combinations, or as iterative networks. It is further hoped that the present research results will be helpful in the formulation of allied methods whose resulting realizations use flip-flops instead of delay units as the basic memory elements.

References


A 48-Channel PCM Tape Data-Acquisition System

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Abstract—A high-performance data-acquisition system, now operational, combining analog and digital techniques is described. Up to 48 channels of information can be digitized continuously at rates up to 240K samples per second and then divided into standard contiguous computer records by a tape shutting method. Various input and output modes permit the tailoring of data gathering and matching of output to a number of subsequent digital processing systems. It may also be used as a "black box" analog recorder with a wide choice of bandwidth and channel capacities or as a digital recorder with transfer rates to 5 Mbaud. The uniqueness of the system lies in the use of a 33-track, 1-inch inline recording head which permits densities above 2000 bit/in, multiple A/D converters to economically match tape capacity, and a shutting operation instead of a buffer to produce gapped output records.

The system will be of interest to anyone confronted with a massive requirement for data acquisition and processing, either digital or analog.

Index Terms—Analog–digital conversion, analog–digital systems, data acquisition, data storage, digital recording, input-output systems, magnetic tape recording systems.

Manuscript received May 26, 1967; revised October 26, 1967.

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MODERN DIGITAL computers permit exacting analysis of large volumes of (digitized) analog data, so exacting in fact that in many cases normal instrumentation recording techniques do not provide adequate recording fidelity, interchannel timing, or channel capacity. Typical analysis examples are problems in oceanographic research, locating mineral deposits, radar data analysis, acoustics, and research in television picture information content.

One solution to the data-acquisition problem would be a computer tied directly to an A/D converter. This would be impractical in most cases, especially those concerning acquisition of data in the field or involving a leased general-purpose computer shared by many users. Also, reliability of software and that of a large computer system could present difficulties for nonreproducible experiments. Another more practical solution is a flexible data-acquisition system capable of producing standard computer tapes or direct digital output to a computer. Such a system has been designed by Bell Telephone Laboratories to aid in the study of the acoustic
properties of the ocean. Data are normally gathered at remote field locations, and the resulting PCM tapes are returned to the laboratory for further processing. Up to 48 channels are observed simultaneously with a precision of up to 1 part in \(10^4\) (9 to 12 bits), extremely low interchannel time skew to permit cross correlation, and continuous recording times up to hours of data (equivalent to over 25 standard computer tapes).

The following features are included:

1) field digitizing and recording of multichannel analog data at a variety of channel capacities and system rates: from 240 kS/s\(^1\) (corresponding to 48 channels at 5 kS/s to 3 channels at 80 kS/s each) at a tape speed of 60 in/s to 3.75 kS/s (corresponding to 48 channels at 78 S/s to 3 channels at 1.25 kS/s each) at a tape speed of 15/16 in/s;

2) digital outputs in a number of forms suitable for computer analysis including standard blocked computer tapes by a unique method of marking and shuttering the original tape;

3) a variety of data recording and reproducing modes enabling the data to be “tailored” for each experiment and subsequent computer processing costs reduced;

4) laboratory digital-to-analog reconstruction equipment to permit high quality conversion of the data to analog form; and

5) direct digital input and output of data at rates up to 2.5 or 5 Mbaud, depending upon error rate requirements.\(^2\)

The equipment is packaged in six racks, three of field equipment and three of home laboratory equipment. Some of the equipment is duplicated so that the field unit(s) need not be returned home to use the data.

The overall organization of the system is shown in Fig. 1. The field system components are explained in the following list.

1) Signal conditioners—Provide the proper input levels to the multiplexers (Fig. 2).

2) Multiplexers—Sample the input signals and provide a sequential multiplexed output to the analog-to-digital converters. Optional simultaneous hold of all channels is provided.

3) Analog–digital (A/D) converters—Convert each sequential analog sample point to a corresponding 12-bit parallel digital code.

4) PCM tape subsystem—Record and reproduce the digital output codes from the A/D converters and/or other digital data.

The other important sections of the field equipment are:

1) Format plug—Selects the number of A/D subsystems, number of bits of precision per subsystem to be recorded, and format for the PCM tape.

