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Advanced Measurements:
A Postgraduate Tutorial

Part 1 — Instrument Selection and Programming

This multi-part tutorial article covers electrical measurement techniques you probably didn't learn in an engineering undergraduate course. It is intended for those concerned not only with accurate measurements of low-level signals, but also with maximizing test system throughput, particularly in a production environment. The information presented in the article goes beyond the usual admonitions about careful attention to cabling and connections. Instead, it emphasizes what a test engineer or technician can do in terms of instrument selection, programming and setting up test configurations to optimize throughput and accuracy tradeoffs. The topics covered will be pertinent to many types of data acquisition systems and benchtop instruments.

MARK CEJER & DALE CIGOY

Creating a test system to maximize speed or accuracy is comparatively easy; creating one that simultaneously optimizes both is more challenging.

Imagine you just installed and configured your new instrument and started making measurements. Just as you begin to feel successful, you notice that the display is flickering so wildly you can't get a good measurement. Why the noisy readings? What can you do to correct the problem? Maybe a slower reading rate will produce more stable, accurate measurements, but then throughput is reduced.

Keithley Instruments Model 2700

In this first installment of a five-part series on improving measurement results, you will learn fundamental concepts associated with noise, accuracy and test throughput. The starting point will be an analysis of the device-under-test (DUT) and your measurement requirements, which provide the foundation for specifying signal source and measuring instrument performance.

ANALYZING THE DUT AND TEST REQUIREMENTS

Whether your DUT is a component, printed circuit board, module or end product, identify all the measurement points, along with the type and magnitude of the electrical variables at those points. While doing this, note the test techniques you plan to use and whether a stimulus (signal) must be applied to some of the test points. If so, what are the voltage, current and power limitations of the DUT?

Next, identify the most critical test requirements. What levels of measurement resolution, sensitivity, accuracy and repeatability are required to satisfy the application? Is absolute accuracy important or is good repeatability sufficient? Note the nature of the test environment and potential noise sources. What degree of noise immunity is required in order to accurately measure your lowest signal levels?

Then specify how collected data will be utilized and the data output format. For example, do you really need to observe or record data, or is a pass/fail indication all that is needed? Do you want to use such an indication as a go/no-go signal for an operator's graph-

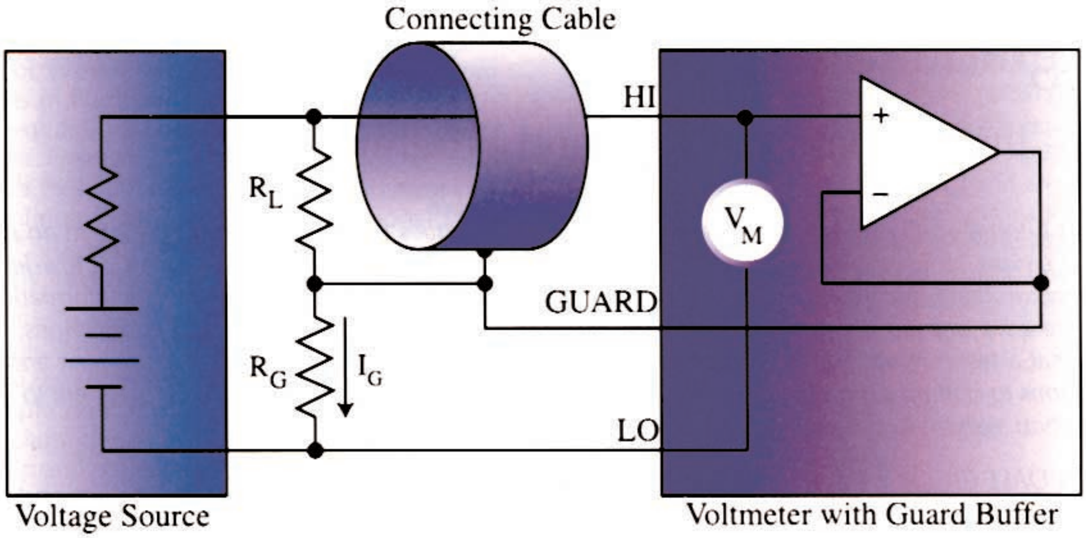

Figure 1 - Diagram of guarded/shielded connections in a test circuit. Use shielded and guarded connections to help alleviate noise and current leakage problems that affect measurement accuracy and speed.
(Courtesy: Keithley Low Level Measurements Handbook)

ic display, or will it be used to control a test fixture, do parts binning or mark the DUT? Will the data or pass/fail signal be sent over a data communications bus to a PC controller, or stored in a measurement instrument's internal memory?

