,
then the resolution can be expressed as °F/count. Usually the DAQ system will be purchased
separately from the sensors and so the resolution of the A/D can be expressed in mV/count (or
just mV). An n bit A/D converter has an inherent resolution of 1/(2^n-1). This is frequently just
written as “n bit resolution.”

\[
\text{Resolution of n bit A/D converter} = \frac{1}{2^n-1}
\]

We can also increase the resolution by using a 10 bit or more A/D. This would probably cost
more and operate slower. Resolution is strongly correlated to cost.

**Conversion time:** The conversion time is the time that the A/D takes to convert a voltage into a
set of digital bits. The conversion time determines how fast the A/D can sample a signal. A
conversion time of one microsecond means the A/D can sample signals at one million times per
second.

The A/D conversion time is a function of the technique used to convert the signal. Simple, low
cost microcontrollers often use a successive approximation technique which is slow and subject to
inaccuracies. These A/D converters can take a few milliseconds to convert a single 8 bit value.
Fast converters, used for video and audio work for example, can perform conversions in
microseconds or nanoseconds. Conversion time is also strongly correlated to cost.

Other parameters of A/D converters are similar to those already discussed for instrumentation systems. i.e. linearity, drift, temperature drift, etc.

Many control and DAQ systems need to output analog values as well as input them. Once the (digital) output value has been calculated it must be sent to an actuator. D/A converters (DAC) are the inverse of A/D converters and specified with similar parameters. Examples are: industrial valve control signals and CD audio signals. Industrial valves are driven open or closed by an analog electrical (4-20 mA) or pneumatic (3-15 psi) signal. The loudspeaker of the CD player is driven by an analog voltage (audio signal).

Digital Signal Concepts

Nyquist Sampling Theorem. A signal from a sensor can be considered as a data waveform. The data waveform is sampled producing instantaneous values of data. Output data is reconstructed from discrete samples with a low-pass filter. To reconstruct data or to be able to interpret all the meaningful information in the data we need to sample the signal often enough so that we can reconstruct all the information including all spikes etc. Fourier transforms are a mathematical technique that allow us to consider any waveform as a collection of sine waves of different frequencies and amplitudes added together. The sampling theorem states that if we are sampling a waveform whose highest frequency component is \( f_M \) then the original signal can be reconstructed if we sample it at a rate (sampling frequency) of \( f_S \) where

\[
f_S > 2 \times f_M \quad \text{f}_S \text{ is the Nyquist Sampling Frequency.}
\]

This assumes ideal sampling and ideal low-pass filters. In practice we want to sample the waveform at a higher rate, say three to five times the highest frequency of interest. This allows for practical low-pass filters with a normal roll-off.

If we sample less often than twice the highest frequency we will lose information or, even worse, high frequency information will appear as lower frequency information. This is called aliasing.

Aliasing. If data or noise with a higher frequency exists in the waveform then it will be sampled and appear as lower frequency data (aliasing). Once aliased data is in the discrete form it cannot be distinguished from genuine low frequency data. Solution: Always use anti-aliasing filters. (low-pass filters). The frequency of the aliased data is \( F_s - F_a \) where \( F_s \) is the sampling frequency and \( F_a \) is the actual frequency.

Example: A 850Hz signal is sampled at 400 samples/second. What aliased frequencies will appear.

The highest frequency we can (theoretically) sample at 400 samples/sec is 200 Hz. The signal will
appear as 400-850=-450. 450 is still larger than 400, 400-(-450)=50Hz. The 850 Hz signal will appear as an aliased 50 Hz signal in the output of the sampler.

**Digitizing and resolution:** Sampled data is discrete. It is also digitized i.e. it has a finite resolution. Note that *discrete* data does not necessarily have a finite resolution. Resolution is defined by the number of bits in the binary word storing the data. Digitizing introduces additional distortion of the data. The difference between the actual sampled data value and the digitized data value is +/- ½ smallest step size.

**Sample and Hold:** A sample and hold reads the value of the analog signal at the sampling time (instantaneously) and holds it while the digitizing circuitry processes it. The simplest S/H is a zero-order S/H. This just holds the value constant between samples.

S/H is essential for some types of A/D e.g. successive approximation.
Aperture Jitter in Sample and Hold systems

How fast can an A/D read a varying input without a sample and hold?

Our A/D has n-bit resolution and we want accuracy of \( \pm \frac{1}{2} \) l.s.b.

