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Miniature-MCA Technology Developments*

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Abstract

We have recently reduced the size of multichannel analyzers (MCAs) and have implemented more features in hardware to relieve software requirements. We built and tested a spectroscopy grade, 4096-channel MCA. Exclusive of amplifier and power supply, it fits on two boards each approximately 7 by 15 cm. This paper discusses the features and performance of the analyzer and some reasonable applications of these technologies.

I. INTRODUCTION

The applications for multichannel analyzers (MCAs)—and safeguards instrumentation in general—are growing in number, and requirements from some existing applications are evolving rapidly. We see many new requirements being answered by versatile, well-engineered building blocks with resident intelligence instead of stand-alone boxes, which have been used in the past. We also prefer a "bus independent" interface to these building blocks. For this interface we use the common serial port. It has great versatility, but the limited data transfer rates of some serial transfer media can be a drawback. However, the resident intelligence of the building block can usually be used to solve this problem.

We used this concept when we were asked to build a miniature MCA to replace an existing NaI MCA system. We were given a needs list from which we developed specifications. The unit we provided was to receive signals from an external linear shaping amplifier and was to control an amplifier and high-voltage system provided by a commercial manufacturer. The unit itself was to be controlled by a computer program running in an MS-DOS machine miles away from the MCA in a very unfriendly environment.

Credibility was given to the "building block" approach when the unit just described was interfaced to a completely different application by a potential user in less than 1 day.

The size of the circuitry used for the miniature-MCA building block was kept small by trading off performance against hardware components and by using a versatile single chip microprocessor with on-board capabilities for communications, timing, and analog to digital (A/D) conversion. The processor increments the conversion memory through software instead of by hardware-direct memory access. Most of the hardware logic was implemented using a programmable, application-specific, digital integrated circuit (ASIC). The ASIC not only reduces the size of the circuitry, but lends great versatility without re-layout of the circuit boards.

We are using these ASIC techniques in a design to enhance the high-count-rate throughput of the portable MCA used extensively in safeguards.

II. NEEDS

We needed to upgrade an existing NaI system design to provide high-resolution spectral (HRG) data. The size of the new circuitry was to be the same as existing circuit boards (7 x 15 cm).

The necessary capabilities are summarized as follows:

- 4096-channel pulse-height resolution;
- 24-bit counting capacity per channel;
- Low noise to allow analysis to below 17 keV;
- Control lines for selecting time constants for NaI and HRG-type detectors;
- Control lines for selecting fixed-gain ranges to allow the study of spectra up to 0.4, 0.8, 1.6, and 3.2 MeV;
- Pulse-height analysis gated by a second, shorter time-constant analog input;
- Serial-communications rates up to 9.6 k baud. (The local interface was to use RS-232 signal levels.);
- Peak-position stability in the range of 0.05-0.1% of full scale for a 4096-channel (4-k) spectrum. This is specified over a 2- to 4-hour period after a 2-hour warmup.); and
- Interface capabilities as follows

  1. Turn on/off the bias supply (binary control)
  2. Set amplifier gain (binary control)
  3. Turn on/off power to an auxiliary circuit (binary control)
  4. Program the bias set point (analog control)
  5. Monitor bias set point (analog read-back)
  6. Provide operational status (on/off) of the bias supply (binary read-back)

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Auxiliary equipment used with this application creates heat and vibration in the housing in which the electronics are mounted.

Commercial vendors are providing the NaI detector electronics, the HRG detector bias, and signal shaping and amplification circuits.

III. HARDWARE

A. *Features*

- Analog-to-Digital Converter (ADC)

  The ADC is a 12-bit Wilkenson type with a clock speed of 40 MHz.

  The analog input will accept unipolar or bipolar pulses. The full-scale conversion is 4.096 V. The input signal can be attenuated by a factor of two.

  A separate analog fast-channel input is provided so the fast channel can be jumper connected to either this special input or the normal analog input.

  The upper- and lower-level discriminators and fast-channel thresholds can be set from the software. The zero level is manually adjusted.