When multiple DUTs, measurement points, signal sources or instruments are required, you should think about a switching system to automate and speed up measurements. Which type of switching topology is best for your application and throughput requirements? The choices are:

- Simple Switch — Independently connect one input with one output. The inputs and outputs can be DUTs or instruments. This is a 1:1 switch topology.
- Multiplexer — Connect one instrument to multiple DUTs or multiple instruments to one DUT.
- Scanner — Scanning is similar to multiplexing except the connections are made in sequence. The is a 1:N or N:1 switch topology.
- Matrix Switcher— Simultaneous connect one input to multiple outputs, multiple inputs to one output, or multiple inputs to multiple outputs. This is an M:N switch topology.

Finally, determine the connection configurations for each test setup. Identify the number and location of source and measurement connections, including their grounding, shielding, guarding and high impedance requirements.

Shielding is the use of a metal enclosure to surround the test circuit, or a metal sleeve surrounding wire conductors. This lessens induced noise from electromagnetic or electrostatic sources and reduces current leakage problems. Guarding, used with low-level signals, consists of a conductor driven by a low-impedance source and surrounds a test lead connected to a high-impedance signal. This arrangement reduces current leakage errors due to cable capacitance and decreases measurement response time. High impedance measurements with picoammeters, electrometers, and sensitive source-measure units typically require coaxial or triaxial cables, which provide signal paths for shield and guard connections.

Understanding Source And Measure Instrument Specifications

With all these measurement requirements in hand, you can begin comparing them to manufacturers' instrument specifications. Instrument speed (reading throughput) and overall measurement accuracy are the first criteria to consider. Still, comparing test requirements with hardware specifications can be confusing because dif-

TABLE 1

Percent	PPM	Digits	Bits	dB	Portion of 10V
10%	100000	1	3.3	-20	1 V
1%	10000	2	6.6	-40	100 mV
0.1%	1000	3	10.0	-60	10 mV
0.01%	100	4	13.3	-80	1 mV
0.001%	10	5	16.6	-100	100 µV
0.0001%	1	6	19.9	-120	10 µV
0.00001%	0.1	7	23.3	-140	1 µV
0.000001%	0.01	8	26.6	-160	100 nV
0.0000001%	0.001	9	29.9	-180	10 nV

Table 1. Specification conversion factors — equivalent methods of specifying measurement resolution and accuracy. (Courtesy: *Keithley Low Level Measurements Handbook, 5th Edition.*)

ferent manufacturers use different concepts and engineering units. The most important elements of overall accuracy are sensitivity, resolution, calibration traceability, repeatability and noise immunity, all of which may be specified in different units, such as digits, bits, percentage, PPM or dB. (See Table 1).

Resolution is the smallest portion of a signal that can be observed with the measurement device. It is determined by the A/D converter in the measurement device, and is usually specified in bits or digits. These two parameters are interchangeable and can be roughly converted with the proportionality equation: 12 bits ≈ 3.5 x (number of display digits); for example, 16 bits ≈ 4-1/2 digits (3.5 x 4.5 = 15.75). For multimeters, resolution is stated in terms of digits, such as 6-1/2. This means that for the most significant digit, the instrument displays only values of 0 and 1, or possibly 0, 1, and 2. The other three digits can take on values from 0 to 9. (See Table 2).

Sensitivity is defined as the smallest change in the measurement value that can be detected. It is normally calculated from the resolution of the lowest measurement range using the equation: Sensitivity = Measurement Range/Resolution.

Calibrated accuracy (also referred to as traceable accuracy) is an expression of the degree to which a measurement result agrees with a value arrived at using an accepted standard measuring device. In order to maintain acceptable accuracy, a measurement device must be periodically calibrated with a standard device. Recognizing the dynamic nature of calibrated accuracy, manufacturers often specify it for a given temperature range and period of time. Typically this is simply called 90-day or one-year accuracy.

