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ABSTRACT

The Solar Energy Research Institute's (SERI) Wind Research Program is using pulse code modulation (PCM) telemetry systems to study horizontal-axis wind turbines. SERI has developed a low-cost PC-based PCM data acquisition system to facilitate quick PCM data analysis in the field. The SERI PC-PCM system consists of AT-compatible hardware boards for decoding and combining PCM data streams and DOS software for control and management of data acquisition. Up to four boards can be installed in a single PC, providing the capability to combine data from four PCM streams direct to disk or memory.

This paper describes the SERI PC-PCM system hardware, focusing on the practicality of PC-based PCM data reduction. A related paper highlights our comprehensive PCM data management software program which can be used in conjunction with this hardware to provide full "quick-look" data processing and display. The PC-PCM hardware boards support a subset of the Inter-Range Instrumentation Group (IRIG) PCM standard, designed to synchronize and decommutate NRZ or Bi-Phase L PCM streams in the range of 1 to 800 Kbits/sec at 8 to 12 bits per word and 2 to 64 words per frame. Multiple PCM streams (at various rates) can be combined and interleaved into a contiguous digital time series. Maximum data throughput depends on characteristics of the PC hardware, such as CPU rate and disk access speed.

INTRODUCTION

PCM-encoded telemetry data systems provide highly accurate measurements over a wide dynamic range with low noise (Strock 1983). These systems are ideal for collecting data relating to the study of wind turbines, especially in multiple-turbine wind parks. Typical test installations require multiple-channel measurements taken from a variety of different locations. These can be grouped into three basic categories: turbine rotating, turbine nonrotating, and meteorological.

In the rotating-turbine frame, measurements are made on the turbine blades, blade attachments, and hub. Typical parameters include strain-gauge bending moments and torsion, airfoil surface pressure distributions, total dynamic pressure, and blade pitch angle. These measurements provide data to determine blade aerodynamic and structural loads.

In the nonrotating turbine frame, measurements characterize machine performance and determine turbine loads. This requires data from the turbine nacelle and tower, such as generator power production, tower bending, azimuth and yaw angles, and rotation speed.

To determine characteristics of the wind at a turbine or wind park, meteorological conditions are measured. Anemometers are used to measure near-field horizontal and vertical wind shear. This requires many channels of wind speed and wind direction data from local upwind anemometer arrays. Atmospheric stability measurements are also important in evaluating characteristics of wind park inflow and outflow. This requires far-field atmospheric boundary layer measurements, including anemometry, temperature, barometric pressure, and dewpoint.

In an effort to increase accuracy, simplify instrumentation, and reduce noise, data are digitized and encoded into PCM streams as close to the measurement source as possible. The streams are then telemetered to a convenient central receiving location and recorded on multitrack tape. Streams from the rotating frame can be transmitted over an RF link or conducted through slip rings. Local streams are usually conducted through cables, and far-field streams are most easily transmitted.

Figure 1 depicts the current "Combined Experiment" (Butterfield 1989) under way at SERI, sponsored by the U.S. Department of Energy (DOE), to provide detailed measurements on a 10-meter, 3-bladed horizontal-axis wind turbine. The objectives of the experiment are to develop an understanding of how turbulent inflow affects unsteady aerodynamics, fatigue loads, and yawed operation loads. The experiment uses seven PCM streams for data collection. Three streams are recorded in the rotating frame, two from local inflow, one from the turbine/tower, and one from far-field meteorology. Characteristics of the streams are summarized in Table I.

