LABORATORY INTERFACING

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A medical researcher examines the capabilities and limitations of an important laboratory device

ALMOST ALL LABORATORY computer applications can be described as one of the following functions: (1) control of experiments, including timing and synchronizing external events and setting external voltages; (2) data acquisition, usually through the digital conversion of analog electrical signals; (3) data storage; and (4) data analysis. While data storage and analysis make computers most appealing in the laboratory, these functions are common to most computer applications. The functions that make laboratory applications different from other computer uses are the first two, control of experiments and data acquisition. The following discussion is directed at these two areas. The two functions together require five distinct hardware components: analog-to-digital (A/D) converters, digital-to-analog (D/A) converters, digital input-output (I/O) ports, counters, and an accurate frequency generator. This discussion is developed from my experience with a hardware device that provides all five functions.

A/D CONVERSION

In a typical application, analog signals from some electronic device are sampled and converted to digital data at regular intervals. Usually sampling continues for some well-defined period. The sampling may progress at different speeds at different times. For example, it is frequently desirable to record high-speed events that occur within the setting of lower-speed events. To record both types of events with an analog recorder (an oscilloscope or chart recorder), it is usually necessary to make two recordings, one at a high speed and one at a low speed. Using a computer, it is relatively simple to record a single input at different speeds.

Analog-to-digital conversion is perhaps the most critical of laboratory applications because errors at this step will greatly distort the data. It is also frequently the function that most taxes the speed of the computer. Speed at this stage is sometimes limited by the A/D converters, but more often it is limited by software. Ultimately, the software is limited by the design of the computer, but more frequently it is limited by having to perform some other task concomitantly. One such task is the generation of control pulses during A/D sampling.

In many instances the initiation of an A/D recording must be synchronized with the experiment. Instead of having an external device initiate the A/D conversion sequence, it is tempting to have the computer control the experiment at the same time that it is collecting data. An additional advantage of this combined approach is that the data collection is very accurately synchronized to the experimental procedure. The difficulty with this approach is that it requires the computer to perform two tasks at once. This can call for some relatively sophisticated programming, particularly when high speeds are necessary.

INTERFACE BOARDS

There are several commercially available devices that will perform at least four of the five functions required for

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the laboratory applications described above. Several of my colleagues and I bought the LabMaster board made by Tecmar because it provides all five functions and because it was the first one available. It also costs less than more recent devices. It consists of a motherboard that fits into the IBM PC and a daughterboard that houses the A/D converters outside the computer. This arrangement isolates the incoming analog signals from electrical interference inside the computer.

The Data Translation Company makes a similar board that has the capability of direct memory access not available on the LabMaster but does not have the Tecmar board's progammable counters. We preferred the Tecmar board in part because we wanted to put out logic pulses to control the experimental apparatus while collecting data with the A/D converter. The five programmable counters simplify this task because they operate independently of the central processing unit of the host computer. The counters can be programmed to begin counting the same frequency pulses that trigger the A/D conversions. When they have completed their count they toggle their external outputs without intervention from the computer. Thus, the logic pulses are synchronized exactly to data acquisition without interfering with the high-speed operation of the central processor.

When very high speeds are not required, the digital I/O port can be used for applications control. Although most commonly used as a single interface to other digital equipment, the individual channels in the port can be used separately to control different pieces of apparatus. In addition, these channels can be configured to accept logic pulses from the apparatus, thereby allowing a bidirectional interaction.

A final way of controlling experiments is to use the D/A converters to set voltage levels for external devices.

Possible Improvements

In spite of our general satisfaction with the Tecmar board, we found several areas that need improvement, both in the LabMaster and in the other devices that are available. As explained in John Mertus's letter to BYTE ("Data Collection with an IBM PC," October 1984, page 14), the absence of direct memory access on the Tecmar board severely limits this board in multitasking operations.

The cable connections could be greatly improved. Tecmar sells a set of cables for external connections to the board, but they are simply that—bare cables. Users must make their own interfaces. We have made an interface box with BNC connectors for each connection, and while we were at it, we put in some buffer chips to protect the digital I/O ports. Several other manufacturers supply slightly less primitive connections for their devices, but at best these consist of screw terminals for bare wires. I do not know of many laboratory scientists who relish the thought of bringing their signals out on bare wires. Any manufacturer who supplied a device with an interface having standard connectors such as BNCs and well-protected inputs would find a ready market.

