Technical Note

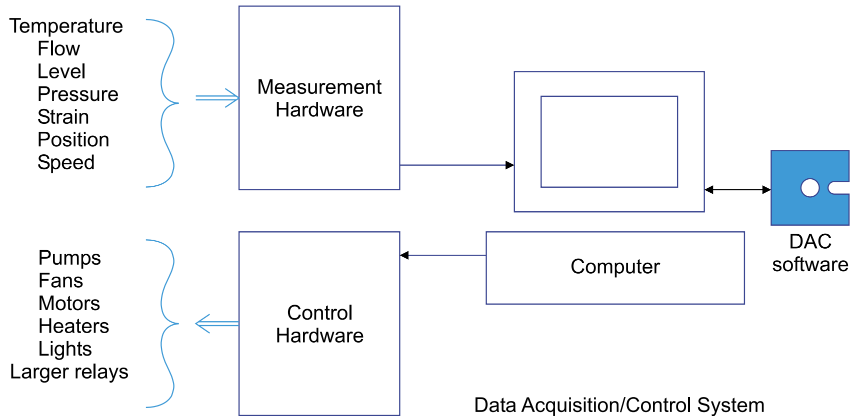

Figure 1

Fundamentals of Data Acquisition

What is Data Acquisition?

Data acquisition systems make various types of physical measurements, such as temperature, pressure, flow, strain, position, and speed, using electronic equipment. The data collected is usually sent to a computer for analysis and display. Data acquisition and control (DAC) systems also take action (control) based on the data they receive. Turning on or off lights, motors, valves, heaters, and fans are common functions of control. Sending out voltage, current, digital words, pulses, and waveforms are also forms of control from the DAC system. DAC software running in the computer coordinates and executes these functions. (Figure 1)

Temperature • Flow • Level • Pressure • Strain • Position • Speed • Pumps • Fans • Motors • Heaters • Lights • Larger relays

Why Use Data Acquisition?

Collecting data is a tedious and time-consuming component in many research projects or experiments. Although necessary, it is a task that we would rather not spend much time on. Data acquisition and control allows us to automate the long hours of routine data collection, freeing us for tasks that can make a difference.

What will data acquisition and control do?

IMPROVE: Quality, Efficiency, Cost

SAVE: Time, Money

Data acquisition can help us gather data that would otherwise be difficult to obtain manually. This data can help us better understand a product or process. Improvements can take the form of higher quality, more efficiency, or lower costs, resulting in savings of time or money. (Figure 2)

Key benefits:

- **Reduce time needed to manually collect data**
- **Reduce errors that can occur when inputting data to a computer by hand**
- **Operate unattended for days/months/years**
- **Make high-speed collection rates possible**
- **Provide tighter control than is possible manually**

Where do we use data acquisition and control?

Characterization: Measure the response of a product or process relative to all variables. Typically used in engineering to test new designs.

Monitoring: Measure the response of a product or process relative to key variables. Alarms are invoked when the key variables go outside prescribed limits.

Control: Measure the response of key variables and take corrective action when the variables go outside prescribed limits. Typically used in manufacturing, environmental, and process control.

For Products:
- Save time by automated testing of new designs
- Access new designs by collecting more accurate data
- Understand the response of a product to various stimuli
- Document test results in less time
- Document multiple test results to satisfy the conditions of a contract
- Improve product quality with more thorough testing

For Processes:
- Maintain more accurate control over a successful process
- Improve a process by studying the collected data
- Document the effects of changing variables in a process
- Monitor a process for trends and react accordingly

A DAC system not only saves time and money but also has the potential for helping you document a significant breakthrough - one that "makes a difference".

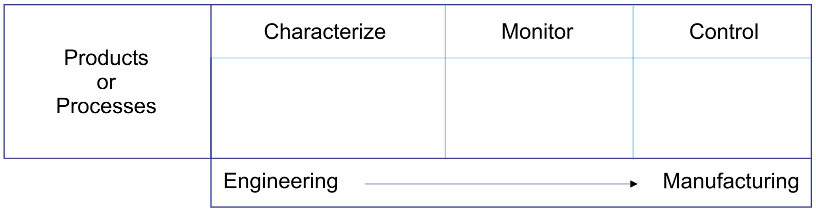

Figure 2

Applications

The following table summarizes other applications and uses for DAC equipment in those applications to improve a product or process.

APPLICATION	DAC SYSTEM USES
Chemistry research	• Characterize a chemical reaction • Control chemical mix in a reaction • Easily perform "what if' scenarios
Energy research	• Characterize new fuels • Monitor output of wind farms • Control solar energy collection
Facility monitoring	• Monitor energy consumption • Control heating/ventilation • Switch on/off lights at night
Greenhouse	• Control watering/ humidity
Material test	• Characterize new materials • Monitor production of plastics • Control production variables
Mechanical test	• Monitor machinery for failures • Test new mechanical designs
Plant research	• Control environment for better growth results

How Does a Data Acquisition System Work?

Overview

A data acquisition and control system turns physical phenomena (temperature, pressure, flow, position, speed) into data that can be stored, analyzed, displayed, or acted on. DAC systems can be divided into 10 key parts for further discussion (Figure 3).

Transducers

Transducers are devices that transform physical phenomena (temperature, pressure, flow, strain, position, speed, pH, acceleration, etc.) into electrical parameters (voltage, current, resistance, pulses, etc.) that can be measured by instrumentation.

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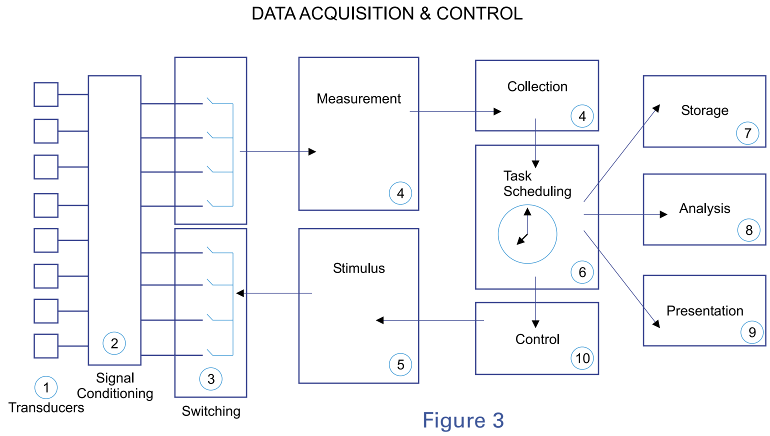


Figure 3

Fundamentals of Data Acquisition

Signal Conditioning

Signal conditioning is used in data acquisition systems to put the analog or digital signal into a form that can be accurately measured by the equipment. The signal may be too weak, too strong, too noisy, or in the wrong shape to be measured accurately. The conditioning may be accomplished on the transducer end of the wiring or in the measurement hardware.

Switching

A switch is a mechanical or electronic device that is used to make or break the connections in an electrical circuit. Switches can be used to route the output signals from multiple transducers to one measurement instrument (scanning). Switches are also used as control devices to switch power to external fans, heaters, pumps, lights, and motors (Figure 4).

Switches come in a variety of forms. A relay is an electrically-controlled device where a mechanical part moves to make or break the circuit. Reed relays and armature relays are two examples. A solid state switch is an electronic device that makes or breaks the circuit. Field Effect Transistor (FET) switches are examples of solid state switches. In general, solid state switches will outlast relays but can only switch low voltages. The following table summarizes some common switch types.

Switch Type	Range	Speed	Offset	Life
Reed relay	(0 - 170) V dc	500 Hz	2 µV	10^9 Closures
Armature relay	(0 – 170) V dc	60 Hz	4 µV	10^8 Closures
Power relay	(0 - 300) V dc	10 Hz	10 µV	10^6 Closures
FET switch	(0 - 10) V dc	10 MHz	5 µV	10^3 Hours
Solid state	(0 - 100) V dc	1 kHz	10 µV	10^3 Hours

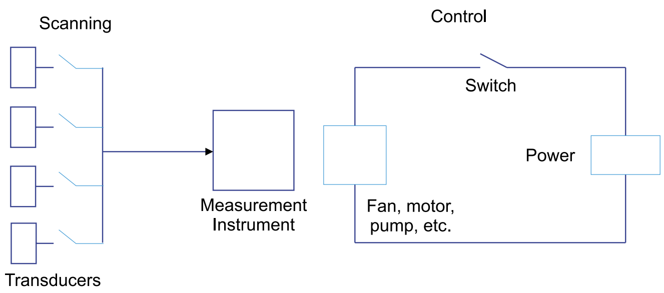


Figure 4

Scanning

Multiplexers are electronic devices that are used to switch multiple channels to a single measurement instrument, one at a time. They operate much the same way as a television set; although several channels are available, only one channel is viewed at a time.

Multiplexers are available in one-wire, two-wire, three-wire, and even four-wire varieties, each with its own special usage. One-wire (sometimes called single-ended) multiplexers are used in applications where the measurement instrument is close to the transducers and a common ground is practical. Two-wire (differential) multiplexers are the most common type and are used with instruments that have a differential (high and low) input.

Three-wire (guarded) multiplexers are used with high-end, guarded voltmeters for the best accuracy in analog measurements (see the measurement hardware section on A/D converters). Four-wire multiplexers are used in making four-wire measurements on transducers such as RTDs (see Appendix C) that require a current source (Figure 5).