Repeatability is the degree to which two measurements of the same value agree with each other when tested under the same conditions, and is usually stated as a percentage deviation between the two measurements. In some applications, relatively low accuracy can be tolerated if repeatability is high (i.e., deviation is low).

Noise immunity is the ability of a measurement device or system to separate the signal being measured from a noisy background. Key factors are the signal level relative to noise induced by the environment, input filtering available, and the measurement device's noise floor (i.e., maximum noise level).

Throughput is usually specified in readings or samples per second and is affected by several factors. (See discussion below.)

Features and Functions Affecting Accuracy and Throughput

There are inherent limitations in the speed and accuracy of typical measurement system architectures. This is illustrated in Table 3, a comparison of typical benchtop instruments and PC-card data acquisition systems.

TABLE 2

8 Bit (2^8)	1 part in 256	0.039 Volt (39 mV)
12 Bit (2^{12})	1 part in 4096	0.00244 Volt (2.44 mV)
16 Bit (2^{16})	1 part in 65536	0.000153 Volt (153 µV)
3-1/2 digits	1 part in 2,000 counts (0000 to 1999)	0.01 Volt (10 mV)
6-1/2 digits	1 part in 2,000,000 counts (0000000 to 1999999)	0.00001 Volt (10 µV)
8-1/2 digits	1 part in 200,000,000 counts (000000000 to 199999999)	0.0000001 Volt (100 nV)

Table 2: Resolution examples for a 10V full scale input range, expressed in terms of digital display and the number of processed bits in the measurement equipment's A/D converter.

TABLE 3

Parameter	Benchtop Instruments	Data Acquisition Products
Sensitivity	1 nanovolt	5 microvolt
A/D resolution	20-28 bits	12-20 bits
Noise immunity	excellent; built-in	Limited; add-on
Sample rate	2 kS/s	1 GS/s

Table 3. Accuracy and throughput for typical measurement systems

For many applications, you may be able to select from a list of several measurement devices or systems that, on the surface, appear to provide sufficient accuracy and speed. A quick look at typical specifications reveals information on inherent accuracy and maximum measurement rate, the latter usually being expressed as number of readings per second, samples per second or scan rate in hertz. However, the specifications may not explicitly state there is a tradeoff between speed and accuracy for any given set of measurement parameters, which is usually the case. In fact, you can program these tradeoffs in most benchtop instruments and data acquisition systems. Programming may be done with instrument pushbuttons or by writing an application program for PC control using Standard Commands for Programmable Instruments (SCPI), or by using application development software with a graphical user interface (GUI). (There will be more on software and programming in a future installment.)

In a data acquisition system, the first speed consideration is the maximum aggregate scan rate and the number of channels (inputs) to be scanned. The maximum scan rate per channel generally is the aggregate rate divided by the number of channels. Benchtop instrument with internal scanner cards, and those connected to DUTs through a switching system have similar speed considerations.

Usually, benchtop instrument throughput is stated for a specific measurement function and fixed range; speed is limited by the maximum rate of range change when making multiple measurements. Similarly, if the instrument has an autorange function, then maximum autoranging time may be a limiting factor. However, actual speed with autoranging is not predictable and its use should be avoided when optimum speed is required. This is possible when the sampled signal level can be reliably estimated. Disabling the autorange function eliminates the time it takes an instrument to determine the appropriate range, which dramatically increases throughput. (See Figure 2.) When autoranging is not used, the best accuracy is usually attained from a measurement on a full-scale range just above the signal level.