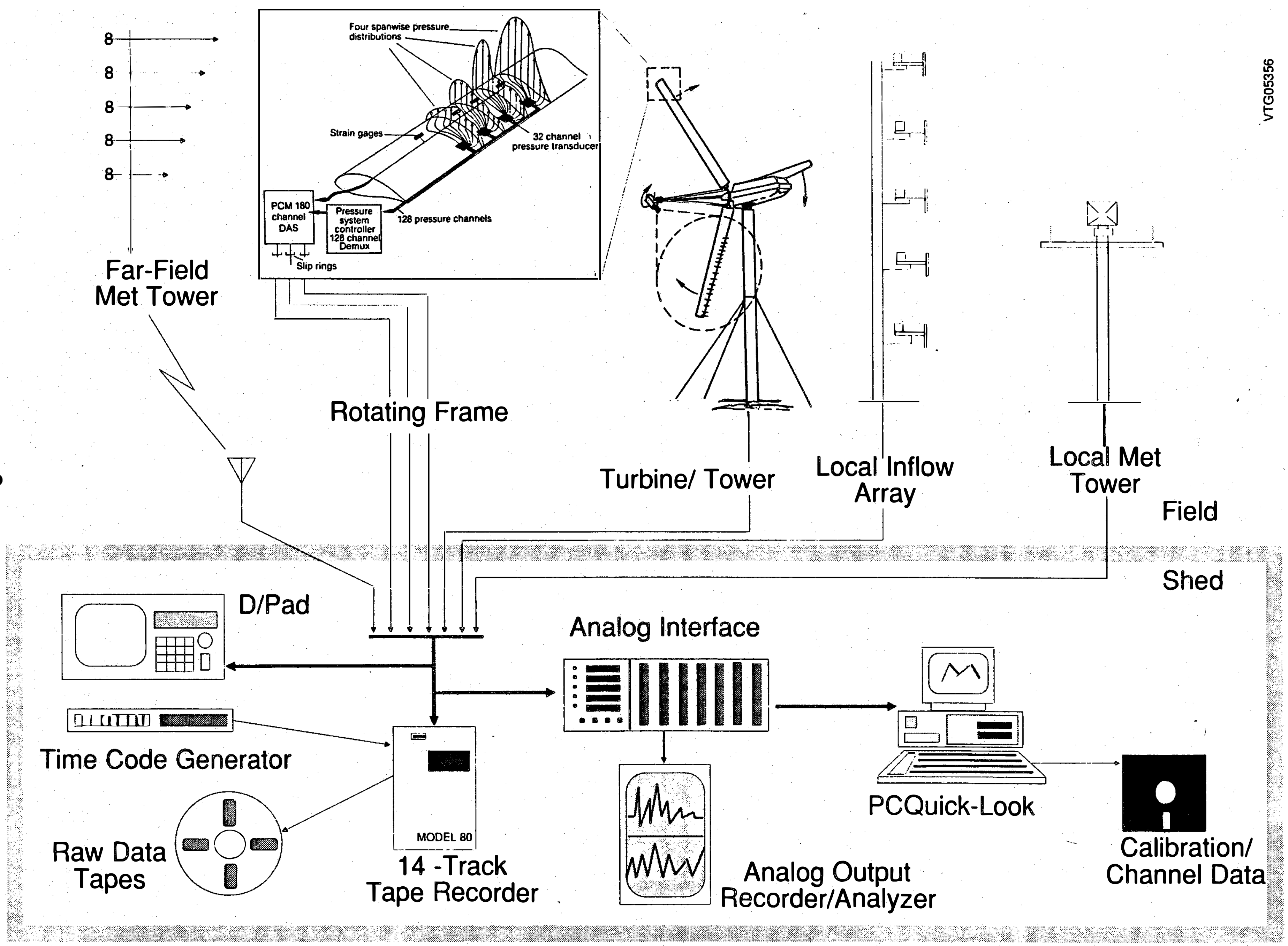

Figure 1. Combined Experiment PCM Streams

Table I. Combined Experiment PCM Configurations

PCM #	Bit rate (Kbit/s)	Sample rate (Hz)	Number of channels	Sample interval (msec)	PCM source location
1	7.5	34.72	16	28.8	Far met
2	15	69.44	16	14.4	Inflow
3	60	277.78	16	3.6	Local met
4	400	520.83	62	1.92	Rotor
5	400	520.83	62	1.92	Rotor
6	400	520.83	62	1.92	Rotor
7	60	277.78	16	3.6	Turbine

PCM data streams from the Combined Experiment are recorded on wide-band tape and postprocessed on an extensive laboratory-based telemetry data-reduction system (Fairchild Weston 1985). Figure 2 shows the complete data processing path used to reduce PCM data recorded in the field. This system processes all recorded data, providing them in digital format for use in subsequent data analysis on a UNIX-based computing system.