  Circuitry for two separate ramp currents is provided.

- Application-Specific, Digital Integrated Circuit (ASIC)

  Logic in an ASIC digitally controls the analog ADC circuitry. The Wilkenson counter is included in the ASIC. The ASIC also controls all conversion-address adjustments for spectrum sizes from 256 to 4096 channels. The adjusted conversion address output has a single-stage buffer. The processor is interrupted when data is available in this buffer. In response to this interrupt, the processor increments the appropriate channel in the conversion memory.

- Microprocessor

  The processor, a Motorola MC68HC11A, has an onboard UART, 8-channel, analog multiplexer with an 8-bit A/D converter and timer functions, which are used in this application. It runs in the expanded address mode with approximately 32 kbytes of EPROM, or nonvolatile RAM, and at least 24 kbytes of available RAM in its memory map. A 16-kbyte, ADC-conversion memory resides in the processor memory map, and the processor increments the channels. The capacity of each channel is 32 bits. The serial communications will run from 150 to 9600 baud. The serial port interface supports a long BREAK reset.

- Software

  All functions of the building block are configured and controlled by resident software. Commands may be used to call a selection of standard MCA "macro" functions. Serial port interrupts drive the communication port software.

- Auxiliary Device Interface

  Analog and binary command and read-back capabilities are provided to control amplifier gains, turn on power supplies, determine bias set points, and read bias and temperatures.

- Diagnostics

  The 5 V, ±12, mains supply, and bias voltages; detector leakage currents; and detector and ambient electronics temperatures are all monitored. A digital pulse string is provided to drive a test pulse input.

B. *Performance Goals*

The performance requirements for this application were not stringent. We set the following goals.

- When interfaced to an Ortec 572 amplifier and an HRG detector, which does not degrade the following specifications, the MCA will meet or exceed the following specifications:

  1. Maximum peak drift operating from 0°C to 40°C after a 2-hour period and at counting rates up to 10 k/s should be 0.05% to 0.1% full scale for a 4-k spectrum.
  2. Maximum differential nonlinearity should be <5% over the middle 90% of the ADC range.
  3. Deviation from linearity should be <0.05% of full scale over the middle 90% of the ADC range.

- All external control and communication occurs over a 3-line RS-232 serial link operating at 9600 baud.

- The electronic operating-temperature range for binary control and read-back of the digital circuitry will be -20° C to 50°C. The analog operation is specified over the range of 0°C to 40°C.

C. *Implementation*

Figure 1 is a photograph of the circuit boards. One board is for the power supply. The microprocessor board contains the memory, ASIC, and external digital interface. The ADC board contains the analog circuitry for the ADC, the digital-to-analog converters for discriminators, thresholds, and the bias programming voltage. The boards plug together to eliminate cables. A prototype assembly is shown in Fig. 2.

IV. SOFTWARE

The software for the miniature MCA is written in the C language. The miniature-MCA interface to the outside world is a serial port; no front panel is required. This serial port can be connected to a computer, a programmable data logger or bar-code reader, or simply a terminal.

The software performs the following functions:

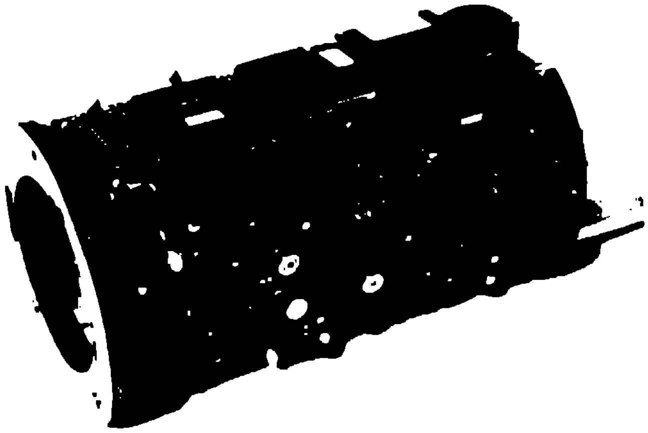

Fig. 1. Miniature-MCA prototype.