One primary limitation is the A/D conversion time

\[
\text{eg 10 \( \mu \)sec} \mid 100 \text{ kHz sampling frequency}
\]

| Theoretically sample 50 KHz wave. (Nyquist frequency)

But if the input is changing then the time allowed for it to change less than \( \frac{1}{2} \) lsb = \( 2^{N+1} \) i.e. max voltage drift during A/D conversion is \( V/2^N T \), where \( N \) = number of A/D conversion bits

Consider the highest frequency in the sampled wave as a sine wave

\[
V(t) = V \sin (2\pi f t)
\]

Max change is at the point where the derivative is a max: \( \frac{dV(t)}{dt} = 2\pi f V \cos (2\pi f t) = 0 \)

\[
\left| \text{max} \right| \quad 2\pi f V \quad (\text{when } \cos = 1 \text{ (max), } t = 0)
\]

\( \hat{f} \) for accuracy \( V/2^N T > 2f_{\text{max}} V \)

\( \hat{f} f_{\text{max}} = 1/2^{N+1} \mu \text{T.} \)

So 10 \( \mu \text{sec} \) conversion time

@ 8 bits | 62 Hz (max sampling rate without error)
@ 10 bits | 15 Hz (max sampling rate without error)

Sample and Hold

The standard solution to this problem is to use a Sample & Hold Amplifier (SHA).

The SHA reads the input very fast and holds it constant while the A/D converts it. The \( T \) parameter now becomes the Aperture Jitter of the SHA, typically in the range 20 ps | 20 ns.

\( f_{\text{max}} = 1/2^{N+1} \mu \text{T.} \)

Where \( f_{\text{max}} \) = highest undistorted frequency

\( T \) = aperture jitter

\( N \) = # of bits of A/D conversion.

For 20 ns aperture jitter @ 8 bits \( f_{\text{max}} = 1/2^{8+1}(20 \times 10^{-9}) = 31 \text{ KHz} \)

31 KHz is close to the theoretical best of the A/D converter (50 KHZ, see above)

Review Question

What is the maximum aperture jitter permissible for a 12 bit A/D converter with a 5 \( \mu \text{sec} \) conversion time to operate at maximum speed?
A/D Converter Technologies

1. **Techniques:** Successive approximation, single vs. dual slope, voltage comparator - counter loop, multiple comparator, voltage to frequency conversion.

2. **Specifications:** Resolution, conversion time, linearity and noise, serial vs parallel (binary or BCD) output, temperature drift, control signals (interfacing) etc.

D/A Converters

1. **Types:** Voltage or current output, uni-polar or bi-polar, with or without multipliers.

2. **Techniques:** Binary-weighted ladder network. R/2R ladder network, resistor divider chain etc.

3. **Specifications:** Resolution, linearity, offset, settling time stability, serial vs parallel input etc.

Compromising Signal Accuracy. As discussed in the section on A/D converters, signals are often amplified before being converted. Inaccuracies in the transmission and amplification process are added to inaccuracies of the sensor. Each of these amplifiers must be calibrated to minimize these inaccuracies.

Reducing System Precision or Resolution. This is also discussed in the A/D section. The following example illustrates the problem.

e.g. A pressure sensor is used to measure pressure changes in the range 0-2500 psi and needs to be able to detect a change of 0.1 psi. What A/D converter resolution is needed to maintain this resolution? The pressure sensor/transducer outputs a voltage of 0-8V over the above range. The A/D converter has a 0-10V input.

We need a resolution of one part in \( \frac{2500}{0.1} = 1:25000 \) over 8V and a resolution of \( 1: \frac{(10/8) \times 25000}{10} = 1:31,250 \) over 10V to detect 0.1 psi change. To find out the number of bits needed we use

\[
\log_2 \left( \frac{1}{31,250} \right) = 14.93
\]

i.e. \( 2^{15} = 32,768 \) and so we need a 15 bit A/D converter to maintain a transparent conversion.

Slowing System Response. The response time of the DAQ system must be faster than that of the
There are various definitions of response time. Two of the commonest are

1. The response time is the time for the output of the system to go from 10% of its final response to 90% of its final response.

2. The second definition of response time assumes that systems are approximately first order exponential systems, i.e., they follow the curve \( output = (1-e^{-t/t}) \times 100\% \), where \( t \) is the time since the output started responding. For these systems the response time is \( t \), the time taken for the output to reach 63% of its final value. \( t \) is also called the time constant of the system. For systems of this type the settling time is usually defined as the time for the system to reach 99% of its final value which is 5\( t \).