SERI's wind program is also conducting various other field tests in an effort to assist wind industries in the United States to improve reliability and performance of wind turbines. Some current studies include wind park inflow-outflow characterization and advanced airfoil testing. These tests are not as comprehensive as the Combined Experiment described above. They are typically of short duration, designed with one or two specific objectives in mind. Data collection needs are typically less than 50 channels with 10-Hz maximum resolution bandwidth. Multichannel hub-mounted rotor packages (McKenna 1990) facilitate rotating frame measurements from multiple turbines.

One area of field testing in which we were severely limited was our ability to decode multiple PCM streams for quick-look data processing and display. We originally relied on a D/PAD Mark II (Loral) PCM decoder to examine channel data values. The D/PAD can decode one PCM stream, convert values to engineering units, and display data from 12 channels in real time. Used within its designed capabilities, the D/PAD is an excellent instrument. However, we required some additional capabilities for which it was not suitable, and finding a cost-effective alternative was difficult. We needed multiple-stream decoding, derivation of parameters from multiple channels (across PCM streams), graphic display, data storage, and a means to rapidly update calibration coefficients. We also needed the ability to monitor long-term meteorological conditions for evaluating current test status. These field capabilities are essential, because debugging using laboratory-based postprocessing is inefficient and impractical. We therefore developed the PC-based PCM decoding hardware and wrote a custom quick-look PCM data management software program (Simms 1990).

OBJECTIVES OF PC-PCM SYSTEM DEVELOPMENT

Our main objective was to provide a cost-effective PCM decoding system which could be duplicated at our many test sites to maintain consistency among systems. Future plans include development of an inexpensive turnkey data-acquisition system which could be used by the wind industry. For many reasons described below, we decided that a PC-based system was most practical.

We contracted with a local electronics development company (Apex Systems, Inc. 1988) to develop the PC-based PCM decoding capability. We wanted a system built on printed circuit boards which could be installed in the expansion slots of a PC/AT or compatible computer. The system should include basic control software to initialize and operate the boards. It should also provide simple user interface to allow easy acquisition and examination of data from different PCM streams.

We specified four PCM input channels for each board, from which one could be software-selected to read data. A maximum of four boards could be installed, which would allow access to 16 PCM streams from a single computer. Multiple boards would permit acquisition from up to four streams simultaneously, and would tag and interleave multiple incoming data into a contiguous digital time series.

We also specified that data be written directly to PC memory or disk files. This would enable subsequent data processing and analysis to take advantage of the huge resource of software packages available for PC's, according to user preference. It also would enable easy development of custom packages in the many available software languages. The widespread use of PC's also would permit easy distribution of a developed data acquisition and processing package to interested users.

PC-PCM DECODING SYSTEM HARDWARE

The PC-based decoding boards do not support the full set of IRIG standards for PCM. Rather, they were designed to work with our specific hardware, which is a subset of standard PCM. We typically do not supermultiplex or subcommutate channels in the PCM frames. All channels on a given PCM encoder are sampled at the same rate as that required of the highest rate channel. Those channels that do not require the fast rate are anti-alias filtered to a lower bandwidth and can be subsequently decimated in software. The PC-PCM decoder board specifications are summarized in Table II.

Table II. Specifications for PC-PCM Decoder Board

Bit rate	1-800 Kbits/sec
Input streams	4 (only one processed at a time)
Input polarity	Negative or positive
Input resistance	>10 Kohms
Codes	Bi-phase L, NRZ
Bit sync type	Phase locked loop (PLL)
Input data format	8-12 bits/word, MSB first
Words per frame	2-64 (including sync)
Sync words per frame	1-3 (maximum 32 bits)

In conjunction with the PCM decoder boards, we developed an analog interface module which reconstructs analog output from up to eight channels per stream. The