Fundamentals of Data Acquisition

Some A/D converter cards come with a multiplexer on the card. In cardcage products, the multiplexers are generally on a separate card from the A/D converter. In this way, several multiplexers can be tied to one A/D converter. Some multiplexers require the user to solder wires to the card while others supply screw-down terminals. For convenience, some cardcage multiplexers supply a separate terminal block. Wires from the transducers are attached to the terminal block without removing the multiplexer from the cardcage. The terminal block simply attaches to the end of the multiplexer card (Figure 6a).

Control switching

Switching can also be used to supply power to external fans, pumps, motors, or lights by completing a circuit. Power is normally supplied outside the DAC system. The switch card acts much like a light switch, turning power on or off to the device. In some cases, the DAC switch card supplies a small voltage signal to a larger external relay which in turn supplies the power to the device (Figure 6b).

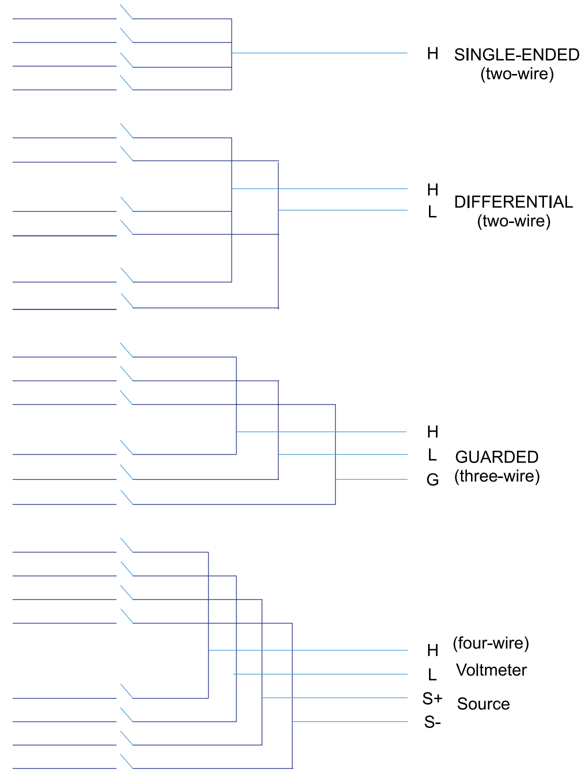


Figure 5

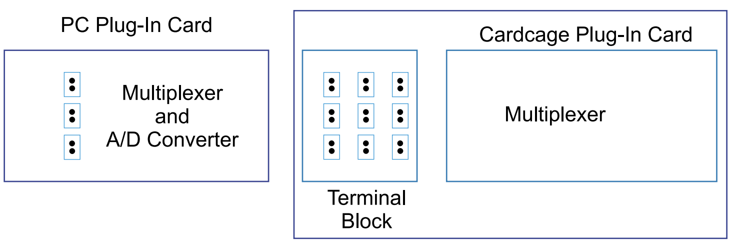


Figure 6a

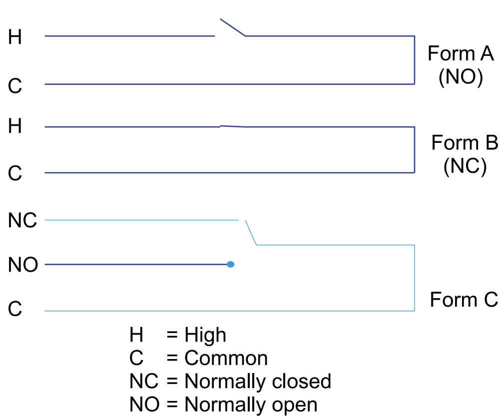


Figure 6b

Measurement

A/D Converter

The A/D converter, a key element in a DAC system, is used to convert dc voltages from transducers into digital words (data). The voltage represents a temperature, pressure, flow, pH, or speed and must be converted to a digital word before it can be passed to an intelligent device like a computer.

A voltmeter performs the same task as an A/D converter. A multimeter is a superset of a voltmeter and A/D converter. In addition to measuring dc voltages, the multimeter can measure ac voltage, resistance, and sometimes current. The A/D converter is specified in bits. (Figure 7b).

The number of bits defines the resolution, the smallest voltage change that the A/D converter can distinguish. If an A/D converter is 8 bits, it can distinguish up to 28 or 256 parts. If the A/D has a range of (0 - 10) V, it can sense changes in steps of 10/256 = 0.0391 V. Voltmeters are usually specified in digits. (Figure 7b).

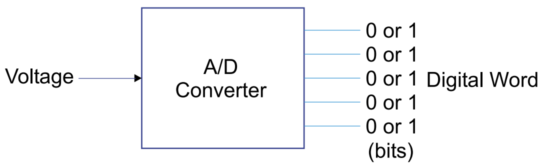


Figure 7a

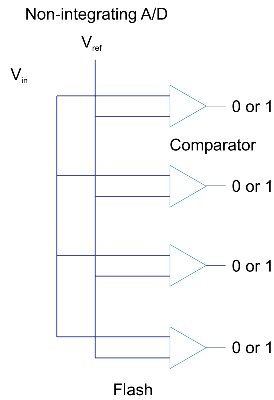


Figure 7b

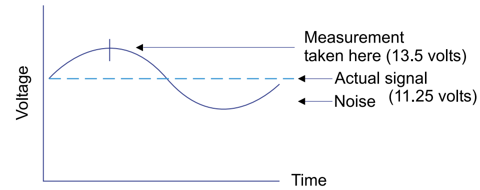


Figure 8

Bits	Parts	Digits
8	256	2 1/2
10	1024	2 1/2
12	4096	3 1/2
14	16384	3 1/2
16	65536	4 1/2
18	262144	5 1/2
21	2097658	6 1/2

DIGITS = $\log_{10}$ (2*bits -1)

There are two types of A/D converters - integrating and non-integrating.

Non-Integrating A/D

The non-integrating Flash converter compares the input voltage (V_{in}) to a set of known (reference) voltages (comparator). A digital value (0 or 1) is assigned based on the results. If any noise is present on the signal at the time it is digitized, the digital word will reflect that error. Flash converters tend to be expensive because of the cost of accurate voltage references. (Figure 8).
Another type of non-integrating A/D, the successive approximation A/D, is less expensive than a Flash converter. It uses one comparator and generates reference voltages, comparing each one to the input signal. If the input signal is varying, a voltage error can occur.

Integrating A/D

The integrating A/D converter integrates the input signal over a period of time. Over that time period, the noise on the input signal is integrated to zero, leaving the actual signal value. Most noise is related to power lines and exists at 60 Hz in the U.S. and Canada and at 50 Hz in Europe and other parts of the world. (Figure 9a).

A digital input card is used to determine whether an external device is on or off by sensing the presence or absence of a voltage. In the DAC system, the computer can interrogate the digital card to determine which channels contain a high/low voltage. The digital input can only report ON/OFF status and not the value of the voltage on each channel (sometimes called a bit). The bit is considered to be ON if the voltage exceeds a certain value. Digital cards are usually 8, 16, or 32 channels. They can monitor a number of devices. For example, a digital card can be attached to a simple operator panel to sense the position of switches on that panel. In other cases, a digital input card can be connected to machinery (like a dynomometer) that outputs its status in the form of digital words (8 bits).

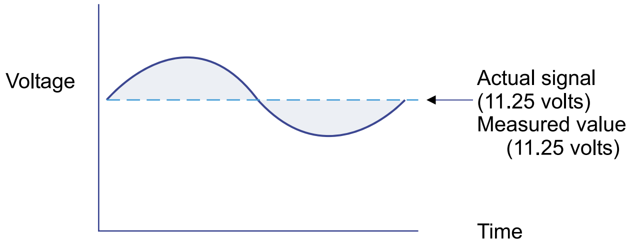


Figure 9a

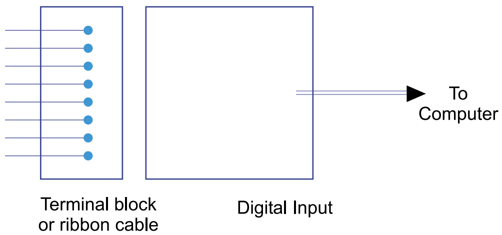


Figure 9b

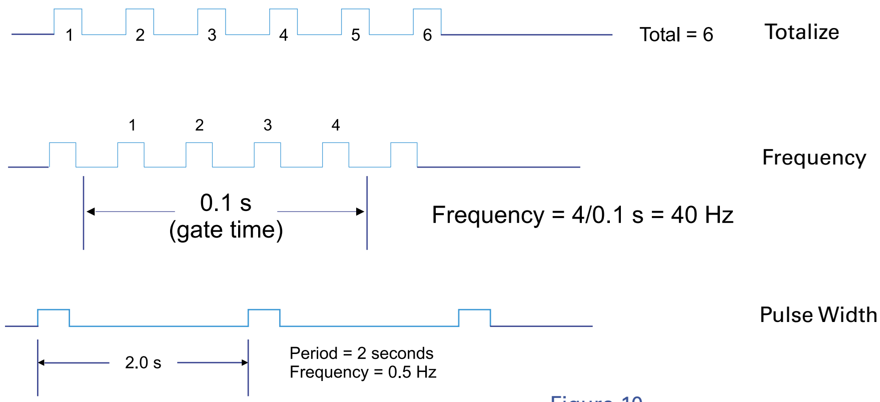


Figure 10

Fundamentals of Data Acquisition

Digital input cards use a terminal block much like that used with a multiplexer or may simply attach to the external world with a ribbon cable. (Figure 9b).