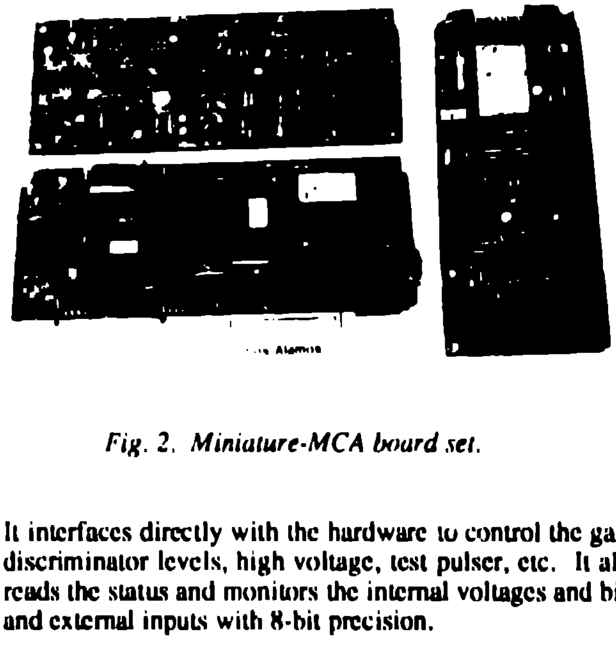

Fig. 2. Miniature-MCA board set.

- It interfaces directly with the hardware to control the gain, discriminator levels, high voltage, test pulser, etc. It also reads the status and monitors the internal voltages and bias and external inputs with 8-bit precision.

- It acquires spectra in the conversion memory for a specified period of time.

- It dumps an acquired spectrum to the device connected to the serial port. It has the ability to transfer one spectrum while it is acquiring another spectrum.

- It interfaces to the timer hardware and registers, and it controls the ADC acquisition time.

- It processes interrupts coming from ADC-control electronics. Because count rate requirements are quite low, spectra are accumulated in the software-incremented counters in conversion memory on each interrupt.

- It services an interrupt-driven serial-port driver, which receives commands from and sends responses to the serial port.

- It responds to the controlling computer's commands that the serial port receives. The commands can do the following:

  1. Start/stop the single acquisition
  2. Start/stop continuous acquisitions
  3. Set count time for acquisition
  4. Select one of four gains
  5. Select the conversion memory size
  6. Select which conversion memory group to use for acquisition
  7. Transfer a spectrum to the serial port in either ASCII or binary format
  8. Report MCA status
  9. Read MCA and auxiliary device voltages
  10. Respond to a software/hardware reset
  11. Set baud rate for serial port
  12. Turn high voltage on/off
  13. Set high-voltage operating point
  14. Turn auxiliary device on/off
  15. Start/stop test pulser

The miniature MCA communicates with the outside world using a simple protocol only through its serial port. All commands consist of two ASCII characters terminated by a carriage return [cr]. When a command is successfully received by the miniature MCA, the command is echoed back to the serial port. In addition to the echo, some commands' responses include additional information. All responses are in ASCII except for a binary spectrum dump. All responses are terminated by a carriage return and linefeed [cr][lf]. If an invalid command is received, the response is ??.

Because transmission of full 4-k spectra over the serial port is a requirement, the transfer time was a design consideration. If each channel of data is 4 bytes deep and the information (16384 bytes of data) is transferred in ASCII at 9600 baud, it would take a minimum of 25 s for each spectrum transfer. Because 25 s between updates is not acceptable in many cases, two methods were used to reduce the spectrum transfer time. First the spectra are transferred in binary format, not ASCII. This cuts in half the number of bytes to be transferred, and hence the transfer time is approximately 12 s. The second method transfers 1, 2, or 4 bytes per channel, depending on the maximum number of bytes the data in any one channel requires. If the maximum number of counts in any channel's data is less than 256, then only 1 byte for each channel needs to be transmitted. This can reduce the number of bytes transferred for a 4-k spectrum to 4096, and the transfer time (in binary format) at 9600 baud to 4.3 s.