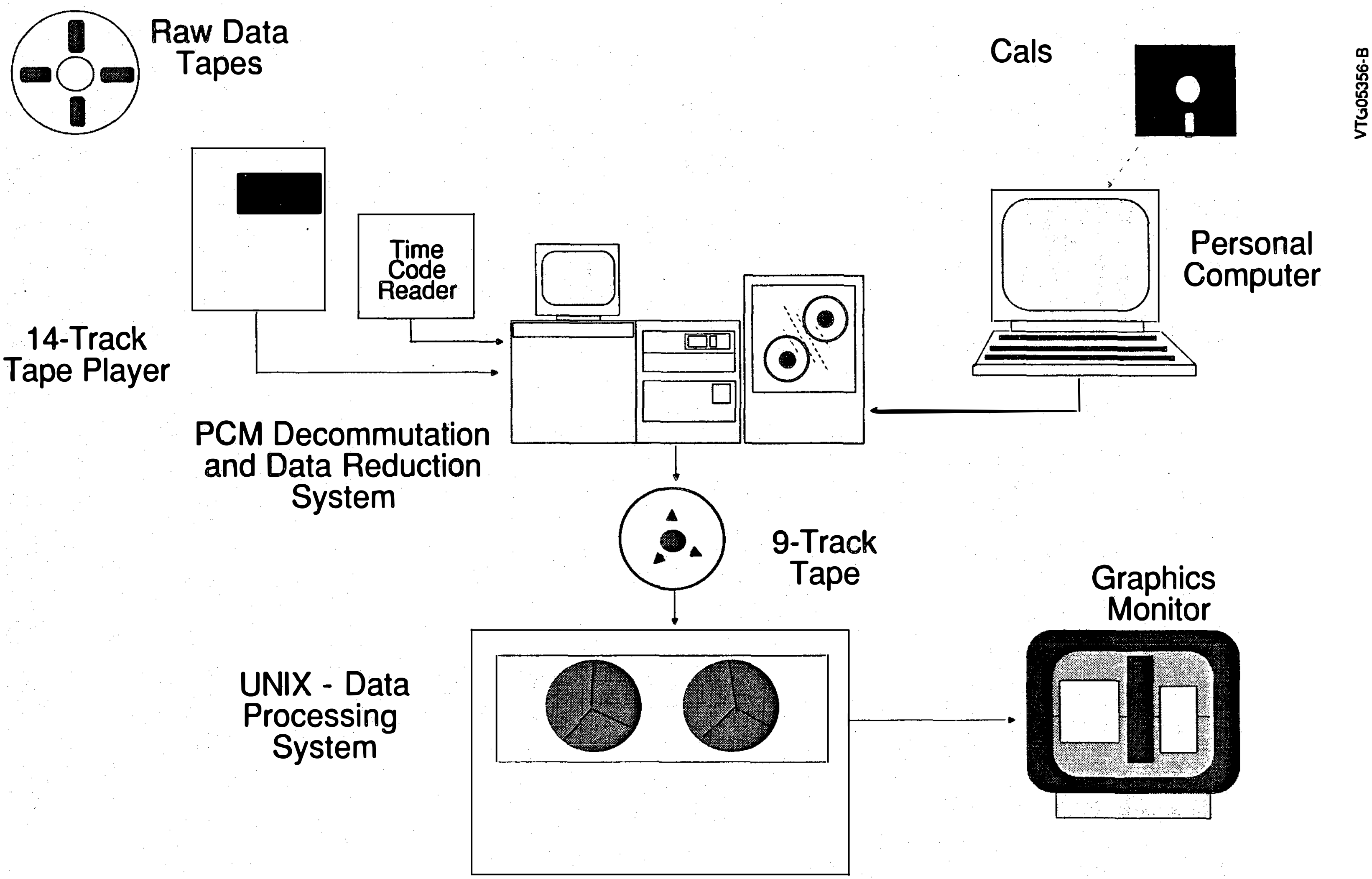

Figure 2. Full PCM data reduction and processing

basic intent was to provide the ability to use real-time analog test instruments such as a spectrum analyzer or chart recorder. The analog module is an optional part of the system. Specifications are shown in Table III.

Table III. Specifications for Analog Interface Module

Analog outputs	8 channels (user selectable via thumbwheels)
Output polarity	Unipolar or bipolar
Output range	0 to 10V, 0 to 20V, -5 to +5V, -10 to +10V
PCM inputs	4 (Only one processed at a time)
Status lights	PLL lock, frame sync, FIFO, disabled

PC-PCM DECODING SYSTEM SOFTWARE

The PC-PCM hardware boards are controlled by DOS software written in C. Three programs and three ASCII configuration files provide basic capabilities. The first program, PCMTEST, initializes boards and captures data. The second program, PCMDUMP, reads captured binary data files. The third program, PCMBAR, generates a real-time bar chart graphics display. These programs input PCM system description from DOS ASCII format data files which are easily accessed and modified by the user. A configuration file (.CFG) contains information describing how PCM hardware boards are configured in the PC. A stream file (.STM) defines characteristics of each PCM stream. The capture file (.CAP) contains a list of instructions for a capture operation. These parameters and the range of options are summarized in Table IV.