2) Control system—Controls the timing and speed of the entire system (Fig. 3).

3) Record length counters and copy control—Control the length of the final computer records and data strings by counting scans or units of time, and generate the proper pulse for the subsequent data gapping and transfer operation to a computer or computer tapes (copy-control pulse).

4) Mode controls—Start and stop the acquisition of data in various types of operations using record length counters, an external trigger, and a mechanical interval timer.

5) Error checking—Parity generation and checking, analog reconstruction of signals to and from tape for quick-look purposes.

The main elements of the home laboratory equipment are as follows:

1) PCM tape subsystem—Reproduces data recorded in the field.

2) Analog reconstruction—Reproduces the equivalent of the input channelized signals.

3) Digital output processing—A scanner to break up the PCM data word into 6- or 12-bit bytes, a transport to produce tapes in standard computer format, and logic to produce direct digital outputs.

4) Control system—Controls the timing and formatting of all data, and shuttles the PCM tape for computer tape production.

5) Error check—Constantly counts and displays errors on the PCM tape and flags the digital output when PCM errors occur.

\(^1\) S/s = Samples per second, kS/s = thousand samples per second.

\(^2\) Typical computer tape error rates are very low since errors which may reflect in program instruction errors cannot be tolerated. However, the requirement for a tape of analog data is not as stringent. For example, a comparison can be made to find the error rate which produces an amount of tape error noise equivalent to quantizing noise.

Assuming only single errors, the total error voltage may be expressed as

\[ e^2_t \approx \left[ (\frac{N}{2^{N-1}})^{2} \right] \sum_{i=1}^{N} 2^i \]

where tape error is expressed as one error in \(10^N\) bits, \(e_t\) = error voltage produced, and \(N\) = the number of bits of precision. This may be reduced to

\[ e_{\text{max}} \approx \sqrt{\frac{1}{2 \ln 2}} \cdot (N)10^{-N} \]

and equated to the quantizing noise which yields the following when solving for \(E\).

12 bit encoding: 1 error in \(10^{5.1}\) bits on tape
9 bit encoding: 1 error in \(10^{4.1}\)
5 bit encoding: 1 error in \(10^{3.1}\).

By using the criterion that tape error can only add 1 dB to quantizing noise, the above exponents are increased approximately 0.3.
Fig. 1. Block diagram of digital data-acquisition system.

Fig. 2. Typical analog signal conditioning.

Fig. 3. Data-acquisition system—field equipment-control block diagram.
SYSTEM DESCRIPTION

Since the system organization centers around the choice of three similar A/D subsystems and the degree to which they match the high-performance tape, they will be discussed first. The rest of the system is dependent upon this approach.

FIELD EQUIPMENT—A/D

The basic requirement was to record 48 channels at 5 kS/s per channel (240 kS/s system) with at least 9 bits of precision. There were no acceptable single A/D systems on the market in this speed range. After a careful investigation, the decision was made to operate three 80 kS/s systems in parallel. Many cost and equipment compatibility advantages are inherent in this approach. Relatively inexpensive A/D's can be used. The 80 kS/s rate also represents the highest speed attainable with conventional, high-accuracy, stable converters. Speeds beyond this would have required a more sophisticated, much higher speed approach that would not have been as desirable or used to its fullest advantage. In addition, the choice of three units provides an excellent match between the number of A/D parallel channels and the information rate per track attainable in state-of-the-art digital recorders.

The system has been designed for the three independent multiplexers and associated A/D converters to operate in parallel from a common control system. Each multiplexer-A/D subsystem handles 16 analog channels. The corresponding input analog electronics and plugs are also constructed in modules of 16 channels. The multiple converter approach also proves a form of reliability since one subsystem may fail without affecting the other two.

Sampling is sequential over the number of channels selected. An input patch panel allows selection of any desired sequence of sampling on selected channels. If sample and hold is not used, all samples are uniformly spaced by a master clock. This allows the equivalent of higher speed sampling on selected channels by using the patch panel to repeat the same analog channel many times in the sampling sequence.