**Standard methods for Transmission of Signals.**

**Analog**
- 0-5V, 0-10V -5 to +5V, -10 to +10V, 4-20mA

**Digital**
- Individual signals or networked
- Serial - RS232, 432 etc.
  - Firewire, Universal Serial Bus (USB) (IEEE 1394 etc.)
  - Proprietary (HPIL etc.)
- IEEE488 (HPIB) - 20 meters
- VXI - 20 inches
- Networked - Ethernet etc.
- Fieldbusses (Several competing standards)
- Proprietary - parallel, PLC standards, etc.

**Calibration.** Incoming analog signals can be calibrated or the signal can be calibrated digitally (providing information is available).

Calibration can include several functions.

- Zero (offset) and slope (gain) for linear systems
- Linear curve fitting
- Polynomial curve fit equation (e.g., T/C)
- Non-linear curve fit equation (e.g., pressure difference to fluid flow)
- Look up tables
- Look up tables with interpolation (linear or higher order)
Real Time Issues.

C Definition
C Compare polling vs. Interrupt
    -efficiency
    -reliability
Examples of Data Acquisition Systems

Different types of industrial DAQ systems:

1. **Continuous Flow Systems:**

   These systems have a continuous flow of material through the manufacturing process. Typically this means liquids flows through pipes, mixers, pumps etc. Processes tend to be difficult to start and stop so usually the plant is brought to a stable operating system and then maintained there. Controllers and sensors here are often designed to regulate. i.e. they are designed to keep the plant operating at a single, stable set point.

   Typical Applications, Petrochemical plants (oil refineries, etc.), food and chemically based consumer products (detergents, paints, etc.).

   **Characteristics**
   - Typically big. 0.5 to 10 M$. 1000’s of sensors and actuators.
   - Plants can be miles long.
   - Centralized control with a mini-computer (workstation class).
   - Continuous flow processes rather than batch.
   - Response time measured in seconds.
   - Proprietary interface, network, and software systems programmed by supplier, configured by customer (or consultant) engineers.

2. **Batch/Workcell Systems**

   Products are made one at a time or in batches. Each product or batch is taken through the process.

   Typical Applications: Mechanical and production line environments. Robots and machine tools.

   **Characteristics**
   - Digital signals and Boolean logic.
   - CNC standards for machine tools.
   - PLC’s used widely.
   - Networking tends to be less proprietary. Some networking standards (Manufacturer’s Automation Protocol-MAP in some industries).
   - Size ranges from small ($500) to big (millions $).
   - Programming often done by customer or consultant engineers.
   - Response time measured in tenths of seconds.

3. **Test Systems**

   These systems are used to measure quality of products or to develop new products or processes.
Systems need to be flexible to measure a wide variety of signals. Set-ups may change fairly frequently as the process changes or as the product changes. Individual instruments tend to be much more powerful, accurate and expensive.

Typical Applications: Quality control on production line. Laboratory based DAQ.

**Characteristics**
- High speed DAQ.
- Response time in milliseconds or microseconds.
- Bus-based instrumentation e.g. IEEE 488.
Review Questions and problems

DAQ - Review Questions

Q1. What are the important characteristics of a A/D converters in data acquisition?
Q2. What is an "op amp" and what is it used for?
Q3. What is the resolution of a 12 bit A/D converter expressed as a percentage?
Q4. What limits the accuracy of a 12 bit A/D card?
Q5. What is the typical throughput rate of a fast PC based data acquisition board using DMA?
Q6. Place the following measurement systems in order from fastest to slowest (typical figures)
   a. Instrument on IEEE 488 bus
   b. PC based data acquisition board using DMA
   c. PC based data acquisition board writing to fast hard disk
   d. Instrument communicating with PC over RS232 serial line at 19.2 Kbaud
Q7. What are the factors governing the real-time measurement speed of a DAQ system?
   Order the factors from slowest to fastest.
Q8. Compare analog signals such as 4-20 mA and 0-5V to digital signals such as IEEE488 and RS232 as transmission media for DAQ systems.
Q9. What is the definition of “real time”

Sampling - Review Questions

Q4. What sampling frequency does the sampling theorem indicate we need to sample a particular signal accurately?
Q2. What is a more practical sampling frequency than that specified by the?
Q3. What is "aliasing" and "anti-aliasing"?
Q4. What is “interpolation and when do we use it?”
DAQ - Review Answers

A1. Resolution (# of bits), and speed of conversion.