The PCMTEST program can capture any amount of data, up to the available space limit. If data is captured to disk, the maximum amount is determined by the space remaining on the hard disk drive. If data is captured to memory, the maximum amount is determined by available remaining system memory. Larger memory captures are possible by using extended memory configured as a RAM disk. The amount of data to capture is specified in time (seconds), file size (kilobytes), or frame count.

PCMDUMP is a postprocess program used to generates time series data files from the raw binary capture files. This facilitates examining PCM data and interfacing with data analysis software. The PCMDUMP program can generate either ASCII or binary data files and can separate an individual stream from a multiple-stream data set.

The resulting delivered system had one benefit which we did not anticipate. Invoked from a batch file, the software can reinitialize a board fast enough to enable quick sampling from each input PCM stream. Therefore, a single board can cycle through, sample, and store data from four streams rapidly enough to update a real-time display run from other application software. Many factors affect the scan rate, including number of channels, number of samples per channel, interim calculation requirements, and so on. Typical update rates for a 15-channel display from four PCM streams (including first-order engineering unit conversion and derived parameter calculations) occur in less than a second. The usefulness of PCM stream scanning depends on the nature of the data, because intermittent sampling may cause aliasing or transients may be missed. However, for many of our averaged data applications, the monitoring of many channels by scanning across multiple streams is very useful.

Table IV. User-Definable Options for the PC-PCM System

Configuration File:	
Base IO address	I/O address of the first PCM board (Board 0) (2-3 Hex digits)
Number of cards	Number of PCM cards installed in the PC (1-4)
Signals per card	Number of input streams attached to card (4)
DMA channel	DMA channel that PCM board 0 is configured for (5-7)
Interrupt channel	Interrupt channel that PCM board 0 is configured for (0-15)
Buffer size	Size of memory buffers, in bytes (512-65,024)
Buffers	Number of memory buffers (2-64)
Stream File:	
Bit rate	Rate of transmission in bits/second (1000-800,000)
Data format	PCM format (NRZ or Bi-phase L)
Signal polarity	Whether signal is inverted (positive or negative)
Bits per word	Bits in each word (2-13)
Words per frame	Length of frame, including sync words(2-64)
Synchronization	Binary or hex sync pattern
Capture File:	
Card n	Specifications for board n (0-3)
Signal = stream	Links PCM stream to input signal (0-3)
Use	Which signal to read data from (0-3)
Capture channels	List of channels to capture (1-62)
Max frame count	Total number of frames to capture (optional)

DATA FLOW IN THE COMPUTER

A clear understanding of the data flow inside the computer is helpful in understanding the capabilities and limitations of the PCM decoder board. Figure 3 shows the data flow inside the PC, described in the following section.

PCM data streams can be input directly to the PC-PCM decoder board, or interfaced through an analog module. The analog module allows the user to select up to eight desired channels (via thumbwheel dials) for analog output. The analog voltage output can be selected in the 10- or 20-volt span range, bipolar or unipolar. The analog module also interfaces the PC-PCM boards to panel-mounted LED's to inform the user of system status. (The status LED panel could also be built independently of the D/A system.) Status lights indicate capture activity, PLL (phase-