The output of the A/D subsystems goes through a format plug and tape buffers to the recorder electronics. The format plug acts as a patch panel to provide flexibility in choosing the number of bits of accuracy per subsystem and number of subsystems to be recorded. Twelve-bit parallel output A/D converters are used, and the number of bits recorded depends on the desired accuracy of the particular experiment being performed.

PCM Tape Recorder-Reproducers

Recorder-reproducers were investigated at the same time as A/D systems since the two had to be closely matched. "State-of-the-art" instrumentation and digital recorders were examined. A high-performance instrumentation transport equipped with PCM digital electronics was chosen in conjunction with the three A/D systems to maximize the transfer rate and storage capacity and minimize interface costs.

The field recording requirements imply the use of continuously moving instrumentation (analog) tape recorders. The requirements are: high transfer rate, a choice of operating speeds, long recording time, high capacity, good timing accuracy, and less emphasis on fast start-stop. The playback requirements for transmission to a computer (or digital tape) imply fast start-stop of data, transfer of relatively small blocks of data, and a fixed transfer rate. A method of controlling the tapes was developed to obtain the advantages of continuous analog transports during recording and, at the same time, simulation of the operation of digital transports for playback purposes if desired. This is achieved by means of a copy-control pulse recorded on the original tape that is used to control both a shuttling operation and blocking during playback. For analog reconstruction, the playback is continuous as recorded.

Some special development of the recording head and electronics was required. However, the amount of development effort was small compared to the cost and other disadvantages of using any other A/D subsystem configuration. The recorders are equipped with 1-inch 33-track inline heads and transport mounted preamps. The mechanical tolerances of the instrumentation recorders and tape allow a maximum parallel strobed packing density for the 33 tracks of about 3000 bit/in. (As a comparison, standard computer tape is capable of about 1000 bit/in and 9 tracks.) The inline head developed for the system allows the maximum utilization of tape and least costly A/D approach by equating one A/D output bit to each track.

An example of the tape configuration is given in Fig. 4. 27 data tracks are grouped around 5 control tracks. Note that the timing (servo and strobe) tracks are adjacent and in the very center of the tape. This permits the most accurate timing with the least amount of equipment.

The densities for this particular system (based on desired sample rates and tape speed) are 667, 1334, and 2668 bit/in. The typical dropout as stated by the manufacturer rate is 1 bit in $10^7$ at 1000 bit/in and increases as density is increased. The highest density is used for analog reconstruction purposes only and is most useful for obtaining long playback times.

Various recording times, channel capacities, and sampling speeds at different speeds are given in Fig. 5.

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3 It is interesting to note that this concept could be extended up to 50-60 inline tracks on a 1-inch head. Construction of such a head would be costly. However, it might only be a small fraction of the cost of the necessary electronics to achieve the same transfer rate by operating at a higher density or using wider tape.

4 Note that this is higher than the necessary error rate as calculated previously.
Fig. 4. PCM tape configuration.

<table>
<thead>
<tr>
<th>Tape Speed</th>
<th>Recording Time 7200 ft Tape Reel</th>
<th>A/D Clock Rate</th>
<th>Typical Channel Sampling Rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>120 in/s</td>
<td>12 min</td>
<td>80 kHz</td>
<td>Rate/Channel = System Rate/Channels per subsystem</td>
</tr>
<tr>
<td>60 in/s</td>
<td>24 min</td>
<td>40 kHz</td>
<td>5 kHz/s, 13.3 kHz/s, 240 kS/s</td>
</tr>
<tr>
<td>30 in/s</td>
<td>48 min</td>
<td>10 kHz</td>
<td>2.5 kS/s, 6.67 kS/s, 120 kS/s</td>
</tr>
<tr>
<td>15 in/s</td>
<td>96 min</td>
<td>5 kHz</td>
<td>1.25 kS/s, 3.33 kS/s, 60 kS/s</td>
</tr>
<tr>
<td>7.5 in/s</td>
<td>18 h 12 min</td>
<td>10 kHz</td>
<td>625 S/s, 1.67 kS/s, 30 kS/s</td>
</tr>
<tr>
<td>3 in/s</td>
<td>6 h 12 min</td>
<td>5 kHz</td>
<td>312.5 S/s, 825 S/s, 15 kS/s</td>
</tr>
<tr>
<td>1.5 in/s</td>
<td>12 h 48 min</td>
<td>2.5 kHz</td>
<td>156.25 S/s, 417 S/s, 7.5 kS/s</td>
</tr>
<tr>
<td>15/16 in/s</td>
<td>25 h 36 min</td>
<td>1.25 kHz</td>
<td>78.13 S/s, 208 S/s, 3.75 kS/s</td>
</tr>
</tbody>
</table>