The COUNTER card can be used to sense the presence or absence of a voltage, much like digital input card. The counter is used to count the number of electronic pulses (totalize), the duration of the pulse (pulse width), or the rate of pulses (frequency) coming out of an external device. Counters may come with a terminal block or, if they measure frequencies above 1 MHz, they may come with BNC connectors. Totalize is a common function used in production applications to sense the number of items being tested or produced. When an item breaks the beam of an optical sensor, its output voltage changes and the counter records the event as another count. (Figure 10).

Frequency measurements are common measurements made on flow and RPM transducers. These transducers output a series of pulses proportional to the rate of movement. The counter records the number of pulses (counts) per unit of time (gate). Frequency is the count divided by the gate time.

If the frequency is quite low, a reciprocal counter is used to make a period measurement. In a period measurement, the counter records the amount of time from one pulse to the next. The frequency can be obtained by taking the inverse of the period.

Pulse width measurements are used to determine the length of time a pulse stays at a high (or low) voltage level. One practical application is to use a sensor and measure the amount of time it takes an object to pass this sensor. This measurement can be used to determine the speed of a known object or, if speed is known, the length of an object where size is not known.
Time interval measurements can be made by the more sophisticated counters. These measurements are the time between one edge of a pulse and another. If the edges are both the same, the time interval is the period. If one edge is rising and the other is falling, the time interval is equal to the pulse width.

Gated totalize is a special case where two counter channels are used. A count is taken on the A channel only when the B channel has a high or low voltage. Otherwise, the pulses entering on the A channel are ignored.

Position is often measured with a counter card in the up/down count mode. In this mode, the counter will increment the count if the pulses occur on channel A and will decrement the count

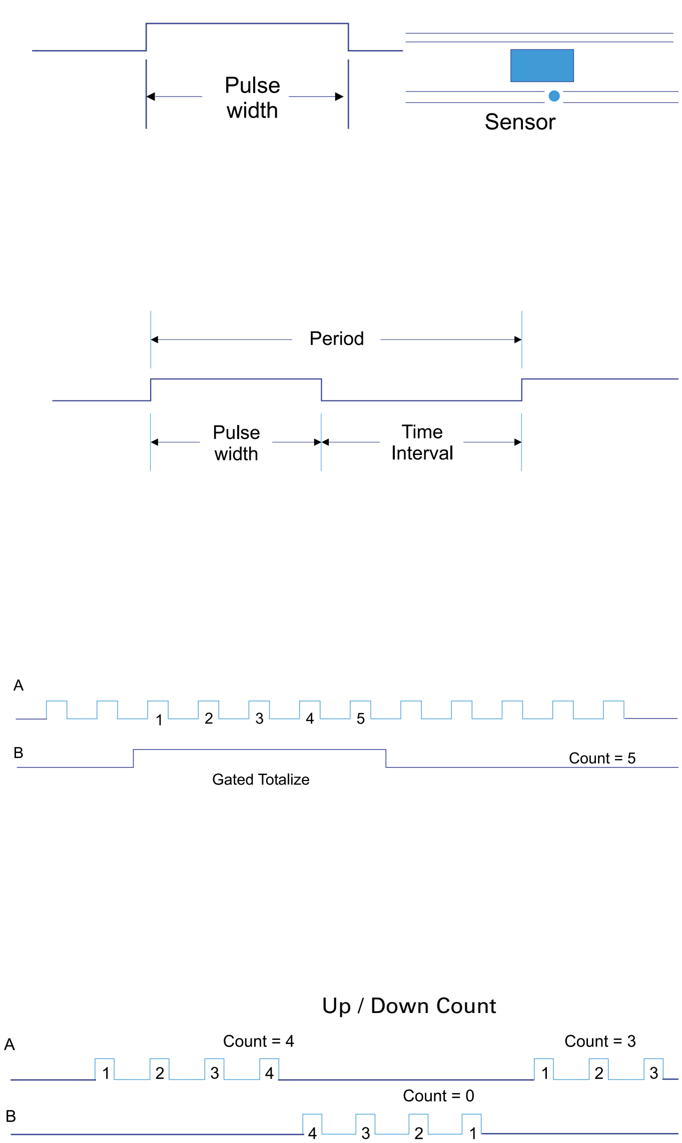


Figure 11

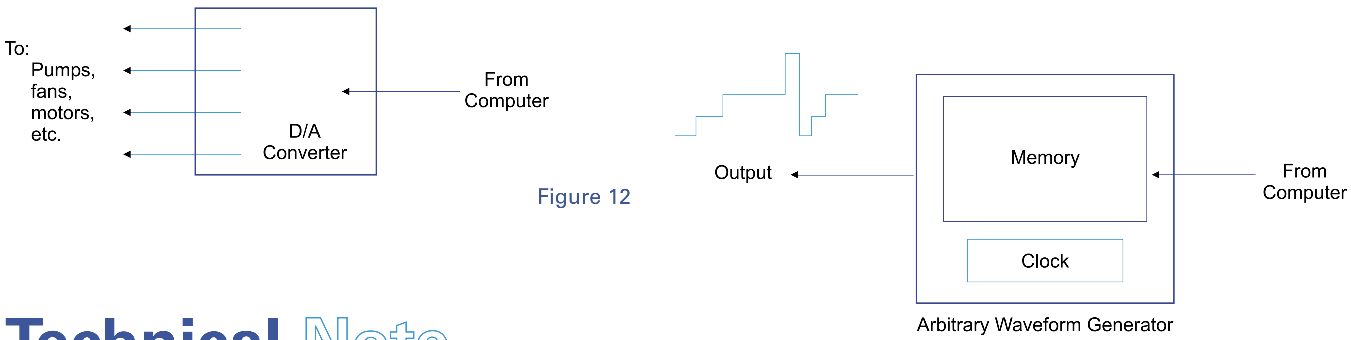


Figure 12

if the pulses come in on channel B. Movement in one direction is the "up" count and in the other direction the "down" count. (Figure 11).

Control Hardware (Stimulus)

The control hardware performs an opposite task from the measurement hardware, interpreting digital words (commands) from the computer and outputting the appropriate electrical signals (voltages, currents, pulses, waveforms). These signals control fans, motors, valves, and heaters or route power and signals to external devices. Control hardware can be used for three types of control: analog output, digital output, and switching.

Analog Output

The D/A converter performs the opposite function of an A/D converter. It interprets commands from the computer and outputs the proper dc voltage or current. The output stays at this output level until the computer tells the D/A converter to output a new value. The voltage or current from the D/A converter can be used to control the speed of a fan, the position of a valve, or the flow rate of a pump. D/A converters are used in applications that require precise control of external devices. One specialized type of D/A converter is the arbitrary waveform generator. (Figure 12).

This device contains memory and a clock and can output a series of dc voltages at varying rates. The memory is used to store these voltage values and the clock determines the output rate. When the clock rate is fast enough, these dc voltages or waveforms take shape of sine, square, or ramps output. (Figure 12).

Digital Output

The digital output card interprets a command from the computer and outputs a high or low voltage on each of its channels (bits). It is commonly used to turn on/off small lights or to send digital words to machinery.

The pulse output card is a combination of a digital output card and an arbitrary waveform generator. Like the waveform generator, it contains a clock. It outputs a series of pulses at varying rates. The most common use of a pulse output card is to control stepper motors. That is the reason this card is sometimes called a stepper motor controller. Stepper motors are used in applications to move an object. These motors vary in size from miniature to large overhead cranes. The number of pulses determines the distance traveled while the frequency of the pulses is the speed at which this distance is traversed. Sophisticated stepper motor controllers can be programmed to accelerate and decelerate the motors. (Figure 13).

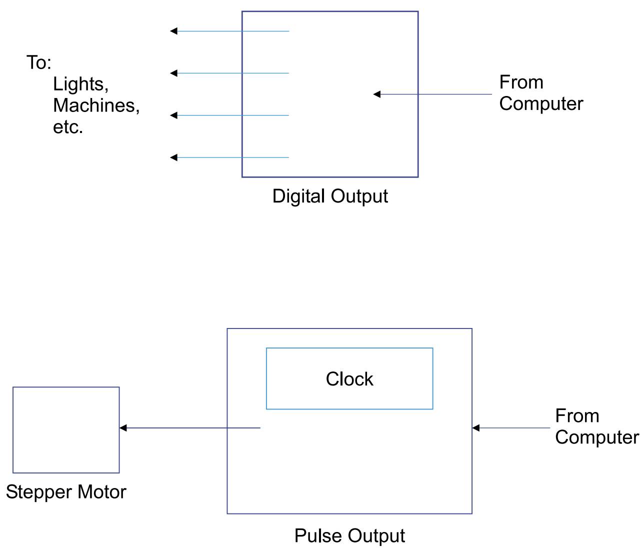


Figure 13

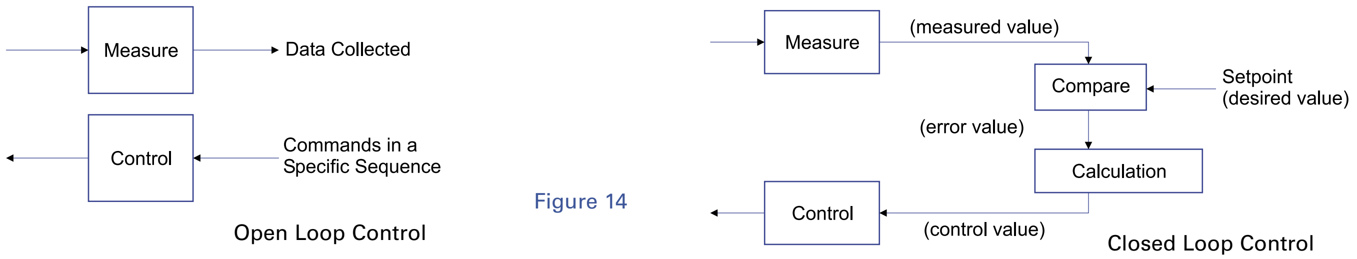


Figure 14

Fundamentals of Data Acquisition

Task Scheduling

The scheduler is a component in data acquisition software that coordinates all other activities, such as sending commands to the instrumentation, as well as the collecting, storing, displaying, analyzing, and printing of data from the instruments. The scheduler ensures that data is collected at prescribed times and at prescribed rates. In menu-driven software, the user fills out menus to define tasks. These tasks consist of the channels to be scanned, measurement type to be made, rate at which measurements are to be made, and the duration of the tasks. The scheduler controls the timing of commands being sent to the measurement hardware (CONTROL) with data being returned to the computer (COLLECTION).

