The Digital I/O Survival Kit

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Introduction

In the world of computerized Data Acquisition (DAQ), few would dispute that analog measurements, with gigasample rates and high-resolution A/D, enjoy a position of glamour. However, DAQ applications frequently require reading of switches and status signals, control of indicator lamps, actuation of relays, and other more mundane digital tasks that form the "glue" of data acquisition.

The Technology

Digital integrated circuits are fabricated with the same components used in analog ICs. The difference is that digital circuits are optimized to deal with signals that are either ON or OFF, rather than linear in nature.

One of the first, and still popular, logic families is Transistor-Transistor Logic (TTL). TTL logic remains the de facto standard for digital I/O for several reasons. TTL is fast and inexpensive, can handle relatively high load currents, and is unlikely to be damaged by static electricity. TTL has spun off related device families optimized for specific operating parameters such as power consumption and speed, one of the most popular being Low Power Shottky TTL (LS-TTL). Other digital devices and discrete circuits are often created to be compatible with TTL signal levels, permitting engineers to design new logic circuits in terms of tried-and-true TTL rules.

Input and Output Characteristics

The standard power supply voltage for TTL logic is +5Vdc. The voltages and currents corresponding to LS-TTL logic 1 (ON) and logic 0 (OFF) input and output levels are listed in Table 1.

Input High Voltage:	2.0V minimum, 5.0V max.
Input Low Voltage:	0.0V minimum, 0.8V maximum
Input Low Current:	-0.4 mA
Input High Current:	0.02 mA
Output High Voltage:	2.7V minimum
Output Low Voltage:	0.5V maximum
Output High Current:	-0.4 mA
Output Low Current:	8.0 mA

Table 1. Standard LS-TTL Input and Output Levels

Note that the input range is neither symmetrical nor continuous. There is a gap in the input values between 0.8 and 2.0 volts where the signal is ambiguous, defined neither as a "1" nor a "0." In some situations, such as when trying to read an analog or slow-moving signal, this dead zone can require special care to yield reliable triggering of digital circuits. Further, a TTL output is effective at sinking current to create a logic 0, but sufficient variation exists in the design of TTL output stages that a logic 1 output voltage must be defined more broadly. Some TTL

outputs swing to 3.5 volts or higher, and can source a small amount of current. However, open collector TTL outputs "float" when set to logic 1, and have no current output capability.

The basics of TTL circuit design and logic operation are well documented in texts such as the *TTL Cookbook.* Rather than restate what is readily available from other sources, let's zero in on a few specific, less frequently discussed concerns of digital I/O. This document reviews those points likely to be overlooked or misunderstood by novice users as they deal with digital I/O cards. For specific procedures concerning hardware and software configuration and installation, refer to the documentation for the specific digital I/O product you may be using.

Interfacing with Mechanical Switches

Switch contacts can be interfaced by adding a "pull-up" resistor as shown in Figure 1. Some digital I/O boards already include this pull-up resistor, or provide a socket and header to facilitate user installation. The use of a pull-up resistor assures that the digital input will be tied to +5Vdc when the switch is open, providing a solid TTL high input level. Generally, unterminated inputs should be avoided because they can be affected by noise, and cause unreliable operation.
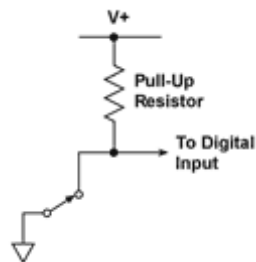

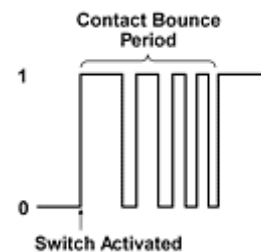**Figure 1.** *Pull-Up Resistor*

Figure 2. *Contact Bounce*

There are two other problems with mechanical switches that need to be addressed: First, when a mechanical switch snaps shut, there is a short period -- typically 1-5 milliseconds -- when the contact surfaces bounce against each other. Some logic inputs, notably digital counters, may read this contact bounce as a burst of pulses or ON/OFF signals (Figure 2). Software debouncing solutions include slowing the scan rate to avoid multiple readings during the bounce, and/or making several rapid readings (typically, a few milliseconds apart) until the readings stabilize. Hardware debouncing is more predictable, but more complex. It requires a flip-flop circuit (Figure 3) for each digital input channel to provide a clean signal.