Two types of spectral acquisitions are supported. The traditional type of MCA acquisition is the single acquisition for which data are collected for a predetermined amount of time. After the acquisition time has elapsed, the acquisition is halted and the MCA waits for another command. The second type, continuous acquisition, was implemented to allow the MCA to transfer a previously collected spectrum while a second spectrum is being collected. In these acquisitions the software stores data in one region of conversion memory. When the acquisition time has elapsed, the software switches to another conversion memory region and begins a second acquisition. The software transfers data from the first memory region through the serial port while the second memory region is being filled. To keep both the MCA and external computer systems synchronized, we had to include a command that the external computer can give when it has finished digesting a spectrum; this command indicates the computer is ready to receive another spectrum.

The commands and implemented responses are shown in Table I.

TABLE I: Miniature-MCA Commands and Responses

Command	Response	Definition
BD xxxx	BD	Set baud rate (xxxx is either 9600 or 4800).
CN	CN	Turn auxiliary ON.
CF	CF	Turn auxiliary OFF.
CM	CM	Clear MCA conversion memory.
DC xxxx	DC	Set the number of data channels (4096, 2048, 1024, 512, 256).
DD	DD . . .	Dump a spectrum from detector to computer based on spectrum transfer mode set by MA or MB command. The response is the spectrum dump.
DG xxxx	DG	Set detector gain where xxxx is 1, 2, 4, or 8.
EC	EC	End continuous spectrum acquisition.
ES	ES	End single spectrum acquisition before the MCA timeout.
FC	FC	The command sent by the controlling processor to the MCA to signal that it is ready to receive another spectrum in continuous mode.
HE	HE	Print a menu of all available commands to serial port.
LLxxx	LL	Set the low-level discriminator to a value from 0 to 255.
MA	MA	Set the spectrum-transfer mode to ASCII.
MB	MB	Set the spectrum-transfer mode to binary.
MM	MM	Exit the MCA program and go to the monitor mode.
PN	PN	Turn the test pulser ON.
PF	PF	Turn the test pulser OFF.
QF	QF 0x.xx	Query - Send back 5-V reading.
QP	QP 0xx.x	Query - Send back +12-V reading.
QM	QM -xx.x	Query - Send back -12-V reading.
QA	QA 0xxxx	Query - Send back electronics environment temperature.
QS	QS 0xx.x	Query - Send back power-source voltage.
QR	QR 00xxx	Query - Send back percent live time.
QI	QI 0xxyy	Query - Interrogate the detector status.
QL	QL 00xxx	Query - Send back leakage current (0-255).
QT	QT 00xxx	Query - Send back crystal temperature (0-255).
QV	QV 00xxx	Query - Send back the high-voltage reading (0-255).
RS	RS	Software reset of detector—all values are set to their default values.
" "		Hardware reset long break (+12 V for 64-200 μs). Same effect as power on reset.
SC	SC	Start continuous spectrum acquisition and auto data send.
SS	SS	Clear memory and start single spectrum collection.
TH xxx	TH	Set threshold to a value (0-255).
TI xxxxx	TI	Set length of time for data collection (1-32767).
UL xxx	UL	Set upper-level discriminator (0-255).
VS xxx	VS	Set the high voltage (0-255).
SR xx yyyy zzzz	SR	Set a region of interest (ROI) where xx is the ROI number (1-99), yyyy is the beginning-channel number, and zzzz is the ending-channel number. The response is just the echo of the SR.
RR xx	RR	Read ROIs. The response is to list one or all of the ROIs with their beginning- and ending-channel numbers in addition to the ROI sum.
CR	CR	Clear all the ROI settings (no ROIs are defined after this command is executed).
DB	DB	Print current settings. The response prints the current status of several hardware registers and some software parameters.