Clock and tape speed relation shown is for a density of 1334 bit/in, for 667 bit/in double speed (computer data tapes only); for 2668 bit/in, halve speed (analog reconstruction tapes only).

Fig. 5. Continuous recording rates.
Field System Control (See Fig. 3)

All subsystems are driven by a common control system. The internal clock used to drive the system is a crystal clock which is also used to control the tape recorder servo. The crystal rate is counted down to 80 kHz or lower by a factor of 2 depending on the tape speed selected to control the sample rate of the system. Sampling takes place on one half cycle and strobing of the data on tape on the alternate half cycle. By this method, timing of data sampling, data recording, and the tape strobe (clock signal displaced exactly one half clock from data) can all be derived from the basic clock without the use of any critical fixed delays. Since timing is by countdown rather than fixed delays, any external clock speed can be used to drive the field equipment.

The system control also includes multiplexer channel-addressing equipment to control the scanning of the selected number of channels at the proper time. The addresser is driven from the sampling clock and includes generation of frame and sample pulses. 2 to 16 channels (per subsystem) may be selected.

Record Length Control

A control signal (copy-control pulse) is also recorded so that continuously recorded data may later be broken into typical small gapped computer records of data without use of a buffer or loss of data. The record lengths are determined by either of two methods: 1) by counting scans of data for a selected number of scans per record (1 to 32 768), or 2) by counting clock pulses for a selected time per record. Selected lengths vary from 0.1 to 16 seconds at the highest speed, and to 17 minutes at the slowest speed. The selected sample speed is used as the clock input to this counter. This provides a choice of times commensurate with the sample rate required by the input data.

Mode Controls

The following modes of recording data are provided to simplify the gathering of data and the subsequent computer processing. Note that modes are provided in which an exact length string of data can be recorded. This allows a prescribed number of sample points or period of time to be taken and eliminates paring of the data later in the computer, where it would be expensive. Fig. 6 is an example of the various modes.

1) Continuous—In this mode, the operation is started and stopped manually just as with any instrumentation tape recorder [Fig. 6(a)].

2) External trigger—In this mode an external trigger is used to start the data acquisition. One data string is recorded for each trigger. There are two options provided. In the first, the tape is at rest and a five second delay is required for the tape to reach speed before data acquisition begins. In the second, the tape is left running and data acquisition begins immediately after receipt of the external control pulse. In this option the trigger could actually be derived from the incoming data [Fig. 6(b) and (c)].

3) Periodic data strings—This mode is similar to that described above, but a built-in repeating mechanical timer is used in place of the external trigger. Timing intervals varying from a minute to an hour are provided. This makes possible the following type of operation: "Record exactly 1024 scans on 24 channels at a 10 kS/s rate/channel and repeat the string every 13 minutes." Two variations are provided as above, so that the tape may be left running continuously if the interval between strings is very short [Fig. 6(b) and (c)].

Just the portions of tape with data will be transferred to the final computer tape. Because of cost limitations, the counters used to determine string length are the same ones used to count record length; therefore, the string length options are the same as for record length, and each data string is one record long.

Signal Conditioning

Analog circuitry is also provided to bandlimit the input signals and obtain the proper voltage levels for the A/D converters. Amplifiers, attenuators, filters, and balanced-line transformers are provided for each subsystem in modular form. The units for each subsystem are pluggable and may be rearranged to permit full scale inputs of a few millivolts or hundreds of volts. All input channels may be individually adjusted and monitored in both analog and digital forms.

Laboratory Equipment

The following equipment functions, except for monitoring, are located mainly in the laboratory portion of the system.

