

Data Acquisition: An Introduction

Bruxton Corporation

This is an informal introduction digital data acquisition hardware. It is primarily directed towards assisting in the selection of appropriate hardware for recording with the Acquire program.

Overview

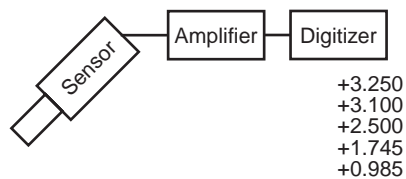
In principle, data acquisition hardware is quite simple. An A/D converter delivers a sequence of values representing an analog signal to an acquisition program. In practice, selecting and properly using data acquisition hardware is more complex. This document provides an informal introduction to the topic.

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Many of the examples are taken from patch-clamp recording. This technique requires accurate acquisition of low-level signals (picoamperes) with bandwidth in the audio range (up to 10kHz).

Background

A data acquisition system converts a signal derived from a sensor into a sequence of digital values. The sensor is connected to an amplifier, which converts the signal into a potential. The amplifier is in turn connected to a digitizer, which contains an A/D converter. The digitizer produces a sequence of values representing the signal.



Signal Source

The source of most signals to be digitized is a sensor, connected to an amplifier with appropriate signal conditioning. The amplifier delivers an electrical signal. This signal is then digitized using an A/D converter.

For patch-clamp recording, the sensors are solution-filled pipettes. The pipette is connected to a patch-clamp amplifier that converts the voltage at the pipette or the current through the pipette to a high-level signal. By convention, the full-scale output range of a patch-clamp amplifier is $\pm 10V$, matching the range of common instrumentation-quality digitizers.

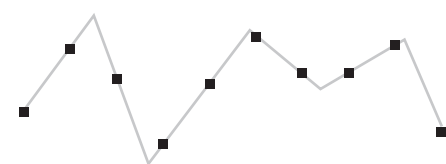
Digitizer

A digitizer converts one or more channels of analog signal to a sequence of corresponding digital values. The heart of a digitizer is an A/D converter, a device that samples an analog signal and converts the sample to a digital value.

For example, for recording from a single ion channel, the digitizer might determine the output of the patch clamp amplifier once every $50\mu s$ and provide the resulting value to the computer.

Sampling Theorem

The purpose of data acquisition is to analyze an analog signal in digital



form. For this to be possible, the sequence of values produced by a digitizer must represent the original analog signal. The sampling theorem states that this is the case.

The sampling theorem states that an analog signal can be reconstructed from a sequence of samples taken at a uniform interval, as long as the sampling frequency is no less than double the signal bandwidth. For example, assume a signal contains frequencies from DC (0Hz) to 10kHz. This signal must be sampled at a rate of at least 20kHz to be reconstructed properly.

As a practical matter, the sampling rate should be several times the minimum sampling rate for the highest frequency of interest. For example, to resolve a 10kHz signal, a minimum sampling rate of 20kHz is required, but a sampling rate of 50kHz or more should be used in practice.

Control

Most of this discussion is about digitizing analog signals for a computer. In many cases, a computer also produces analog control signals. For example, in patch-clamp experiments involving voltage-gated ion channels, the computer is frequently used to produce an electrical stimulus to activate the channels. These control signals are produced using a D/A (digital to analog) converter.

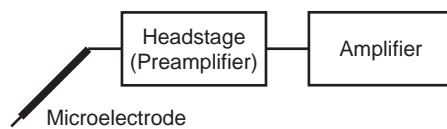
From Sensors to Signals

Many signal sources consist of a sensor and an amplifier. The amplifier converts the output of the sensor into the signal to be digitized.

Pre-amplifier

Many instrumentation systems are built with a pre-amplifier located as close to the sensor as possible. A separate amplifier converts the pre-amplifier output to a high-level signal. Placing the pre-amplifier close to the sensor reduces noise, by allowing the signal to be amplified before being sent over a cable. Since physical space near the sensor is limited, the pre-amplifier is as small as possible, with the bulk of the electronics being located in the amplifier.

For example, in a patch clamp setup, the sensor is a solution-filled pipette, the pre-amplifier is the head stage, and the amplifier is the patch-clamp amplifier itself.



Signal Conditioning

Many sensors deliver signals that must be transformed before they can be digitized. For example, a microelectrode pipette may be used to measure current, while the digitizer measures potential (voltage). The patch clamp amplifier provides a current-to-voltage amplification, usually measured in mV of output per pA of input. This transformation of the sensor signal is called signal conditioning.