Data Collection and Storage

Data returned to the computer can be stored, displayed, or analyzed. In most cases, the data is collected and stored in memory or on disk. When large amounts of data are collected, database software may be used. Depending on sophistication, the software can scale and convert the data returning from the measurement hardware before it is stored. Intelligent cardcage products perform these functions in the instrument, freeing the computer for analysis and display.

Analysis

Analysis is usually performed on data after the experiment is over. Analysis is important in order to understand what is happening in the experiment. Data collected in the experiment is retrieved from storage and analyzed using a specifically designed software package which may or may not be the data acquisition software. The data may also be sent to another computer for analysis there.

In some cases, analysis needs to be made as the experiment is running. It is especially important for real-time analysis to take place for closed-loop control (see CONTROL section) and the automation of an application.

Presentation

The computer display is the most commonplace data presented but printers and plotters are also used for more lasting copies. DAC systems generally allow data to be displayed as it is being collected (real-time), but the display types and amount of data may be limited for practical reasons. When the data is stored, other software can be used for specialized display or printing and plotting of data.

Control

Control comes in two varieties: open-loop and closed-loop. Open-loop control is generally a well-defined set of commands sent to the control hardware that acts as a stimulus in the application. The measurement hardware collects data independent of the control.

Open-loop control is generally used in the characterization of a product or process. The product, for instance, is run through a series of tests and the results are collected. No attempt is made to alter the control signals. Closed-loop control is more sophisticated. The measurement hardware makes a measurement and the result is compared to the desired value (called the setpoint). Using the error value (difference between measured value and desired value), the computer performs one or more calculations and sends out a control value. The control value is used by the control hardware to effect a change.

When closed-loop control is implemented, the DAC system can become fully self-sufficient (no human interaction) because the computer is now making the decisions. In high-performance DAC systems, these decisions may be made in the DAC cardcage, offloading the computer for analysis and display functions. (Figure 14).

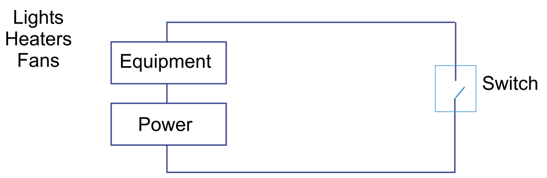
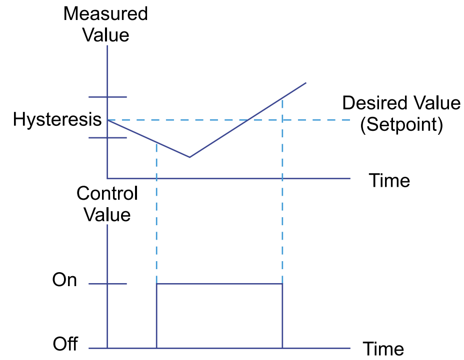


Figure 15



Technical Note

Fundamentals of Data Acquisition

ON/OFF Control is the simplest method of control. A switch card is used as the control hardware to turn something on or off. When the switch is open, the circuit is not complete and power is not sent to the equipment (light, heater, fan, etc.). When the switch is closed the circuit is complete and the equipment is turned ON. In a data acquisition system the switch is normally a general purpose relay switch card. The computer or the data acquisition system controls the position of this switch. Hysteresis is generally built into the DAC software in order to keep the switch from continually opening and closing when the measured value is very close to the desired value. In this example, a heater is turned on when the measured value is 1 degree below the desired value and OFF when it is 1 degree above the desired value. (Figure 15).

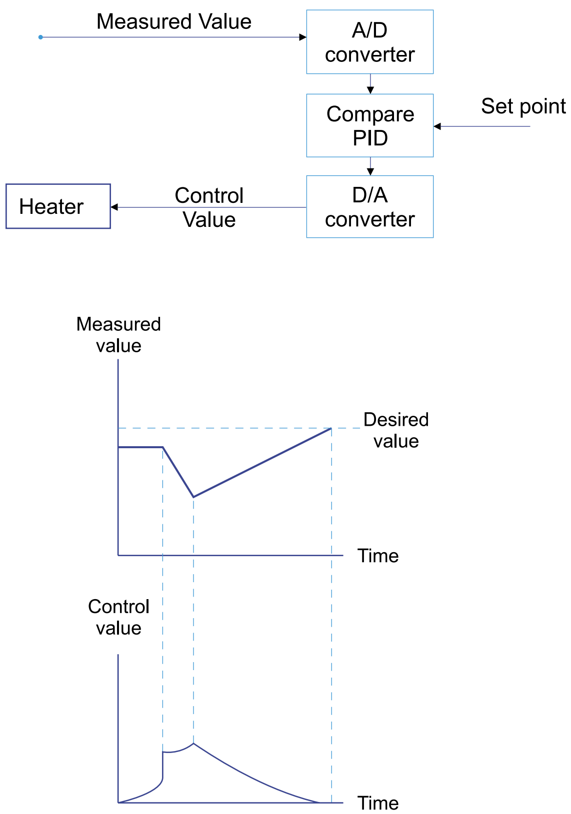


Figure 16

PID control is used in applications where tighter control is needed. In PID control, a measurement is taken (measured value), the error value is obtained (measured value - setpoint), the PID algorithm is applied to the error value to obtain the control value, and the control value is output using the D/A converter. The PID algorithm combines P - a value proportional to the error value, I - a time integral (accumulation of past errors), and D - a time derivative (rate of change) of the error value. The P, I, and D factors may vary depending on the process being controlled. PID control has the advantage of being able to respond to rapidly changing errors before they get too large and yet send out control values that will not cause the process to overreact. (Figure 16).

How to make Better Measurements

Better measurements are a result of using high-quality equipment and good measurement techniques.

What is accuracy and resolution?

Accuracy is the deviation of a measurement from a known standard. Resolution is the smallest change that a measurement instrument can sense. Both are affected by poor equipment and poor measurement techniques. Accuracy and resolution are confusing concepts. If we use a target as an analogy. Resolution is the number of rings in the target (the smallest change the A/D can distinguish) while accuracy is the distance from the center (the deviation from the

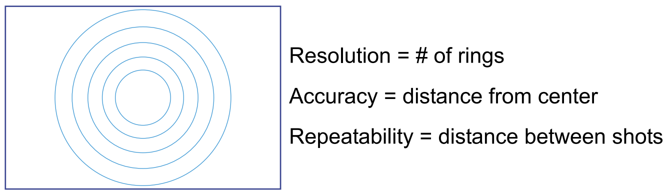


Figure 17a

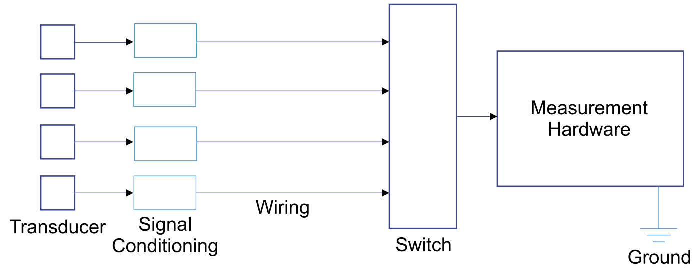


Figure 17b

Fundamentals of Data Acquisition

perfect measurement). Repeatability is the deviation from one reading to another. (Figure 17a).

Specifications are sometimes not clear. For example, a 16-bit A/D converter refers to 16 bits of resolution and may only be accurate to 12 bits.

TIP: Resolution is normally specified in bits while accuracy is specified in percent.

A. Equipment

Transducers

The first step in any data acquisition system is to get good transducers. Transducer accuracies are often overlooked, and, yet, a transducer with a ±10% accuracy means that your entire DAC system cannot do better than 10% accuracy. If your thermocouples have resolutions of ±4 ˚, your DAC system will not be able to spot 2 ˚ deviations in a process. See Appendix C for more information on transducers.

TIP: Read the transducer specifications carefully. Select transducers that give you the type of accuracy and resolution that you need.

Signal Conditioning

Amplifiers, attenuators, strain gage bridges, isolation circuitry, and filters are sometimes necessary to increase the signal strength or to reduce the effects of noise. They can alter the signal slightly.

TIP: Take into account the errors caused by signal conditioning circuitry.

The following techniques will ensure better measurements. A/D converters measure only dc voltage, but, by using completion resistors, it is possible to measure current.
Use high accuracy resistors in current loop completion and bridge networks for better accuracy. (Figure 18a).