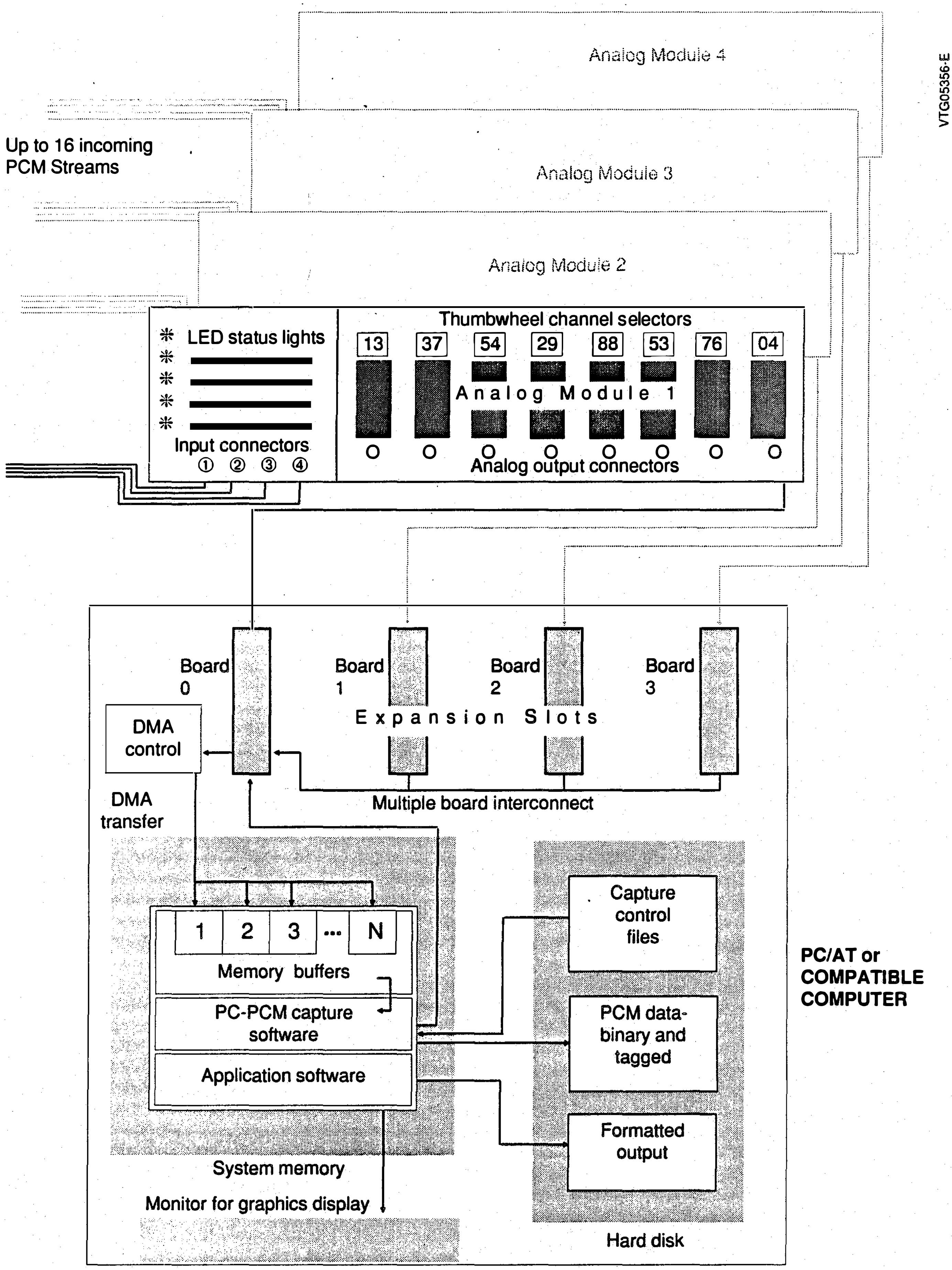

Figure 3. Data Flow in the PC

lock loop) status, frame sync status, PC memory status, and error state.

The PCM decoder boards are under control of the capture software running in PC system memory. This program can be run on its own or via user application software. The capture program writes binary-format tagged PCM data. Each data word is tagged with its corresponding PCM board number. Captured data can be accessed by the application program through memory or disk files.

The capture software reads user-defined parameters from the capture control disk files, then initiates and terminates the capture operation. Before initiating capture, the direct memory access (DMA) controller is initialized to define the starting address and size of the first memory buffer. The DMA controller has a special address generator which allows it to move data from the PCM decoder card to the addresses in memory. When capture is initiated, the DMA controller moves data from the PCM board to the first memory buffer in 16-bit words. When the buffer is full, the DMA controller informs the PCM decoder card, which in turn generates an interrupt to the capture software.

Upon receiving the interrupt, the capture software reinitializes the DMA controller to transfer data to the next available buffer. This process is repeated until the capture is complete. While the buffers are being filled, application software could simultaneously access the data in the full buffers. Flags are provided for each buffer defining when they are full, empty, or in use.