A second difficulty with mechanical switches deals with the contact material itself. Contacts designed for relatively high currents (>100 mA) have large surface areas made of arc-resistant materials. These materials can be unreliable for switching currents of a few milliamps or less, because the limited signal energy cannot break through the film that tends to build up on contact surfaces. Switches designed for "dry circuits" have softer, cross-point contacts which will work well with small voltages and currents. This is one case in which specifying a higher rating for the contact may actually be *less* reliable.
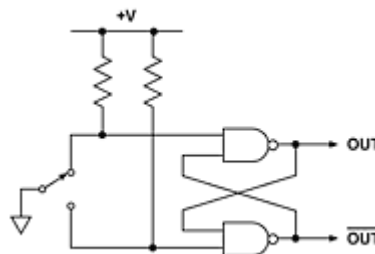

Figure 3. *Hardware Debounce Circuit*

Slowly Moving Signals

As mentioned earlier, a problem can occur with digital inputs if the signal is a slowly changing voltage. Because of the slow rate of change, the signal might remain in the ambiguous 0.8V-2.0V range long enough to cause multiple triggerings, rather than a smooth transition from one logic level to the other (Figure 4). There are several ways to deal with this situation:
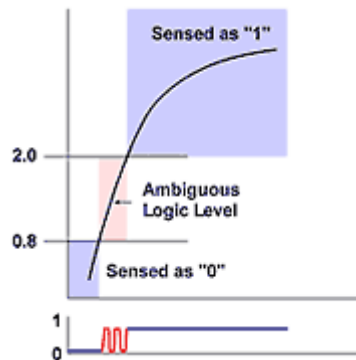

Figure 4. *Slow-Moving Digital Signal
Can Result in Unreliable Switching*

1. Correct the input signal so it changes more quickly.

2. If you need to detect a specific voltage level, read the signal using an analog comparator. If necessary, condition the comparato'ês output with a digital gate.

3. If the exact switching level is not important, but you require clean switching from slow or noisy signals, use a digital input with hysteresis. Hysteresis establishes different voltages for logic 1 and for logic 0, depending on whether the signal is rising or falling. The result is a "snap action" when the input detects a logic 1, because the voltage needed to trigger a logic 0 is considerably lower.

Somewhat the same effect can be achieved in software by ignoring state changes that occur too quickly after the previous change. Whether this kind of pulse-width discrimination can be effective depends on the input signal characteristics, and also whether the additional programming is economical compared to a hardware solution.

Dealing with TTL-Incompatible Signal Levels

TTL switching levels have become the de facto standard for digital I/O cards, although the upper voltage limit that can be applied to digital inputs varies. The input circuits on some digital I/O cards are intended to be used with 0-5V signals, and are protected with internal diodes which clip signals above 5.5 V or below -- 0.5 V. These diodes provide adequate protection against occasional transients, but are not intended to dissipate significant amounts of energy. Signals far outside TTL limits can damage the board and/or the signal source. Therefore, it's important to use proper interfacing when dealing with non-TTL logic levels.
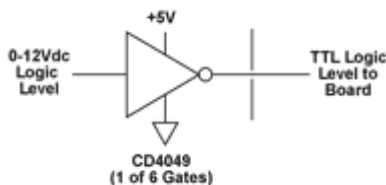

Figure 5. *CMOS-to-TTL Buffer/Inverter*

Signals in the range of 0-12Vdc, such as those found in CMOS digital circuits, cannot be connected directly to TTL inputs. However, the CD4049 hex inverting buffer or CD4050 non-inverting buffer can be used to convert the CMOS to TTL logic levels (Figure 5).

High Current/Voltage

If an output load requires more current or a higher voltage than a digital board can provide, the drive current and/or voltage can be boosted using the circuit shown in Figure 6. For drive current requirements between 15mA and 100mA, select an NPN transistor rated for the required supply voltage with a collector current rating no higher than 0.5A. If higher current is needed, substitute a Darlington NPN transistor.

Solid-state modules enable TTL signals to control outputs up to 250 VDC or 280 Vrms, and to read inputs up to 280 VDC/VAC as a TTL signal. These modules have two further advantages: they keep these elevated voltages physically away from computer boards, and they also provide 4000 volts of electrical isolation. Isolation assures that they can be used safely with signals referenced to a different power ground.
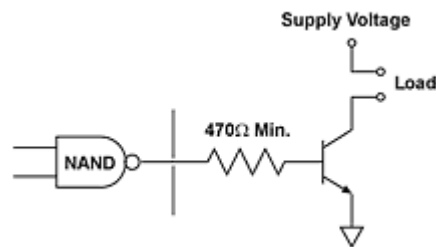
Figure 6. *High-Voltage or High-Current Drive fot TTL Gate*

Isolation and Grounding

Grounding is less critical for digital signals because the large voltage difference between logic levels reduces the possibility of misinterpreting a signal. Be sure, however, that all digital grounds (except for isolated inputs) and the ground of any auxiliary power supplies for accessories are connected to the digital I/O board's ground reference.

Ground *should* be the same potential everywhere, but don't count on it. Even if a signal source supplies a TTL-level signal, the signal can damage measurement hardware if it originates from a system operating with a different ground voltage. This should not be a problem if all devices are plugged into the same power distribution.. Damage can occur, however, in manufacturing environments where the PC is fed from one power system and the remaining equipment is fed from another. If power will be coming from different sources, isolate digital inputs with one of the following methods:

1. **At the source, by using switch or relay closures.** To maintain isolation, use the +5 volts *from the digital input board* as the source for the pull-up resistor to the input -- do not connect to the ground or +5 volt supply of the target equipment.