Thermocouples are the most common type of temperature measurement transducer, but they do require an isothermal block. Since the voltages produced in a thermocouple are in the millivolt range, the voltmeter or A/D converter should have appropriate resolution to see small voltage changes.

TIP: Use an isothermal block with an accurate temperature device. If the temperature of the isothermal block is in error, the thermocouple conversion will also be in error. (Figure 18b).

Signal conditioning circuitry is sometimes part of the data acquisition hardware. Bridge completion networks, thermocouple isothermal blocks, completion resistors, optical isolation networks, filters, and amplifiers are sometimes found on the DAC hardware. If they provide the accuracy desired, it may save you money by buying a solution with the signal conditioning built-in.

Wiring

Wiring becomes more important as the frequency of signals increases. Ribbon cable can be used for low frequency applications, but shielded, twisted wire pairs are better because they can eliminate much of the noise in a system. Above 100 kHz, BNC connectors should be used.

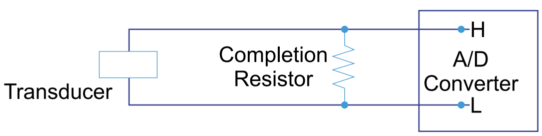


Figure 18a

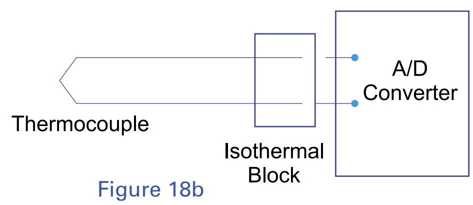


Figure 18b

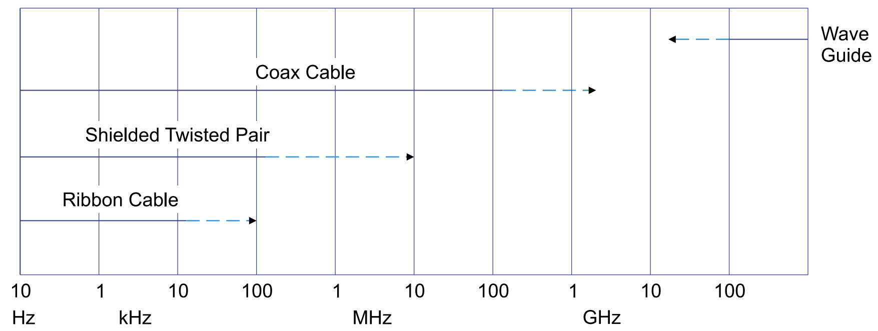


Figure 19a

TIP: Use shielded, twisted wire pairs when practical to reduce the effects of noise on your measurement. Single-ended measurements only work when the measurement instrument is within a few feet of the device being measured and the ground potentials are the same. If in doubt, use differential measurements. (Figure 19a)

TIP: For best results (especially in noisy environments), make three-wire measurements (High, Low, Guard) using shielded, twisted wire.

Switching

Crosstalk is the noise that is capacitively coupled across a switch when the switch is open (off). This noise can interfere with the signal on another channel that is closed (on).

Switches, especially FET switches, will inject very small (picoamp) currents into the signal path. When making sensitive measurements these currents can cause an error.

Measurement Hardware

The selection of measurement hardware is crucial to the success of your DAC system. The architecture of the system may affect the measurements that you make. Placing the intelligence closer to the transducer may improve speed, while placing the instrument closer to the transducers will increase accuracy. Protection circuitry will be important in applications where voltage spikes may be present. Filters, isolation circuits, metal oxide varistors, and contact protection circuitry are all designed for this purpose. Protecting your hardware will keep it making good measurements.

The accuracies of A/Ds, D/As, and counters are usually specified individually. Switches and multiplexers are sometimes not even listed. It is important to take into consideration the accuracy of the entire system solution. This includes not only the measurement hardware, but the isothermal junctions, switches, backplane, signal conditioning, and wiring. Each will contribute errors to the system.
TIP: Don't forget to add errors caused by the transducer and external signal conditioning.
Speed is another consideration when selecting a data acquisition system. Like accuracy, A/Ds, D/As, counters, and digital cards may be specified individually. However, it is important to calculate overall throughput. Overall throughput depends on the transducer response rate, speed of switches and multiplexers function; or range changes on A/D converters, data transfer rate (to/from computer), and the speed of the software to collect and store data.

TIP: Use the system speed specifications, if available, to determine the overall throughput. Individual card specifications do not accurately reflect throughput.

TIP: Speed specifications are normally given for one activity at a time. If several measurements are to be made, the speed will degrade while both the software and hardware reconfigure to new measurement functions.

TIP: Accuracy can decrease as speed increases. Insure that you will get the accuracy desired when running at a particular speed.

Measurement Techniques

The measurement techniques used will depend on the environment and equipment you are using. NOISE (electrical interference) is the most common problem that you may encounter.

Noise Reduction Techniques

Noise is the electrical interference that causes a deviation of a signal to be measured. Noise can be intrinsic to the laws of nature (like thermal noise), man-made (like noise from switches and power supplies), and natural (like lightning or sunspots).

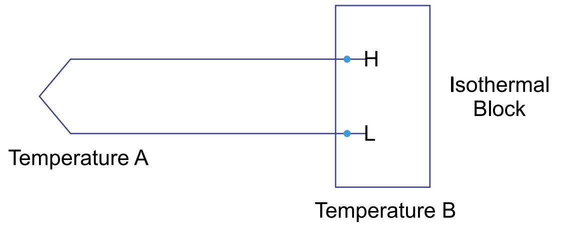


Figure 20

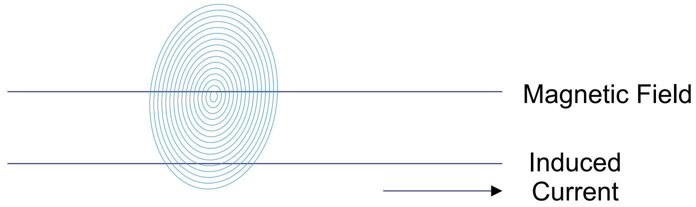


Figure 21

Fundamentals of Data Acquisition

Digital noise

Digital circuitry passes information in the form of voltages, switching from high to low at high speeds. This activity creates high frequency noise that can easily be transferred to analog signals that come in close proximity.

TIP: Never allow sensitive signals to pass near digital circuitry like that found in a computer. (Cards plugged into a PC may be susceptible to digital noise present in the computer).

Thermal noise

When two dissimilar metals are joined together and the temperatures between the two ends are different, a potential (voltage) will be present across the two leads (see Thermocouples in Appendix C). Any connections of dissimilar metals in your system can create the same effect.

TIP: Do NOT connect thermocouple wire directly to the voltmeter. Thermocouples require an isothermal temperature block so that both leads are at the same temperature and the thermocouple effect between the wires and the terminals is negated. (Figure 20).

Transducers like RTDs, thermistors, and strain gages are devices whose output resistance changes. All require power to make them work. When power is applied to a resistive device, it heats up. The rise in temperature causes a change in resistance and an error in the measurement.

TIP: To eliminate self-heating effects, do not apply power to the device any longer than necessary.

TIP: For best results, make two measurements, one without power applied to the transducer and one with power applied. Simple subtraction will eliminate the thermal noise.

Electromagnetic noise

A magnetic field that is changing will cause a current to flow in a conductor running through it. Conversely, a current flowing in a wire has a magnetic field associated with it. Therefore, one wire with a current flowing in it can cause a current to flow in another wire (inductive coupling)

TIP: Whenever possible, keep signal lines away from noise sources (i.e. other wires carrying large currents).

TIP: To eliminate interference currents, twist your wire pairs so that the current induced in one loop cancels out the current induced in an adjacent loop. This is a simple, no-cost way to reduce electromagnetic noise. (Figure 21).

Electrostatic noise

A voltage on one wire can be capacitively coupled to an adjacent parallel wire as a result of an electric field. The signals from power lines are the most common noise sources. (Figure 22a).

TIP: Whenever possible, run signal lines away from noise sources (i.e., other unshielded wires carrying large voltages).

TIP: Use shielded wire to reduce the effects of capacitive coupling. The voltage will couple to the shield and not to the protected wire. (Figure 22b)

TIP: Ground one end of the shield to keep voltages built-up on the shield from capacitively coupling to the protected wire. NEVER ground both ends of the shield!

TIP: For the best possible temperature measurements, use a shielded thermocouple and a guarded voltmeter. Tie the shield to the thermocouple junction and to Guard. Do NOT ground the shield.

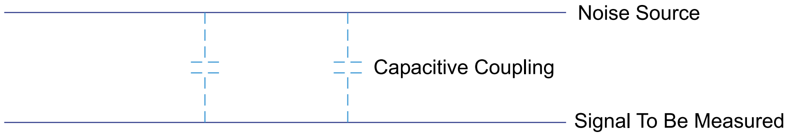


Figure 22a

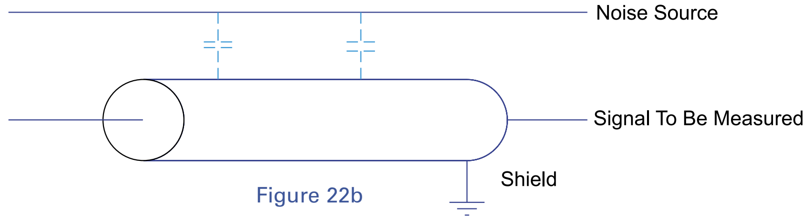


Figure 22b

TIP: If not using a three-wire (shielded) thermocouple, tie Guard to Low. Leaving Guard unattached will not make use of its ability to reduce noise.