A. *Performance*

Spectrum

A spectrum from a sample of 93% enriched ^{235}U is shown in Fig. 3. The low-energy cutoff for this spectrum was well below 10 keV.

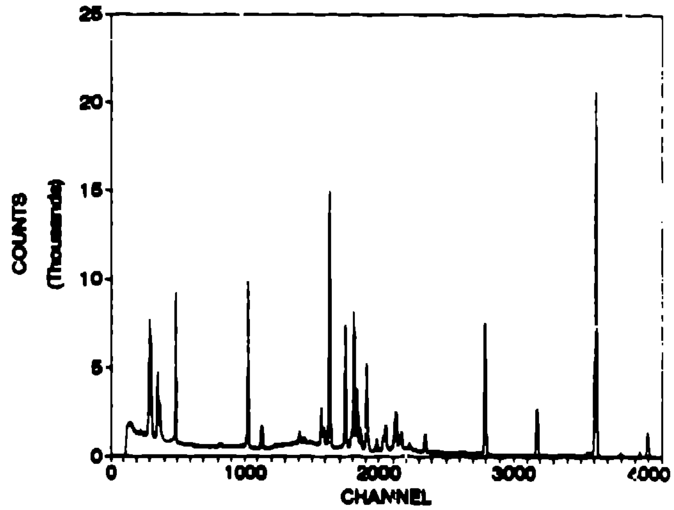

Fig. 3. Uranium-235 spectrum.

Resolution

The resolution obtained at a count rate of 5 k/s using a planar detector and an Ortec 572 amplifier is 0.68 keV at 122 keV and 0.76 keV at 186 keV. At higher count rates, the absence of a pulse-pileup rejector is evident from the observed high-energy tailing.

Linearity

We measured the linearity of the system using a planar detector and an Ortec 572 amplifier. Table II shows the deviations of the peaks from a linear fit to the peak position vs energy. The maximum deviation from channel 300 to channel 3995 was 1.69 channels.

The differential nonlinearity was estimated from a 4096-channel NaI spectrum in a region where the statistical errors were a small fraction of a percent and the spectrum was changing slowly. The observed differential nonlinearity was generally less than 1%, but every 15th and 16th channel had a high-to-low variation of between 1.5% and 2%. The differential nonlinearity seems to be a function of the Actel chip used. Spectra gathered with other chips were more than a factor of two worse.

Table II. Measured Linearity

Energy (keV)	Peak Channel	Fit Channel	Deviation (Channel)	Deviation (% FS)
16.2	300.3	302.0	-1.69	-0.041
25.65	485.1	486.6	-1.48	-0.036
53.24	1025.5	1025.5	0.01	0.000
84.21	1631.9	1630.4	1.47	0.036
143.76	2795.0	2793.7	1.38	0.034
185.72	3613.0	3613.2	-0.22	-0.005
205.33	3995.0	3996.3	-1.27	-0.031

High-count-rate losses

We looked at the area of the 186-keV peak in a uranium spectrum as the count rate increased from approximately 10 k/s to 15 k/s. We collected spectra in both a miniature MCA and a Davidson Portable Multichannel Analyzer (PMCA). The ratio of the miniature-MCA area to the PMCA area was 0.84 in both cases. Hence we have demonstrated that the processor can increment the conversion memory at a rate of at least 15 k/s. By counting program cycles in the routing that accomplishes the incrementing, we feel that the processor should be able to handle throughput rates of approximately 30 k/s. However, this limit has not yet been tested.

Peak drift as a function of temperature

Over an ambient electronics temperature range of -20°C to +40°C, the drift in peak position was found to be approximately constant at -1 channel/C° for a peak at approximately channel 3400 in a 4096 channel spectrum.

B. *Other Applications*

PMCA upgrades

The programmable logic of the Actel* chip used in our development also has great potential in the design of higher performance systems. Two Actel chips have replaced the digital logic in the IAEA PMCA** in a recent design. One chip is a slight modification of the chip used for the miniature MCA; the other is used to implement the direct-memory-access storage of data from the pulse-height conversion. The chips will help interface a high-performance, plutonium-isotopic-grade amplifier, which has been developed and implemented in

*Actel Corporation, 955 East Arques Avenue, Sunnyvale, CA 94086.