2. **At the input, by using an optical coupler (Figure 7).** In this case, the input side of the device must be powered *from the remote hardware* to maintain isolation.
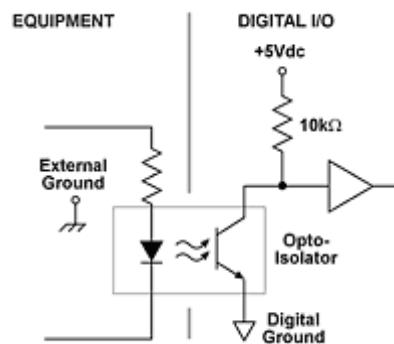
Figure 7. *Opto-Coupler for Isolating a Digital Input Channel.*

Output Protection

A common problem with control of inductive devices -- solenoids, relays, motor windings, etc. † is tha-- when coils are de-energized, the collapsing magnetic field can cause a high-voltage spike through the inductor. This spike can exceed the breakdown voltage of unprotected outputs and cause permanent damage, or it can propagate through nearby circuits, causing spurious triggering, resetting, and other problems. There are several ways to deal with such possibilities.

Snubber networks. A resistor-capacitor network across the output will absorb much of the spike energy, but has no inherent voltage limiting. This is adequate for relay contacts but insufficient to protect solid-state outputs. (Typical values: R = 100 ohm, C = I2/10 µF, where I = load current)

Clamp diodes. A clamp diode will limit the voltage at the output pin to no more than a diode-drop (typ. 0.7 v) above the output supply. The diode should be rated for at least the voltage and current of the output. Alternatively, a zener diode in parallel with the output [sketch 1c] provides clamping at defined positive (Vz) and negative (Vdiode drop) voltage levels, but at a higher cost.

MOV protectors. Metal-oxide-varistors have a characteristic curve similar to a bipolar zener diode, clamping at a defined voltage for both positive and negative spikes. This makes them ideal for protecting contacts switching AC voltage, so they are most commonly found in values suitable for power line voltages, e.g. 140 or 280 V breakdown. However, they are equally effective for protecting solid-state DC outputs if you can obtain them in a compatible rating. Look for transient voltage suppressors in product listings of electronic suppliers.

In-rush Currents

Some devices (incandescent light bulbs, for example) may have initial currents many times higher than their steady-state operating requirement. This can cause contacts to weld or solid-state outputs to fail. A suitable small resistor in series with the load (sized to drop about 10% of the voltage at the steady-state current, i.e. R = V/[10*I]) can limit peak current with little affect on normal operation. In the case of lamps, this will also extend the life of the bulb.
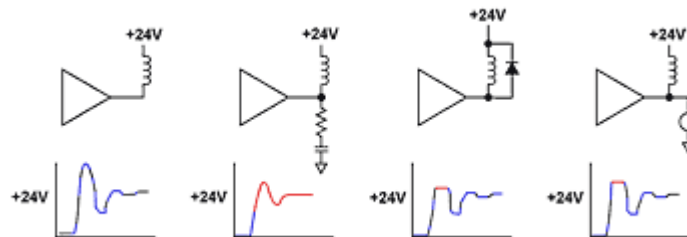
Figure 8. *Output protection for use with inductive loads.*

Conclusions

Circuit design for digital data acquisition is clearly more complex than might be assumed, given that signals are either on or off. However, most digital monitoring and control applications can be analyzed and designed according to a few simple input and output requirements:

1. Reliable triggering of digital inputs requires that a proper voltage level be applied, and that the controlling signal be capable of sinking a specified current. Mechanical switches usually require a simple "pull-up" resistor network tied to the digital supply voltage to drive digital inputs reliably.

2. Digital outputs generally cannot source any significant drive current, but are much more effective in sinking current. This sink current is usually adequate for controlling 10 inputs of a similar logic family, or possibly fewer non-IC loads such as LEDs, lamps, or relays. Auxiliary devices, such as power transistors and solid state relays, are useful for controlling higher-current loads.

3. Control of certain types of signals and loads requires special attention because of elevated voltages, heavy load currents, inductive effects, or other transients capable of damaging digital circuitry.

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Dwight Spreng works with Data Acquisition products at Keithley Instruments, Inc., Cleveland Ohio. Spreng earned a BS in Engineering and Applied Science from Yale University in 1974. He has over 25 years experience in test, measurement, and control for a variety of industries, including textile, photofinishing, medical equipment, semiconductor wafer test, and data acquisition application engineering. Spreng joined Keithley in June 1999 as Senior Applications Engineer, and recently assumed the newly created position of Senior Sustaining Engineer for Data Acquisition.