Common mode noise is electrical interference on the two signal lines that causes both lines to change in potential relative to ground. Common mode noise most often results when the ground potential between the measuring instrument and the device being measured are different. The difference in grounds results in a ground loop, a current flowing through ground and the low lead. Once this current appears in the low lead wire it will cause a voltage because the wire has some resistance. The longer the lead, the more lead resistance and the greater the voltage error.

TIP: To reduce common mode noise, use a guarded voltmeter. Tie the guard to the low side of the device being measured. This will shunt any ground loop currents away from the high and low measurement wires. (Figure 23).

Normal mode noise is electrical interference that appears differentially across the two measurement lines. This noise is the most difficult to eliminate because it appears to be part of the signal.

Normal mode noise can occur as a result of common mode, electrostatic, or electromagnetic noise finding its way to the signal. In most cases, the noise is related to ac power lines. If so, it appears as a 50 Hz or 60 Hz sine wave added to the dc voltage that we want to measure.
A filter can be used to reduce 50 Hz or 60 Hz noise, but the slow response of the filter will slow down the measurements speed. Filters also inject some errors of their own.

TIP: The best way to eliminate power line noise is with an integrating voltmeter. The noise signal is integrated out with only minimal loss of speed.

Counters sometimes must measure slowly varying signals. If the signal is too slow, the counter may not even notice a change.

TIP: Use a reciprocal counter for better accuracy on slowly changing signals. Sometimes it is necessary to measure the frequency of an ac signal. If the ac signal is centered around ground potential (0 V), it will be measured accurately. If it is riding at a dc level above ground, the counter will never see the transitions of high and low.

TIP: Use ac coupling, if available, on a counter to accurately measure the signal that is not centered on 0 V. (AC coupling may not work well if the signal is at a low frequency - see hardware specification for exact frequency). (Figure 25).

Common Mode Noise

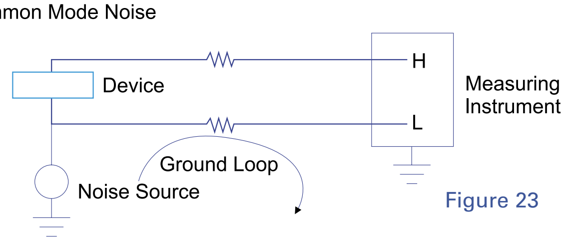
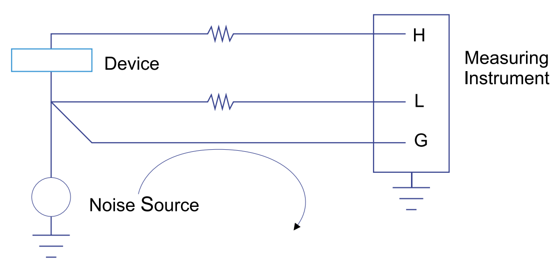


Figure 23



- Enclose noise sources in shielded enclosures
- Place sensitive equipment in shielded enclosure and away from computer equipment
- Use separate grounds between noise sources and signals
- Keep ground leads as short as possible
- Ground measurement equipment separate from transducers
- Twist signal leads
- Shield signal leads
- Ground shields on one end ONLY

- Keep signal leads as short as possible (put measurement equipment as close to transducers as possible)
- Use guarded voltmeters to avoid ground loops
- Use integrating voltmeters to reduce power line noise
- Use noise reduction filters if necessary

Fundamentals of Data Acquisition

When scanning at high-speed, you must be cautious of a phenomena called dielectric absorption. Whenever you switch from one channel to the next, going from a channel with a high voltage to one with a low voltage, you must give the signal path time to "settle". If not, some portion of the high voltage will still be present when a measurement is made on the low voltage channel.

TIP: Put transducers and devices with similar outputs together when scanning through them. When making measurements on two channels where the voltage outputs are significantly different, allow more time between switch closure and measurement. (This time will vary depending on the switch and the measurement instrument design.) As the measurement rate increases both the resolution and the accuracy decrease.

Although it may be advantageous to make fast measurements, if they are not accurate, you may not be getting the information that you wanted.

TIP: Many transducers (e.g. thermocouples) have a finite response rate. Making measurements at speeds faster than these response rates is counterproductive. Voltage measurements can be made much faster than frequency measurements. Frequency measurements require the counter record pulses during a specific gate time.

TIP: For faster frequency measurements, use a frequency to voltage transducer and make voltage measurements with an A/D converter instead of frequency measurements with a counter.

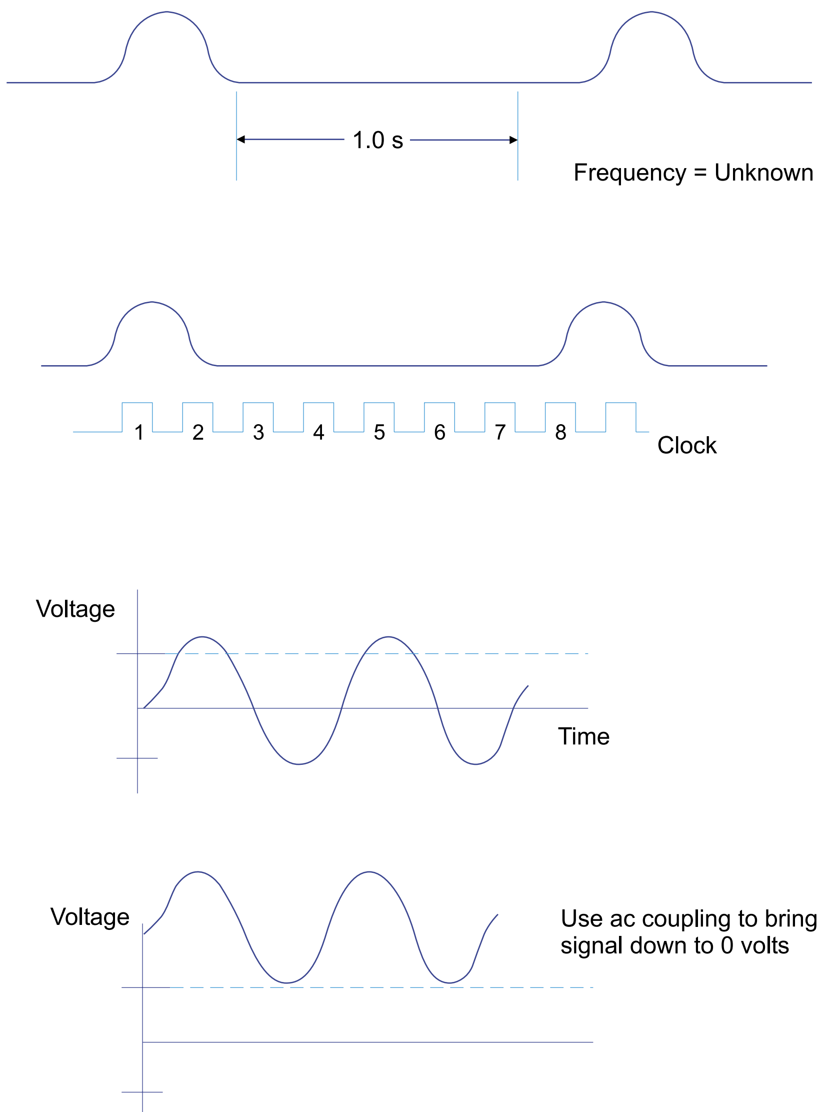


Figure 25

APPENDIX A: GLOSSARY

Accuracy. deviation of a measurement from a known standard

AC. alternating current - a periodic current whose average value overtime is zero

A/D converter. analog to digital converter - measures electric potential and provides results in digital words (see also multimeter and voltmeter)

Amplifier. electronic device that increases the voltage of a signal

Analog output. output signals that can vary on a continuum as compared to outputs that vary in discrete steps

Analog signal. electrical signal that depends solely on magnitude to express information (continuum of magnitudes)

Arbitrary waveform generator. a digital-to-analog converter that can output a timed string of analog signals

Attenuator. electrical device that reduces the amplitude of a signal without distorting it

Backplane. electrical device to which measurement or control hardware (cards) plug into. Backplane is used to pass commands and data to cards plugged into a cardcage - also found inside personal computers to hold various types of interface cards

Bit. a unit of information expressed as 1 or 0 (high or low voltage) - smallest component of a digital word

Bridge. electrical network used to measure a small change in resistance - used with strain gages to get better resolution

Byte. group of bits (normally 8) - read or operated on as a unit

Capacitive coupling. interference induced from one wire to another by an electrical field

Channel. a single path from a transducer to a measurement instrument

Clock. timing device in computers and electronic instrumentation

Closed loop control. a control system in which a quantity measured is compared against a desired value -any deviation is fed back into the system to reduce the difference between the measured and desired value

Common mode noise. electrical interference on both signal leads of an analog measurement which change simultaneously relative to ground

Comparator. electronic circuit that performs a selection between two analog signals

Completion resistor. high accuracy resistor used in data acquisition to change a current measurement into a voltage measurement

Control hardware. electronic equipment used to direct the operation of external devices in a data acquisition application

Counter. electronic equipment used to measure the occurrences, frequency, period, or pulse width of electrical signals

Crosstalk. undesired energy appearing on one signal as a result of signals on nearby paths

Current (I). flow of electrons in a material - measured in amperes (amps)