Signal conditioning may be more complex. An input signal from a non-linear sensor may be converted to a voltage that is linear in the quantity being measured, compensation may be made for second-order effects such as temperature, or an indirect effect such as a frequency shift may be converted to a voltage.

Integrated Digitizer

As the cost of A/D converters declines, the digitizing function can be moved into the amplifier. For example, the HEKA elektronik EPC-9 patch-clamp amplifier contains a built-in digitizing unit (an Instrutech ITC-16).

Integrating a digitizer into an amplifier can substantially reduce total noise in the digitized signal, since the analog signal is not carried over a cable from the amplifier to an external digitizer. Be careful of instrument specifications when comparing an analog amplifier to one with a built-in digitizer. Including the digital electronics in the amplifier housing may increase noise, and the digitizer itself may add noise to the signal. However, the total noise in the digitized signal may be much less than if an external digitizer is used. Compare an amplifier with an integrated digitizer to the combination of an analog amplifier and an external digitizer.

A major advantage of integrating a digitizer into an amplifier is that the amplifier designer can easily include features for computer control. A data acquisition program connected to such an amplifier can then offer an integrated user interface, simplifying operation. In addition, the acquisition program can record all amplifier settings, simplifying data analysis.

From Signals to Samples

A digitizer consists of an A/D (analog to digital) converter that samples an analog input signal and converts it to a sequence of digital values.

Aliasing

The sampling theorem states that, in order to be able to reconstruct a signal, the sampling rate must be at least twice the signal bandwidth. What happens if a signal contains components at a frequency higher than half the sampling frequency? The frequency components above half the sampling rate appear at a lower frequency in the sampled data.

The apparent frequency of a sampled signal is the actual frequency modulo half of the sampling rate. For example, if a 26kHz signal is sampled at 50kHz, it appears to be a 1kHz signal in the sampled data. This effect is called aliasing.

Anti-Aliasing Filter

If a signal to be digitized has components at frequencies greater than the half the sampling frequency, an anti-aliasing filter is required to reduce the signal bandwidth. The anti-aliasing filter must cut off signal components above one half the sampling rate.

Most signal sources are inherently band-limited, so in practice, anti-aliasing filters are often not required. However, some signal sources produce broadband noise that must be removed by an anti-aliasing filter.

For example, patch-clamp amplifiers have built-in anti-aliasing filters. The pipette used for patch-clamp recording inherently filters signals above a low frequency in the range of 1kHz. The good high frequency response of a patch clamp amplifier is achieved only by boosting the high frequency component of the signal to compensate for the frequency response of the pipette. This can produce significant high-frequency noise. A patch-clamp amplifier provides a filter to eliminate this noise.

Integrating Converters

The discussion of aliasing assumes instantaneous sampling. The output value produced by the A/D is represents the instantaneous analog signal amplitude. Such sampling A/D converters are the most common for use in instrumentation.

Some A/D converters employ an integrating conversion technique. The output value produced by such a digitizer represents the integral of the analog signal amplitude over the sampling interval. Such converters eliminate aliasing. They can be viewed as containing a built-in anti-aliasing filter.

Integrating converters are rarely used in high-speed

control applications. The most common techniques for implementing high-speed integrating converters result in a delay of many sample intervals between an analog sample and the corresponding digitizer output value. This delay can introduce considerable phase shift at high frequencies in closed-loop response if the digitizer is used in a control system.

Resolution

Typically a digitizer provides the computer with fixed-length binary numbers. For example, the Axon Instruments Digidata 1200A produces 12-bit numbers, while the Instrutech Corporation ITC-16 produces 16-bit numbers. The length of each value is called the resolution of the device, measured in bits.

The resolution can be translated to an absolute input level. Most digitizers measure swings of up to approximately 10V from zero, for a total range of 20V. A 12-bit value has a resolution of 1 part in 4096, so the resolution of a 12-bit digitizer is 20V divided by 4096, or approximately 5mV. This is expressed by saying that a change of one count (or one least significant bit, or LSB) represents 5mV.

Digitizer Resolution ($\pm 10V$ Range)

Resolution	Distinct Values	1 LSB (approximate)
8 bits	256	80mV
10 bits	1024	20mV
12 bits	4096	5mV
14 bits	16384	1.25mV
16 bits	65536	300 μ V
18 bits	262144	75 μ V

Since analog instruments rarely have an accuracy significantly exceeding 0.1%, it might seem that 10 or 11 bit resolution would be sufficient in a digitizer. However, additional bits of resolution are needed because the input signal frequently does not use the entire input range. For example, even if the instrumentation amplifier gain has been adjusted to yield an input signal with a 20V range, small components of the signal with a 2V range might also be of interest. 0.1% resolution of a 2V signal within a 20V range requires at least 13 bits of resolution.