**D. S. Davidson, 19 Bernhard Road, North Haven, CT 06473.

the PMCA, to the pulse-height-conversion circuitry. The Actel chips save significant space and allow additional circuitry to be included to enhance the throughput at high-counting rates. It is anticipated that units with this upgrade should be operating in the first quarter of 1992.

DOE facility holdup measurements

At the Martin Marietta Energy Systems Y-12 plant at Oak Ridge, there are procedures for routine and direct verification that quantities of fissile holdup in ducts satisfy the safety criteria. To accomplish this, bar codes are affixed to designated measurement points throughout the plant. A radiation-monitoring instrument equipped with a NaI(Tl) detector is interfaced to a bar-code reader/data logger to obtain integral gamma-ray count rates above a threshold set for the ^{235}U pulse height spectrum[1]. The operator uses the bar-code reader wand of the data logger to read the location bar code at a given measurement point. The program in the data logger stores the bar code and then prompts the operator to position the detector for the measurement. After a fixed delay, the data logger automatically starts and stops data acquisition by the radiation-monitoring instrument and transfers the measurement results to the data logger. The gamma-ray count rate results are stored in the data logger memory, along with the date, time, location code, radiation meter number, and operator identification number.

Because of increased requirements on the quality, reliability, and verifiability of the holdup measurements, count rate data from multiple ROIs, rather than integral count rate data, are required of the Y-12 measurements. The staff from Y-12 brought their data logger to Los Alamos, interfaced it to a miniature MCA (see Fig. 4), and were collecting ROI-type data in less than half a day. They reprogrammed the bar-code reader to issue the commands to and receive data from the miniature MCA. Implementation of the miniature MCA in this application will require adding an NaI-bias supply and a simple amplifier to our present design.

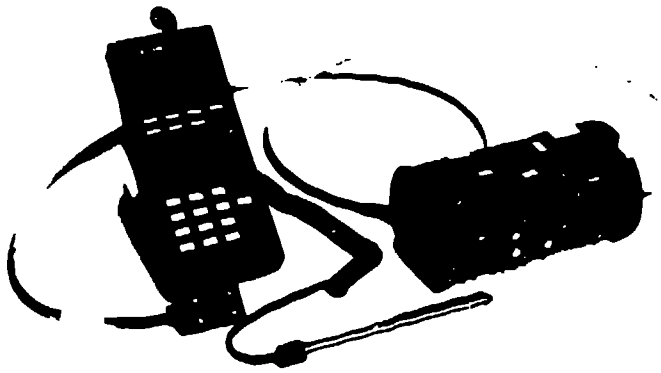

Fig. 4. Portable holdup measurement system.

Safeguards measurements

The IAEA and EURATOM safeguards authorities need a very small, hand-held portable instrument that will acquire and display spectra. The miniature-MCA technology can be readily adapted to their needs. The portable instrument would not have a built-in detector, but the unit would provide all support (amplifier and bias) for a detector. This unit could be operated by hand or by computer, for example, the HP 95LX palm top or a powerful 486 machine. It could be set up by computer much like the Y-12 people do with their present instrument, and if bar codes could be designed into an inspection, a bar-code reader with a serial port interface could also be interfaced directly to this unit. Data could be collected during and off-loaded at the end of an inspection directly into a database, which could aid in the analysis and preparation of the inspection report.

Such an instrument could be used for both DOE plant holdup measurements and safeguards measurements. To log data as is done at Y-12, large amounts of battery backed-up memory can easily be provided.

V. REFERENCES

[1] S. E. Smith, "A Holdup Measurement System for Enriched Uranium at the Oak Ridge Y 12 Plant," MMES Oak Ridge Y-12 Plant report Y/MA-7146 (July 1991).