DAC. data acquisition and control

Data Acquisition. use of electronic equipment to make and record physical measurements

D/A converter. electronic equipment that converts a digital word into an analog signal

DC. direct current - non-pulsating current or voltage with little change in value over time

Dielectric absorption. phenomenon where electrical charges remain in a material and dissipate slowly over time

Differential. measurement technique in which the sensed value is the difference between two input terminals

Digital input. measurement in which one or more channels is monitored to record the existence or lack of a voltage - assigned a value of 0 or 1

Digital output. digital signal (high or low voltage) on one or more channels sent out by control hardware to turn on/off lights, fans, heaters, or external devices that operate based on a digital word

Digital signal. electrical signal in which only the presence or absence of a voltage is important, not its amplitude

Digital word. string of 8,16 or 32 bits (high/low voltages) that a computer interprets as a symbol, letter, or number - groups of words can be sent from the computer to the DAC hardware as commands or from the DAC hardware to the computer as data

Error value. difference between measured value and setpoint in closed-loop control

FET switch. field-effect transistor switch - a solid state device that either allows or prohibits a signal from passing through it – commonly used in solid state multiplexers

Filter. electrical circuit that eliminates or reduces certain frequencies of signals

Firmware. microcode usually stored in read-only memory used to perform computer functions -used in instruments to interpret commands sent by computers

Fundamentals of Data Acquisition

Four-wire ohms. resistance measurement made with four wires, two from the current source to the device and two from the measurement hardware (multimeter) to the device

Frequency. rate of occurrence of a string of pulses - measured by a counter

Gate. electronic device that, depending on one or more inputs, has the ability to permit or inhibit the passage of a signal - used in counters to record pulses only when gate is “on”

Gated totalize. counter function used to measure pulses on one channel only when the signal on another channel is on (high or low voltage)

Guard. a third signal line used to prevent unwanted electrical currents from reaching the voltmeter -guard terminals are found on highly accurate voltmeters

HP-IB. Hewlett-Packard Interface Bus (also known as GPIB) - implementation of the IEEE-488 standard - mechanical and electrical protocol (parallel) for sending data and commands between instruments and computers

Human interface. portion of a software program displayed on the computer screen to display instructions or data

Hysteresis. difference in input signal values that effect the same output value - (for example, a device is turned on when the signal is at 4 V and off when the input value is 1 volt; hysteresis is 3 V) – used to prevent devices from cycling on and off rapidly when input value is near the transition point

Integrating A/D. an A/D converter (voltmeter) that uses an integration technique in order to reduce ac noise present on the input signal

Integration. technique used in some voltmeters to eliminate ac noise by summing the voltage amplitude during a period of time

Interface. mechanical, electrical, and software elements between electronic devices that allow them to communicate

I/O. Input/Output - the interface between a computer and a peripheral or instrument

Isolation. electrical separation of one section of a system from undesired influences of another

Isothermal block. terminal block specially designed to be at a constant temperature. Used with thermocouples

Measured value. data obtained by the measurement hardware and compared to the setpoint to determine an error value

Measurement hardware. electronic equipment used to make measurement on physical phenomena (temperature, pressure, flow, etc.)

Menu-driven software. application software where the user tells the software what to do by filling out screens or choosing selections from a menu of choices

Microprocessor. electronic device that controls the operation of a computer

Multimeter. electronic instrument that converts electrical (analog) signals into digital words (data) - measures voltage, current, and resistance (see also A/D converter and voltmeter)

Multiplexer. electrical device that can switch signals, one at a time, to a measurement instrument - mechanical relays or solid state switches are used to perform this function

Noise. electrical interference that causes a deviation in a signal

Noise rejection. the ability of measurement hardware to eliminate the noise content of a signal in order to make an accurate measurement

Normal mode noise. voltage differentially between two wires that appears to be part of the input signal

Offset. compensated ohms. Resistance measurement in which two readings are taken - one of which is used to cancel the effect of unwanted voltages in the external circuit

Ohms Law. basic electrical principle where voltage = current times resistance (V=IR)

On/Off control. simplest form of control where the output signal either turns on or off an external device

Open-loop control. control where the output does NOT depend on the measurements being taken - output is predetermined by the user, stored in memory or on disk, and output at the programmed time (see stimulus)

Plug-in card. electronic equipment that fits inside a computer or instrument cardcage and is used to make measurements or control external devices

Period. time between pulses or identical points on a repetitive waveform -measured by a counter

PID control. proportional-integral-differential type of closed-loop control in which the output signal is a combination of the linear value, plus time integral, plus time rate of change of deviation between the input signal and value desired

Point. another name for a channel (see channel)

Power. electrical energy - voltage times current - measured in watts

Power line noise. electrical interference caused by radiations from power cables or machinery in the vicinity of the signals to be measured

Programming software. application software to be generated by the user for a specific purpose as opposed to menu-driven software that is already written

Pulse. digital signal that stays at a level (high or low) for only a brief time - counters are used to measure the various parameters of these signals

Pulse output. electronic device that sends out digital signals (pulses) – usually used to control stepper motors

Pulse width. length of time a digital signal is at a high (or low) voltage level

RAM. random access memory - electronic devices used to store data and programs in computers and instrumentation

Rectifier. an ac to dc voltage converter

Relay. electromechanical device for routing electrical signals - used in multiplexers and switch cards

Repeatability. the closeness of agreement among repeated measurements

Resistance. opposition to current - measured in ohms

Resistor. electrical device where a voltage potential is developed across it when a current flows through it

Resolution. smallest change that a measuring instrument can sense in an input signal

RTD. resistive temperature device - a transducer that changes resistance proportional to its temperature

Sample/Hold. measurement hardware that is used to capture events on multiple channels -when triggered, hardware will hold value of input until a measurement can be made

Scanning. making measurements on several channels one at a time, one right after another - multiplexers are used in data acquisition to accomplish this task

Scheduler. software that controls when certain tasks will be performed – in data acquisition the scheduler plans when measurements will be taken and when data will be stored

Sensor. device that converts a physical parameter such as temperature, pressure, flow, strain, or position into an electrical signal -sometimes used synonymously with transducer - a true sensor contains signal conditioning so its output is more easily measured

Setpoint. the desired value from an external device - deviations from the setpoint are used in closed-loop control to adjust output values

Shield. an extra layer of conductive material surrounding a wire to prevent external electrical signals from interfering with the signal on the wire

Signal conditioning. to electrically amplify, reduce, eliminate, or change a signal – used to alter signals (eliminate noise) before they are measured in order to get more accurate measurements

Single-ended measurement. measurement technique where one wire is attached to the device, earth ground serves as a return path - not recommended for accurate measurements

Software program. (set of instructions) that causes a computer to perform a specific function

Stepper motor. electro-mechanical device that rotates (or moves) proportional to pulses it receives from a stepper motor controller - DAC systems sometimes contain stepper motor controllers - used for positioning equipment

Stimulus. electrical signals from data acquisition hardware used to control external devices

Strain change in length of a material divided by its total length – strain measurements are used in order to calculate the stress on a material

Stress. force per unit area - cannot be measured directly (see strain)

Switch. electronic or electromechanical device that is used to route electrical signals or power

Terminal block. a piece of hardware to which wires coming from transducers connect to the data acquisition system

Thermistor. temperature transducer that changes resistance proportional to its temperature

Thermocouple. a pair of dissimilar conductors that are connected together at a point and produce a voltage proportional to temperature

Throughput. the total time it takes a measurement system to switch and convert a signal into data as well as transmit, store, and display the results

Timestamp. a reading of the clock that coincides with a measurement or group of measurements

Totalize. to measure the number of digital signals (pulses) - performed by a counter

Transducers. devices that convert physical parameters such as temperature, pressure, flow, strain, or position into electrical signals such as voltage, current, or resistance

Tree switch. an additional switch on a multiplexer whose purpose is to reduce capacitive coupling between signal lines

Two-wire ohms. resistance measurement made with two wires to the device -current is supplied by the multimeter

Up/Down Count. measurement to increment the count if the digital signals occur on one channel and to decrement the count if they occur on another channel -performed by some counters

Voltage (I). difference in electrical charge between two points - measured in volts

Voltmeter. electronic instrument that measures electrical voltages (see multimeter and A/D converter)

Fundamentals of Data Acquisition

APPENDIX B: Fundamentals of Electricity

Electricity is the flow of charged particles called electrons. Every chemical compound contains electrons but, depending on the compound, these electrons are either free-moving or not. Electrons flow freely through conductors such as gold and copper but do not flow through insulators such as wood and plastic. Semiconductors such, as germanium and silicon mixtures, allow the flow of electrons only under certain conditions. Voltage is the difference in charge between locations. For instance, the voltage rating of a battery is the difference in charge between the positive and negative terminals. Although the ground is usually neutral, there may be a small voltage difference between the ground on one side of a building and the ground on the other side. By definition, an electron has a negative charge. When a compound has an abundance of electrons it has a negative charge. When it has a lack of electrons it has a positive charge. The earth, generally has a neutral (zero) charge which we refer to it as ground.

Current is the number of electrons moving from one place to another per unit time. Current always flows in a conductor between a high and low voltage. If we think in terms of a waterfall, voltage is the difference in elevation between the top and the bottom of the waterfall. The flowing water is analogous to the current flowing from one voltage potential to another. Current is measured in amps or milliamps (l/l000 of an amp).

Resistance is the opposition to the flow of current. It is measured in ohms. In our analogy, resistance is the size of a pipe that restricts the amount of current that can flow.