Accuracy

Several specifications are used to express the accuracy of a digitizer.

The absolute accuracy expresses how precisely the digital values produced represent the analog inputs. For example, a digitizer might have an absolute accuracy of 1 part in 4096. This can also be expressed by saying that the digitizer has 12 bit absolute accuracy.

The relative accuracy expresses how precisely the digitizer measures the difference between two analog input values. This is frequently of greater interest than the absolute accuracy.

The noise specification expresses how much the digitizer output will vary with no change in the analog input. This is frequently expressed as a number of bits. For example, a 16-bit digitizer with two bits of noise will produce effectively the same results as a 14-bit digitizer.

The accuracy of a digitizer varies strongly with its maximum sampling rate. The more accurate the digitizer, the slower it is.

Be careful when reading digitizer specifications. In some cases, manufacturers publish specifications of the A/D converter used in a digitizer as the specifications for the entire digitizer. However, the accuracy of the digitizer may be significantly less. The digitizer may include necessary components such as amplifiers and voltage references that degrade the accuracy. In addition, the A/D specifications apply only under specific conditions described in the converter datasheet. In the digitizer, those conditions may not apply.

From Samples to Computer

Once data has been digitized, it must be transferred to a computer. Usually a digitizer is built as a computer plug-in board, so transfers take place over the computer bus.

Digitizers used for high-speed measurement can feed data to the computer at a high and constant rate. For example, a digitizer running on one channel at 100k samples/second will typically produce 200k bytes/second of data continuously. This is a large stream of data.

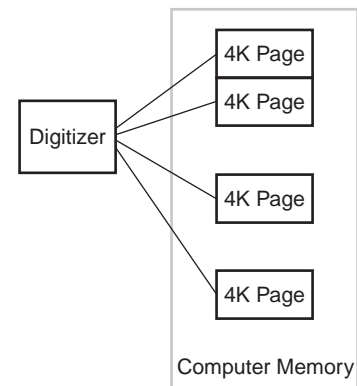
The continuous nature of much data acquisition requires some kind of buffering. For example, if the computer stops for 30ms to write data to disk or to update a display, 6000 bytes of data will accumulate. The data must be stored somewhere, or it will be lost.

Data Transfer: DMA

The Axon Instruments Digidata 1200 uses DMA (direct memory access) to transfer data to the memory of the host computer. DMA transfers proceed regardless of the

activity in the host.

DMA transfers encounter problems during continuous acquisition. The problem is that the DMA controller used on PC motherboards is only capable of transferring data to a contiguous block of memory. However, Microsoft Windows 95 and Windows NT use allocate memory in 4K byte pages. A data acquisition program might have a large buffer, but the buffer will be scattered 4K byte pages in physical memory. The DMA controller can transfer to only one page at a time. When done with a page, it interrupts the host computer. The device driver for the digitizer must then reload the DMA controller for the next page.



Normally these periodic interrupts are not a problem. For example, even at the full 330kHz rate of the Digidata 1200, a 4K page is filled only every 6ms. The interrupt handling in the driver might take 50us on a fast processor. Less than 1% of the time of the processor is taken servicing interrupts.

However, a problem occurs under multitasking operating systems such as Microsoft Windows NT, because many other activities can take place simultaneously. If another device driver is performing processing and has locked out interrupts temporarily, the digitizer device driver may have to wait to service the DMA controller.

To deal with this problem, Axon Instruments has increased the buffer memory in the Digidata from 2K samples in the Digidata 1200 to 8K samples in the 1200A and 1200B. This increase allows the unit to buffer data for up to 24ms even at 330kHz, avoiding problems.

Data Transfer: Buffers

The Instrutech Corporation ITC-16 and ITC-18 do not use DMA. Instead, they use a large buffer to hold data until it can be processed by the host computer. The data is then transferred to the host computer by programmed I/O. That is, the device driver performs the transfer.

On current computers, programmed I/O is about as efficient as DMA. These computers are generally limited in performance by the memory system. Therefore, even through a DMA transfer occurs without the intervention of the host computer, the transfer ties up the memory, which

effectively stalls the processor.

The Instrutech digitizers do not provide interrupts to the host computer. Instead, host computer periodically polls the device to obtain data. This polling is performed periodically by the application program (i.e. HEKA Pulse or Bruxton Corporation Acquire). Since the polling may be infrequent, the digitizer needs a large buffer. For example, if a program can poll the digitizer only once every 100ms, the digitizer must have a 20000 sample memory to operate at 200kHz.