A2. Operational Amplifier - A high gain differential input amplifier. Usually connected with negative feedback which reduces gain and increases stability. Used for:
  - Amplifying signals
  - Performing arithmetic functions
    1. multiplication (scaling)
    2. addition/subtraction
    3. differentiation
    4. integration
  - linearising signals

A3. \[ 2^{12} = 4096 \quad \frac{1}{4096} = 0.00024 = 0.024\% \text{ resolution} \]

A4. It depends on many factors. The best it can be is as good as the resolution. The accuracy will be further degraded by offset errors, gain (scale factor) errors, non-linearities and other errors typical for instrumentation.

A5. It can vary depending on how sophisticated the electronics on the PC card is and how the card interfaces to the PC memory (ISA-BUS, PCI bus etc.). Typically about 250 KHz for the common ISA bus this translates to about 25 KByte/sec.

A6. Order as shown. Same order for decreasing cost (generally speaking).

A7. Measurement time. The settling time of the instrument is usually the slowest operation.
  Command interpretation time. The controlling device often communicates with the measuring instrument with ASCII strings (always for IEEE 488). The instrument has to decode (interpret) these strings, execute the command (see measurement time above) and encode the result into another ASCII string to send back. Command interpretation time can be significantly reduced in some systems (e.g. VXI) by using a binary mode for commands and for data. The cost is less portable and less understandable programs.
  Data Reception time was included with command interpretation time above but could be separated out. The receiving device (e.g. listener) often needs to convert the ASCII data string back into machine values and store them in the receiver's memory. This last step can be greatly speeded up by using DMA to eliminate the need for the receiving CPU to be actively involved in the receiving process.
  Bus transmission time is seldom a problem for IEEE 488 systems. It can become a problem for high data volume systems such as vision systems. These are almost invariably implemented on high speed bus systems (e.g. VXI or specially built PC cards).

A8. Cost, reliability, complexity higher for digital. Simplicity and speed higher for analog (generally). Each analog requires separate wires and so many signals travel in parallel. Over long distances this will be more expensive than digital (cable costs). Digital systems require analog as well to get to a digital conversion unit. Exception to this is “smart sensors” like TMP-01 or DS1620 which give digital signals directly.

A9. A defined and time-limited response time to an input. See class notes
Sampling - Answers

A1. Twice the signal frequency.
A2. 3-5 times the signal frequency.
A3. Aliasing or undersampling is sampling at a frequency of less than the Nyquist rate (2x highest freq). It results in a high frequency signal being interpreted as a lower frequency signal. To eliminate these unwanted signals the sampler (A/D converter) must be preceded by and anti-aliasing filter which is simply a low-pass filter with a cut-off frequency equal to or less than the highest frequency.
A4. Interpolation is calculating a data point between two points given in a table. Interpolation can be linear or can be much higher order for non-linear (rapidly changing, high accuracy) systems.
Data Acquisition and A/D Problems

1. Name the three major functions discussed in class that define a DAQ system.

2. A data-acquisition system is being designed will read data up to 10KHz. A 14 bit A/D converter is available with a conversion time of 35 µsecs. What is the Nyquist frequency for this A/D converter i.e. What is the maximum frequency signal that the A/D can sample undistorted (theoretically)?

3. Using J type thermocouple tables find the (interpolated) temperature for a mV reading of 7.7 mV. Your answer should be as accurate as it can be using the standard tables.

4. We have a pressure sensor mounted on a machine that gives us a signal in the range 0-2500 psi over a voltage range of -5 to +5 V. We want to measure signals in the range 1500 to 2200 psi accurate to the nearest 0.5 psi. We have a series of A/D converters available, all of which read inputs in the range 0 to 5V. Resolutions for these converters are available at 8, 10, 12, 14 and 16 bits. We wish to use the least expensive A/D we can for this application.

A) Sketch a block diagram of this system showing any necessary signal processing stages to make this system work. Circuit details are not required but clearly show what each block does (e.g. Amplifier, Filter etc.). Calculate and show on the diagram the value of any gains, offsets etc.

B) Which of the A/D converters listed would you select to meet the above specifications? Justify your answer with the necessary calculations. State any assumptions needed.