Capacitance is the temporary storage of charge, a resistance to the change in voltage. A capacitor is the device that can store voltage (much like a battery) for short periods of time. Analog voltage measurements are made by an A/D converter, voltmeter, or multimeter. They are the exact potential (in volts) between two points. Using the waterfall analogy, an analog voltage would be an exact measurement between the top and bottom, for instance 3.25 meters. Digital voltage measurements record the existence of a voltage between two points. If one exists it is assigned the digital value of 1 (or ON) while the lack of voltage is 0 (or OFF). The equipment that checks these values assumes that the voltage difference will be at least x volts (for instance 2 V). For example, if the waterfall is less than 2 meters from top to bottom, it is assigned zero (no digital voltage). If it is greater than 2 meters, it is assigned the digital value of 1, regardless of its height.

Ohm's Law

Voltage, Current, and Resistance are all related according to Ohm's Law. Voltage = Current x Resistance (V=IR).
Power = Voltage x Current = $V^2/R = I^2 x R$ (in units of watts)

DC is direct current. Current, and subsequently the voltage, is a constant value and does not change over time. Batteries output dc currents and store dc voltages.

AC is alternating current. Current and voltage vary over time. Generally, the voltage and current vary in the shape of a sine wave. The voltage used to run household appliances is ac. Its sine wave is alternating at 60 times per second in the U.S. and 50 times per second in Europe and other parts of the world. AC voltages and currents allow the transmission of electricity over longer distance with less loss.

Voltages may vary in other patterns such as square, triangular, and ramp waveforms.

Voltage

Counters are often used to measure various parameters in a waveform. The count is the number of signals that the counter senses. The pulse width is the amount of time a voltage is high (or low). The period is used on repetitive waveforms to measure the time from the start of one signal to the start of another.

The peak voltage of a waveform (sometimes referred to as the amplitude) can be measured by devices such as multimeters and oscilloscopes.

APPENDIX C: Transducers Basics

A transducer is a device that sends out an electrical signal proportional to the physical parameter, like temperature or pressure, it is monitoring. For example, a temperature transducer may output a specific value at 50 ˚C. As the temperature changes, the output voltage changes. Transducers can be used to measure temperature, pressure, flow, level, position, pH, strain, and many other physical parameters. You have literally thousands of transducers to choose from. Let's look at a few examples of each type.

Temperature

The transducers most commonly used in data acquisition measure temperature. The three most common types are thermocouples, thermistors, and RTDs. This table shows the accuracies and typical uses for each type.

	Thermocouple	RTD	Thermistor
Range	(-270 to 2320) ˚C	(-200 to 1000) ˚C	(-40 to 100) ˚C
Measurement	Voltage	4-wire Ω	2-wire Ω
Sensitivity	(6 to 60) μV/˚C	0.4 Ω/ ˚C	400 Ω/ ˚C
Accuracy	(1.5 to 5) ˚C	(0.01 to 0.1) ˚C	(0.1 to 1) ˚C
Cost	$1 per foot	$20 - $100	$10 - $100
Linearity	Polynomial	Polynomial	Logarithmic
Applications	Rugged	Fragile	Fragile

Temperature Summary

Thermocouples

A voltage is produced between the two ends of a wire if there is a temperature difference from one end to the other. If two wires (two dissimilar types of metals) are connected at one end, a small voltage potential will be produced between the two wires on the other end. Thermocouples are nonlinear devices that require high-order mathematical formulas or look-up tables to calculate the temperature from the voltage they produce. These voltages are typically measured in millivolts with a degree of resolution in 10s of µV. The pairs of dissimilar metals produce a voltage that is well-understood and documented.

It is not practical to attach the thermocouples directly to the voltmeter terminals. It is absolutely essential that both leads of the thermocouple are at exactly the same temperature. This is accomplished with an isothermal block. If the temperature of this block is not 0 ˚C, its temperature must be measured and used in the calculation of the temperature of the connected end of the thermocouple.

TIP: Do NOT attach thermocouple wire directly to your voltmeter. Use an isothermal block.

A variety of different thermocouples are available (each denoted by a letter- E, J, K, R, S, T). Each thermocouple type (pair of dissimilar metals) causes a different millivolt signal. The millivolt output varies in a nonlinear manner that is well understood. Knowing the output voltage of a thermocouple, the temperature can be looked up in a table or calculated using formulas.

Thermistors

Thermistors are fragile, sensitive temperature devices in which resistance decreases as temperature increases. A typical thermistor has a typical value of 5 kΩ at 0 ˚C and changes at a rate of 200 Ω/˚C. They are used in applications requiring high accuracy temperature measurements. Thermistors are measured by performing a two-wire ohms measurement using a multimeter. In a two-wire ohm measurement the multimeter's internal current supply outputs a small current to the thermistor and the multimeter measures the resulting voltage. Since the thermistor has a fairly high resistance, the lead resistance of the wire does not significantly affect the results. (For example, 10 Ω of lead resistance is less than 0.05 ˚C.)

Resistance Temperature Devices (RTDs)

RTDs are very stable temperature transducers that increase in resistance when their temperature increases. They have typical values of 100 Ω at 0 ˚C. RTDs change their resistance at rates of .385 or .392 Ω/˚C.

TIP: For best results, use a 4-wire ohms measurement with RTDs.

Using the two-wire ohms method to measure RTDs can result in significant errors. (For example, 5 Ω of lead resistance can give an error of 26 ˚C). Four-wire ohms are the preferred measurement technique for RTDs. Two wires run from the current source in the multimeter to the thermistor and another two wires run from the ± input terminals of the multimeter to the thermistor.

If the RTD is platinum and the wires are copper, a thermocouple effect exists. To counteract the thermocouple effect, an offset, compensated ohms measurement, can be made. Using this technique two measurements are taken, one with the current source off and another with the current source on. The first reading (with current source off) contains only the thermocouple effects. It is stored in the multimeter's memory and subtracted from the second reading to effectively eliminate the thermocouple effects.

Other Temperature Transducers

Since temperature measurements are the most common measurements made in a data acquisition system, it follows that there are a variety of different temperature transducers. The other transducers are more expensive and specialized than thermocouples, thermistors, and RTDs. Some of the most common types are IC sensors, radiation pyrometers, and infrared pyrometers.

Strain

Strain is the change in length divided by the total length. Stress, the force per unit area, cannot be measured directly. It must be calculated from the strain. Since the elongation or compression in a strain measurement is very small, most strain measurements are made in microstrain (1 millionth of a strain).

A strain gage is a transducer glued to a surface. It changes resistance as it is elongated or compressed. Strain gages have typical values of 120 Ω or 350 Ω. Mounting strain gages requires special glue, considerable skill, and is best left to an expert.

Bridge Measurements

Strain gages change resistance so slightly (0.00024 Ω/µε) that a bridge circuit is needed to see it. The bridge, in effect, highlights this small resistance change in the form of a voltage. Using an accurate voltmeter, the microvolt signal can be measured.

Strain gage multiplexers normally contain this bridge circuitry including the dc voltage power supply. Quarter-, Half-, and Full-bridge configurations can be used for increased sensitivity.

Fundamentals of Data Acquisition

In the Quarter-Bridge configuration, as the strain gage changes resistance, it unbalances the bridge (4 resistors) and causes a small voltage across the bridge. The strain and ultimately the stress can be calculated from this voltage reading.

For higher resolutions, two legs of the bridge can be filled with strain gages, resulting in a Half-Bridge. If the strain gages are mounted on both sides of a strained material, as one compresses the other elongates, causing twice the sensitivity on the bridge.

By using four strain gages, a full-bridge can be created with four times the sensitivity of the quarter-bridge.

Pressure

Pressure is defined as force per unit area. Pressure transducers are available in many different forms: diaphragm, bellows, bourdon tube, piezoelectric, and LVDT. The diaphragm type is the most common.

The diaphragm pressure transducer makes use of two strain gages on a thin material which forms the diaphragm. This type of transducer requires an external dc voltage to power the strain gages. The pressure transducer normally contains amplifiers so that the output will be either a voltage (0 V to 5 V or 0 V to 100 mV) or a current (0 to 20 mA).

Flow

Flow is the velocity of a fluid multiplied by the cross-sectional area of the vessel it is flowing through. Flow transducers use a number of techniques to measure flow.

The orifice plate (differential pressure) flow meter measures flow by first constricting the movement of fluid in a vessel. The pressure builds up on the upstream side of the constriction causing a differential pressure proportional to the flow, between the upstream and downstream side. This differential pressure is proportional to the flow. This type of transducer outputs a voltage (0 V -10 V) or current (0 mA - 20 mA).

The turbine flow meter works like an airplane propeller, spinning at a rate proportional to the flow rate in the vessel. This transducer outputs pulses whose frequency can be measured with a counter card.

Level

The most elementary level meter simply indicates whether a liquid has reached a certain level. When the liquid in the vessel reaches the top, a simple float makes contact with a dc power supply to complete a circuit and output a 5 V signal. A digital input card can be used to sense the existence of this 5 V signal.

A variation of the simple level detector adds pressure sensors along the side of the vessel. When the liquid reaches the level of the sensor it causes the sensor to make contact with the power supply and output a 5 V signal. Several channels on a digital input card would be used to determine which detectors are in contact with the liquid.

For more exact level measurements, a pressure level detector is available. As the vessel fills with fluid, the pressure of the liquid increases. By using a pressure transducer, it is possible to measure the pressure and calculate the level of the fluid.

More sophisticated (and expensive) transducers are available for