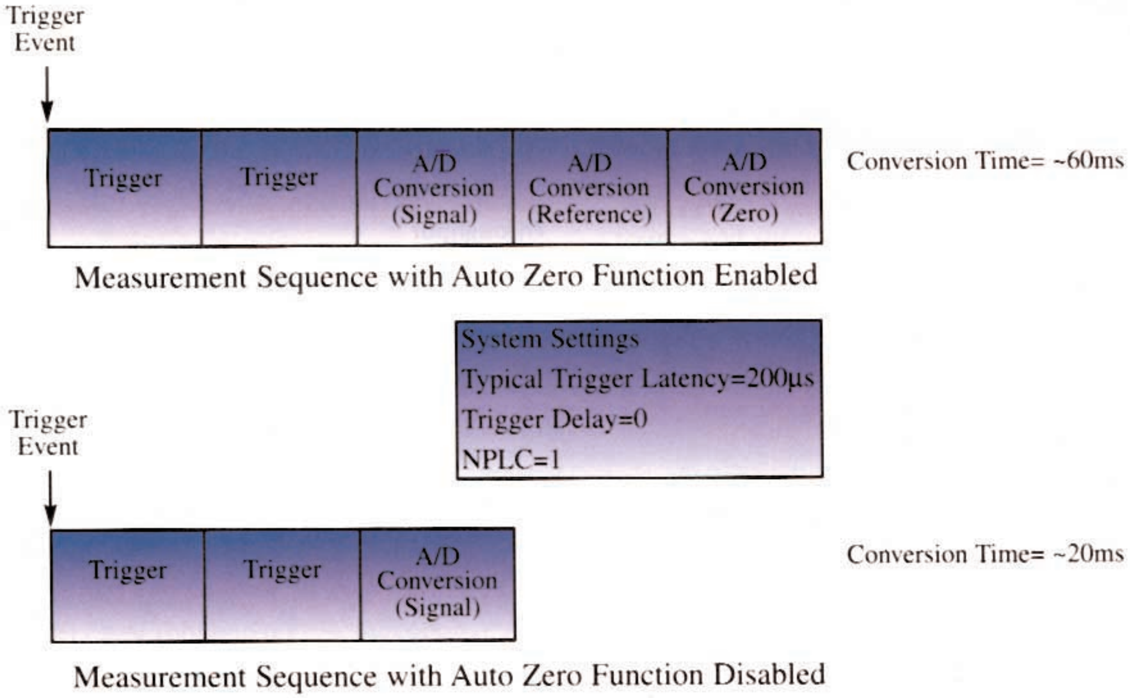

Figure 2. Effect of autozero and trigger latency on measurement time

Autozero is another instrument feature that affects throughput. When this feature is used, the instrument's measurement circuitry periodically acquires a zero and a reference signal in order to maximize accuracy. This is required because temperature changes and thermally generated voltages cause component values to drift. The default setting for most instruments generates an autozero before each measurement, which may not provide the optimum tradeoff between speed and accuracy since three measurements (zero, reference, and signal) are required for each reading.

Usually, autozero can be disabled or forced to occur at a specific time. With autozero disabled, the time required for zero and reference measurements is eliminated. Although readings can drift slightly over time, programming the instrument to perform an occasional autozero may be sufficient. Some instrument manufacturers specify drift; use this information to set the autozero interval and optimize accuracy/speed tradeoffs. For example, if a small amount of drift can be tolerated over the course of several measurements during batch testing, then program the instrument to autozero only at the start of a batch. If requirements are less stringent, you may be able to get away with one autozero at the beginning of a work shift.

Allow Adequate Settling Time Before Making Measurements

Many applications require a signal source to force a response in a DUT and most benchtop instruments have a built-in voltage or current source that can be used for this purpose. To allow for DUT and test cable settling time, which improves accuracy, there must be sufficient delay between signal application and measurement of the DUT response. This source delay is programmable in many benchtop instruments and should be part of a test program run under PC control, regardless of whether the system uses PC plug-in cards or GPIB instruments. To optimize speed and accuracy, the source delay should be based on the total time it takes the DUT and the rest of the system to settle to a steady state value.

Similarly, trigger delay is the period from when a trigger signal is received to the time when the instrument starts the actual measurement. (See Figure 2.) Trigger delay is another programmable value that can be used to allow adequate settling time for switching matrix contacts, pulsed signal rise time, etc. Starting the measurement before the system has settled can result in a noisy, inaccurate result. Solid state and reed relays tend to have settling times of a few hundred microseconds; mechanical relays may take from three to 10ms to settle. Read the relay or switching system spec sheet to determine maximum settling time and set the trigger delay slightly higher, assuming the switching mainframe does not already compensate for relay actuation time.

However there are inherent latencies in various parts of a test system that may otherwise limit throughput. One example is trigger latency; internal or hardware triggering is usually faster than external or software triggering. Also, updating an instrument's front panel display takes time, particularly those that are information intensive. In systems where speed is critical, the display should be disabled -it probably will not be used during high-speed data collection anyway. Still, the longest latencies may well be fixed delays built into a component handler used in a production test system. Latencies such as these should be identified and minimized before examining instruments and test application programs for additional speed enhancement opportunities.