The Instrutech ITC-16 has a 16k sample FIFO. The Instrutech ITC-18 is available with either a 256k sample FIFO or a 1M sample FIFO.

Data Transfer: PCI Bus Mastering

Some PCI bus data acquisition boards can write data directly into the memory of the host computer using bus mastering. Bus master data transfers do not use the motherboard DMA controller, and therefore can potentially support writing directly to a buffer composed of discontinuous 4K pages.

In the future, bus master designs are likely to become popular.

Those familiar with computer system design will notice that the PCI bus master transfers are in fact direct memory access (DMA) transfers. On PC systems, for historical reasons, the term DMA refers to the use of the DMA controller built in to the motherboard.

Data Transfer: Output

The discussion so far has concentrated on data transfer for acquired data. If the digitizer is used for synchronous stimulation or control, the same data transfer problem occurs as for acquiring data. In fact, the total data rate doubles.

Consider, for example, a stimulus/response measurement on one channel with a 100kHz sampling rate. Acquired data is received by the computer at 100kHz. Simultaneously, the stimulus waveform must be delivered by the computer to the digitizer at 100kHz. The full data rate 200kHz.

The Axon Instruments and Instrutech digitizers have symmetric handling of inputs and outputs. The output buffers are the same size as the input buffers, and the same data transfer technique is used.

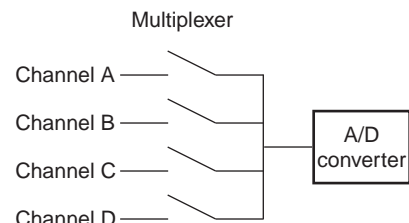
Measurement Accuracy

The following sections discuss the issues that influence the accuracy of dynamic measurements.

Crosstalk

Most digitizers record from multiple analog input channels, with 8 or 16 input channels being commonly supported. An important specification is the crosstalk between input channels, that is, the amount of input signal from one channel that appears on another channel.

Crosstalk is a problem because many digitizers use a single analog to digital converter, and a switch called a multiplexer to select between input channels.



The multiplexer itself is a source of crosstalk. Even when a switch is open, capacitive coupling between the input of the switch and the output of the multiplexer produces a frequency-dependent crosstalk. High-frequency input signals are coupled to the multiplexer output even when they are not selected.

To measure such crosstalk, ground an analog input and sample from it. Meanwhile, connect a high-frequency signal to other input channels. Notice the amplitude of the high-frequency signal that appears on the grounded input. This is the crosstalk. Vary the input frequency and notice the change in the amount of crosstalk.

Crosstalk may not be significant when a digitizer is used for patch-clamp data acquisition. Typically one analog input is used for the ion channel signal, while other analog inputs are used to measure very low-frequency signals. The low-frequency signals do not couple significantly to the ion channel signal. The ion channel signal does couple into the low-frequency channels, but this can generally be eliminated by averaging many input samples on those channels.

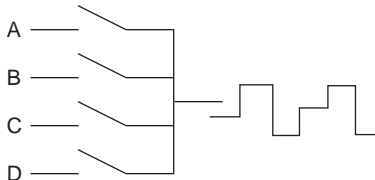
If you measure on several channels containing high-frequency data, characterize the crosstalk of your data acquisition system before you do so. Otherwise you may find yourself measuring correlations in input data due to your digitizer instead of the system being measured.

This problem will become less significant with time, as the cost of A/D converters drops. Digitizer manufacturers can afford to place one A/D converter for each input channel, avoiding the use of a multiplexer.

Settling Time

The settling time of the A/D converter input may limit the rate of multi-channel sampling.

The input Multiplexer
amplifiers on many
A/D converters
cannot follow very
high frequency
input signals.
When the multi-
plexer switches
channels, this appears as a sudden jump in signal level to the input of the A/D converter. At low sampling rates, the A/D input will have considerable time to settle before converting the next sample. At high sampling rates, the input may not have time to settle, and the input signal on one channel affects the value measured on the next.



To see this effect, ground all inputs of a digitizer except one. Connect this input to a variable DC level. Sample at a high rate on multiple channels. Notice if changing the input level on one channel causes the value measured on one of the grounded channels to change.

Frequently, digitizers achieve full bandwidth only when the multiplexer is not being used, and the digitizer is sampling from only a single input channel.

The Axon Instruments Digidata 1200A/B and the Instrutech Corporation ITC-16 both use a single A/D converter and a multiplexer. The Instrutech Corporation ITC-18 uses a separate A/D converter per input channel. While this raises the cost of the device, it essentially eliminates crosstalk.