This structure has many advantages. First, the DMA controller moves data from the PCM decoder board to memory more quickly than a software transfer does, and it is an independent process. The DMA controller actually takes over the PC/AT bus when data are transferred, and does not burden the microprocessor. This makes the application software simpler and more efficient. Memory buffers provide another advantage. When data are being transferred to the hard disk, these buffers store data until the hard disk can rotate to the proper sector to write the data. Without these buffers, data would be lost.

DATA CAPTURE PERFORMANCE ESTIMATES

In single-stream mode, a typical PC/AT can capture PCM data to disk at rates up to 800 Kbits/sec. For multiple-stream disk capture, quantifying performance is difficult due to many possible combinations of PCM stream rates and PC capabilities. An algorithm for estimating disk data capture rate is:

$$DCR = 16 * (BR / BPW) * (CWPF/WPF) \quad (1)$$

where:

- DCR = PC data disk capture rate in bits/second
- BR = Incoming PCM bit rate in bits/second
- BPW = Data bits per PCM word
- CWPF = Words captured per PCM frame
- WPF = Total words per PCM frame, including sync

The data capture rate for multiple cards is the sum of the DCR's for each individual card.

To provide some rough performance estimates, a test was run using four PC-PCM boards installed in a 25-megahertz 80386-based PC. A PCM simulator was used to generate 62 channels of 12-bit words in Bi-Phase L format with 2 sync words per frame. Data was captured to contiguous blocks of disk storage space. The PC system could continuously capture to disk all channels of data from two 800-Kbit/sec streams. It could also capture all channels from four 400-Kbit/sec streams. The maximum occurred with three 800-Kbit/sec streams, each capturing 45 channels. At rates above this, the hard disk could not keep up with incoming data and capture was terminated by a buffer overflow error condition.

Using equation (1), the corresponding upper limit of disk data capture for this configuration is approximately 2.25 Mbits/sec. The PC's hard disk was rated at 10 Mbits/sec, indicating that the required PC disk speed should be 4-5 times the maximum data capture rate in order to insure adequate performance. There are many factors which are likely to affect these values, including disk fragmentation, disk interface type, disk interleave, buffer size, CPU speed, and other installed PC options.

Using the same system configuration, there were no performance limits when capturing data to memory. PCM data from four 64-channel, 800-Kbit/sec streams were successfully captured to an extended memory RAM disk. This is useful for providing higher rate capture, but data quantities are limited due to memory restrictions. Large amounts of memory are less common and more expensive than comparable disk space.

ARCHITECTURE OF PCM DECODER BOARD

The PCM decoder board has a programmable bit detector for extracting the ones and zeros from the PCM signal. These are passed on to the frame and word processing section where the words are extracted, and then interfaced to the PC. The following discusses each of these in detail.

Bit Detector

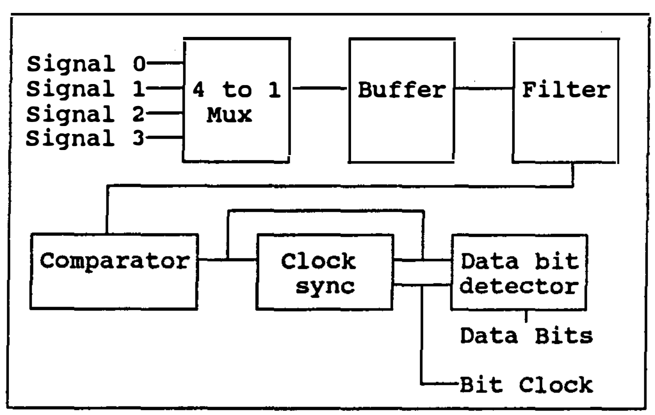

Figure 4. Decoder Board Bit Detector

Figure 4 shows the bit detection circuitry. A multiplexer controlled by software selects between any one of four input signals. Following the multiplexer are buffer, filter, and comparator. These circuits convert the selected signal to digital levels. The data clock synchronizer extracts the bit clock rate from the incoming signal. The data bit detector circuit uses the bit clock and the signal from the comparator to generate a data bit stream of ones and zeros.