There is one improvement related to signal processing that I would especially like to see. This is the addition of filters to the analog inputs of the A/D converters. It is well known that no information can be derived about the frequency components of a digitized signal that are greater than half the sampling frequency. Noise and oscillations in the signal that are faster than the sampling frequency at best decrease the signal-to-noise ratio. In many cases, faster signals introduce "aliasing," spurious low-frequency oscillations that result from sampling a high-frequency oscillation at systematically different parts of its period. Although filters generally introduce lags in electronic signals, the lags introduced by antialiasing filters are likely to cause far less signal distortion than will high-frequency oscillations. The antialiasing device should consist of a low-pass filter with a sharp cutoff frequency near the sampling frequency. The main argument against such a filter is that the sampling frequency varies widely, sometimes within the same record, so that the cutoff frequency must be made to vary in the same way. The solution to this problem is to use an integrator that averages the signal between sample intervals. A. F. Huxley and G. L. Reed recently described a clever circuit that performs this averaging (see "An Automatic Smoothing Circuit for Input to Digitizing Equipment," *Journal of Physiology*, volume 292, 1979, page 11P). It is triggered by the same clock pulse that triggers the A/D conversions, so that its cutoff frequency always varies with the sampling frequency.

A major way in which A/D converters could be improved is by the use of separate converters for each input channel and the use of on-board data buffers. Most computer-controlled multichannel devices have a single A/D converter with a multiplexer that switches different channels into it. Only one channel is converted at a time, so that the samples in each channel are displaced in time relative to those in other channels. This time displacement can cause a systematic error when the data from one channel is plotted as a function of that in another. The samples from different channels can be brought into coincidence either by using separate A/D converters for each channel or by holding the signals from all channels in sample-and-hold circuits that are triggered when the first channel begins its conversion. The advantage of separate converters and on-board data buffers is that they increase the speed of operation while effecting the synchronization.

Computer Considerations

Your choice of interface board has an effect on the size of the central processor and data bus needed. Most data is collected from 10-, 12-, or 16-bit A/D converters, so one A/D conversion will require a 2-byte word. In a machine with a 16-bit bus (a true 16-bit computer) entire words can be moved at once. In a smaller computer

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having an 8-bit bus, words must be moved in two sequential steps. This need to make two-step transfers greatly slows most of the computer's operation. Since most time-critical operations involve data transfers along the bus, this slowing occurs at a very vulnerable stage. Although a true 16-bit computer transfers data twice as fast as an 8-bit machine, it does not follow that a 32-bit computer would be still faster in handling integer data. Since integer data occurs in 2-byte words, increasing the bus size to 32 bits would not produce any increase in speed unless some way could be devised to move two words at once. The 16-bit machines available today are therefore as large as many operations require.

A question related to size is whether it is better to have several small, single-purpose computers or one large, multipurpose machine. My own preference is for the former. A major consideration is cost. In addition, the failure of a single computer in a group does not incapacitate the entire laboratory in the way that the failure of a single large computer does. Another advantage of a group of computers is that each can be dedicated to a single task. Even with the best multitasking arrangements, there will always be some time-critical operation that requires the uninterrupted use of the computer, forcing other users to wait. With multiple computers such interactive interruptions do not occur.

The main disadvantage of small computers is that they are slow. This disadvantage is usually more than offset by the ability to dedicate the machine to a specific task for an extended period.

The IBM PC Compromise

In spite of the negative considerations about the 8-bit bus, my colleagues and I bought several IBM PCs for use in the laboratory. We selected this computer rather than a true 16-bit machine because of its popularity. Many peripherals and programs are available for it, and we felt that it would not go out of production nearly as quickly as some of the other, less popular models.

We have found the PC to be as good as or better than expected in almost all areas except for one peculiarity: the absence of a limited interrupt or a software-controllable wait state. Once an A/D conversion is made, a flag consisting of one bit in a status register is set. The computer must then detect the flag and take the digital data from the converter. The PC can detect the flag in only two ways: polling the status register or generating a full interrupt. A full interrupt, together with its return, requires 83 clock cycles. This many cycles would take more than 20 microseconds (μs) just to detect the flag. Polling takes substantially less time. Using a polling routine, we have written sequential A/D sampling programs that operate at a rate of 22 μs per conversion. Over half that time is spent polling the status register. If a more rapid way of detecting the flag could be devised, this routine could operate at more than twice the speed. If the central processor could be put in a wait state immediately before each A/D conversion and be released by the "A/D done" flag, detection of the conversion would be virtually instantaneous. An otherwise-similar computer that had such a capability would be able to accept A/D conversions about every 10 μs.

Software

Software is the most crucial part of any laboratory system. Clever programming can introduce great flexibility and compensate for many deficiencies in hardware. Poor programming can hobble even the best system. The time required to develop good programs should not be underestimated. Many of us have bought a piece of equipment that was physically capable of performing some desired task only to find that weeks of programming were required to make it work. For those of us who have had this experience, there is no stronger selling point for equipment than the concomitant availability of adequate programs to run it. ■