Grounding

The digitizer is electrically part of your instrumentation system. This can cause problems if you do not consider the digitizer when planning the grounding of your instrumentation.

If your digitizer is used only for acquisition, you can take advantage of differential analog inputs to avoid connecting your digitizer directly to your measurement ground through signal cables. However, if you use the analog outputs of your digitizer this may not be possible, since analog outputs are rarely differential.

Analog outputs are particularly a problem if the digitizer ground is the same as the computer ground. Computer ground lines usually transmit high-frequency switching noise. The noise can be coupled through the common ground into your measurement system. This is a common

failing of low-cost digitizer boards.

The Instrutech ITC-16 and ITC-18 use optical isolation in the digital control path of the digitizer. This completely isolates the measurement system from the computer ground.

Input Impedance

The FET-based input amplifiers used in modern digitizers have a very high input impedance. If inputs are left unconnected, they can pick up unwanted signals and couple them into the digitizer.

The Axon Instruments Digidata 1200A/B and the Instrutech ITC-16 have very high impedance analog inputs. For best results, unused inputs on these devices should be grounded.

The Instrutech ITC-18 has bleed resistors connected internally between the analog inputs and ground to reduce pickup of stray signals. Grounding of unused analog inputs is less critical with this device.

Phase

If you are sampling from multiple input channels, you may be interested in the phase relationship between the inputs.

Digitizers that use a single multiplexed A/D converter inherently have a delay between measurements on different input channels. For example, if two channels are being sampled, each at interval T , most multiplexer-based digitizers will sample successive channels at interval $T/2$. Sample number N on channel A and sample number N on channel B will be separated in time by $T/2$.

For most applications, this delay is not of concern. However, in some cases the phase relationship between signals is of interest.

To limit the phase shift between channels, you can sample at a very high rate. If you can sample quickly enough, you can minimize the delay between samples.

An alternative solution is to sample from successive channels at high speed in a burst. Some digitizers provide sophisticated internal timers that allow you to sample a group of channels quickly, then delay for the next sample. For example, suppose your sampling rate is 1kHz on four channels. With most digitizers, you would sample at an interval of 250 μ s. However, if your digitizer has the capability, you could sample the four channels at an interval of only 10 μ s, then wait until a full 1000 μ s interval has elapsed before the next sample.

You can also correct for the error in software. You may

be able to adjust your calculations for the delay. For example, the HEKA Pulse program is aware of some of the delays in the Instrutech ITC-16, and adjusts for them.

The best solution is to use a digitizer without a multiplexer. Some digitizers, such as the Instrutech ITC-18 and the Markenrich CL522, provide an A/D converter for each input channel. This allows all channels to be sampled simultaneously, with no delay. Using multiple A/D converters is by far the best solution, but it is also the most expensive.

Synchronization

Digitizers may provide analog outputs used for stimulation and control. The analog outputs are updated at the same rate the analog inputs are sampled, and have sufficient buffering to allow continuous stimulation while recording.

When using a digitizer to measure the response of a system to a stimulus, be aware of the time relationship between stimulation and sampling. Two effects must be considered: the pipeline and the device timing.

Digitizers generally have pipelines of input and output samples. For example, the A/D converter usually delivers a digitized data value while it converts the next value. Data values may be temporarily buffered in internal registers while being transferred. This usually leads to a delay of three to five samples in a pipeline.

To see the effect of this pipeline, suppose that at a stimulus value appears on one of the digitizer outputs. Simultaneously an analog input is sampled. Even if the system being measured has no delay, several sample times will pass before the analog input value resulting from the stimulus passes through the pipeline. When measuring the response of a system to a stimulus, this delay must be taken into account. Depending on the digitizer design, this delay may be a function of the number of channels being sampled or stimulated.

Analog input sampling and analog output update may not be simultaneous. The designer of a digitizer usually tries to minimize analog input measurement noise. When analog outputs are updated, the transition may cause electrical disturbances that appear as noise on the analog inputs. Capacitive coupling from the outputs to the input can appear as noise on the inputs. Noise can also be a result of coupling through the power supply or ground.

A simple technique to minimize this noise is to choose the phase relationship of sampling and update to allow as much time to pass following an update before the next sample. For example, if the sampling interval is T , the analog inputs might be sampled at time 0 and the analog out-

puts might be updated at time $T/2$.

If you are interested in measuring the response of a system to a stimulus precisely, you will have to obtain information from the vendor regarding the synchronization of stimulation and response.