Frame and Word Processing

Figure 5 shows the decoder board frame synchronization circuitry. The bit clock clocks the data bits into both the frame synchronizer and the serial-to-parallel circuit. The frame synchronizer is programmed with the sync words. This information is used to detect and synchronize on the data frame. The serial-to-parallel circuit is nothing more than a shift register with parallel outputs. When commanded by the frame synchronizer, the serial to parallel circuit strobes a complete word of information into the first-in-first-out (FIFO) buffer.

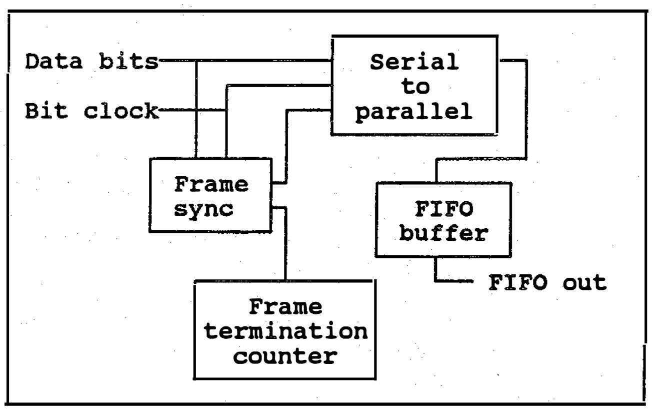

Figure 5. Decoder Board Frame Synchronizer

A FIFO buffer is necessary because the PCM stream is continuous with no gaps in the data, whereas the PC/AT bus cannot continuously accept data. The FIFO acts as a variable-size buffer holding the data until the PC/AT can pick it up. When a large amount of data is captured to the hard disk and the incoming bit rate is very high, it is possible for the FIFO to fill up faster than it can empty. When this happens, a FIFO full error is generated, a warning signal level is activated, and data capture stops.

A frame termination counter option allows the user to specify the number of frames before the capture process is automatically terminated.

PC Interface and Control

Figure 6 shows PC interface and control circuits which interface the PCM data decoder to the PC/AT bus. The FIFO output must be connected to the PC/AT data bus to transfer data. This process is controlled by the control block, which also controls programmable functions and interfaces to the multiple board arbitration circuit. The multiple-board connector provides an independent data path between boards. The master board determines which boards have data ready to transfer to the PC/AT bus. If more than one board has data at the same time, the arbitration circuitry controls the order of data transfer.

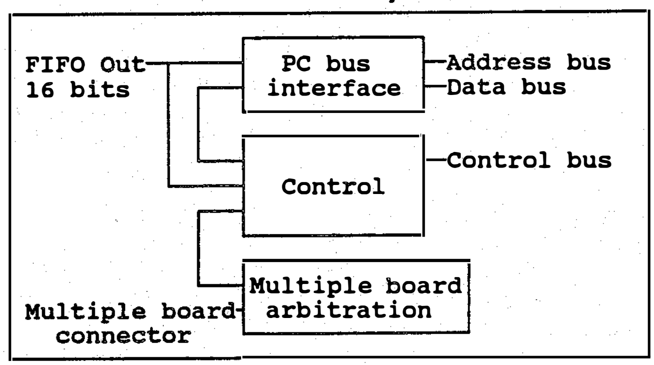

Figure 6. PC Interface and Control

CONCLUSIONS

In a single PC, the PCM decoding system provides continuous data acquisition to memory or disk from up to four streams simultaneously. A variety of software packages can subsequently be used to read and process the data. Single-stream real-time data monitoring is accomplished from a graphic bar-chart display program.

The full complement of boards in a PC permits data handling from a maximum of 16 PCM streams containing up to 62 channels each. The boards are IRIG compatible and are designed for use with standard PCM encoders. The data streams can be accessed by cyclic sampling or simultaneous acquisition or both. Maximum acquisition rates and data storage capacity depend on PC hardware.

Optional analog interface modules can be used in conjunction with the PC-PCM decoder boards. These provides digital-to-analog conversion of up to 8 user-selectable channels per PCM stream, or 32 channels total.

Incorporating the PC-PCM system into small portable computers simplifies remote test monitoring of PCM data. The complete system provides test engineers with the ability to decode PCM data and perform quick-look data analysis in the field.

ACKNOWLEDGMENTS

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