Minimizing Noise Effects

There are three test system parameters affecting noise immunity, which can be modified in some instruments and data acquisition systems to optimize speed/accuracy tradeoffs:

Signal Integration Rate — This is the rate at which an acquired signal is integrated by a measurement device's A/D converter. Typically, it is specified in terms of power line cycles (PLCs), where 1 PLC equals 16.7 ms for a 60 Hz power line frequency, or 20 ms for 50 Hz power. The programmable range for a good quality instrument is from 0.01 PLC to 10 PLC with 1 PLC being the default setting. Because line cycle noise is periodic, integer multiple PLCs can be used to minimize the residual noise on the acquired signal. The shorter the PLC period, the faster the measurement, but with reduced noise immunity and the possibility for errors when measuring low-level signals. (See Figure 3.)

Resolution — As discussed earlier, resolution affects the sensitivity and accuracy of measurements. Some data acquisition boards have A/D converters with programmable resolution. Many instruments have this feature. For example, an instrument's display resolution might be varied from 3-1/2 digits to 8-1/2 digits. Lower resolutions allow faster measurement rates; resolving a larger number of digits and communicating that data to the display or data storage location takes more time. Program the device for only as much resolution as necessary, which is determined by your application requirements.

Filtering — Digital filters can reduce inaccuracies caused by random noise. Some instruments have different filter types built into their input circuitry, which can be selected or turned off as desired. In most PC plug-in board data acquisition systems, such filters must be purchased separately and externally installed ahead of the analog input connector on the data acquisition cards. A typical filter parameter that can be set by the user is the number of A/D conversions averaged for each reading. This parameter typically spans a range from one to 100 conversions and will have a default setting of 10. Of course, a larger number of conversions results in greater noise immunity but at the expense of lower throughput.

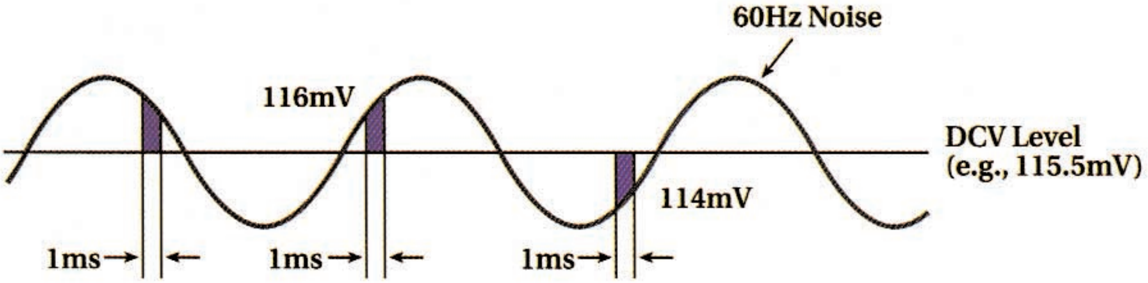

Figure 3. A short signal integration period (in this example, 0.06 PLC = 1 ms) can result in errors as the instrument reads a DC signal with superimposed 60 Hz noise.

Also, different averaging techniques can be selected, some of which take more time than others. Typically, the fastest averaging method for continuous readings is to discard only the oldest reading and replace it with the newest reading before recalculating the average.

The settings for speed and display resolution in an instrument are often interrelated, but manual overrides may be possible. Table 4 lists some programmable instrument settings and their affect on throughput and accuracy.

Instrument flexibility is the key to balancing accuracy and speed. The more programmable parameters you have available, the better.

A Look Ahead To Part 2 — Instrument Designs

In the next installment of this series, important design features of measurement devices will be discussed. This information will provide additional help in the selection and configuring of measurement equipment to achieve optimum results. Major topics will include front-end design and its effect on input impedance and voltage burden errors, A/D technology and its effect on measurement noise, and common interfaces for switching systems and data communication buses.

TABLE 4

Integration Period	Display Resolution	Filter Averaging	Throughput Result
0.01 PLC	4-1/2 digits	1-10 conversions	High Speed
0.1 PLC	5-1/2 digits	10 conversions	Medium Speed
1 PLC	6-1/2 digits	10 conversions	Medium Accuracy
10 PLC	7-1/2 digits	10-100 conversions	High Accuracy

Table 4. Typical instrument settings and their effect on speed and accuracy

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