Reduction of the PCM Data Tape to Standard Computer Tapes

Conflicting requirements exist on the two tapes. Since sampling is continuous, the data recorded must be continuous and without gaps. The entire tape could be one continuous length of data, but the computer tape requires short records of data (short enough not to overflow the buffers allocated in the computer store) separated by 2/3-inch gaps. These gaps would normally mean that the data flow would have to be interrupted.

This conflict is solved by the recording of a control signal (copy-control pulse) on the original tape so that the continuously recorded data may later be broken up into gapped records for the computer tape. This pulse eliminates the need for a buffer between tape units or the loss of data during the creation of interrecord gaps.
The other alternative would have used two buffer memories, which would have been filled and emptied alternately. This approach would have added another 10 to 30 percent to the cost of the system.

The copy-control pulse defines both the length of the transferred record and the interrecord gap. The following example shows how data are copied from the PCM tape to a blocked computer tape (see Fig. 4). The explanation would be similar for data transfers to other digital devices. Note the copy control pulse in Fig. 4. Assume that data are being transferred and that the tape is before point A of the copy control pulse. As point A is passed, nothing happens; but at point B both the PCM transport and the copy process stop. The tape is then rewound to any point between A and the previous pulse. Then the tape starts forward. At A the copy transport (but not the flow of data) starts. At B the transfer of data begins, exactly where it left off before. Again at C nothing happens and at D both machines stop, and the above process repeats. Note that no data are lost or repeated and that the interrecord gap is fully determined by the length of the "one" level on tape and not by any fixed delays in the transfer equipment. In this way, there is no dependence on tape load, rewind time, or any other fixed characteristics of the PCM playback speed. Any density or speed may be used on the original PCM tape and the proper gapping operation will still be achieved.

The "one" level, which defines the interrecord gap, is fairly long (about 80 strobe periods). Logic can be added so that serial data can be inserted in the middle of this pulse. Record length, serialization, or any other record header identification could be added here for a variety of purposes. The proper density of the final tape is achieved by the speed relation between the PCM and copy transports, and by the density of the original PCM tape.

Since the original PCM tape is 27 data tracks and the computer formatted tape only 6 data tracks, a transformation must be made between the two. This is done by assuming 36 PCM data tracks and remultiplexing to 6 tracks at a time on the computer tape. The 27 data tracks, frame, parity error indication, fixed levels, and repetition of certain data are used in the transformation. A plug-in matrix in the form of a prewired plug corresponding to the field format plug is provided for flexibility. Typical PCM and blocked computer tape formats are given in Fig. 7.
Direct Computer Interfaces

There are a variety of methods of directly interfacing to a computer data link or other digital processor. For each of these output methods, any playback rate may be used so that the transfer rate can be precisely matched to the processing speed of the computer. This facilitates programming and reduces core allocation and processing costs.

Two basic output rates are provided:

1) Continuous—In this mode the PCM tape runs continuously and the output is continuous.

2) Bursts—In this mode the output is in bursts, each one record long. The request for a record can be initiated by the computer. This mode uses the same logic as that for generation of standard computer tape.

Matching to parallel data channels of different capacities is also provided:

1) 30–36 parallel bits wide by interfacing to the output of the PCM tape; and

2) 6–7 parallel bits wide by remultiplexing as explained above for producing standard computer tapes (Fig. 7).

Another feature permits the output of data corresponding to user-designated channels only, rather than all data from the PCM tape. This will reduce the computation costs since extra data will not have to be read and then eliminated. For example, 48 analog channels of data can be multiplexed, digitized, and recorded. Then any 2 or 3 can be chosen at playback time and remultiplexed digitally for the computer.

Analog Reconstruction Facilities

Eight bit D/A converter subsystems are available in the laboratory playback equipment. All channels may be reconstructed simultaneously without effects of tape skew or other timing errors. The block diagram of a typical subsystem is given in Fig. 8. Note that two stages of registers are included. The first set of registers is filled sequentially as the data are read from the PCM tape. The second set of registers serves as optional buffering compensation for simultaneous sample and hold if it was used during recording. The registers permit the D/A reconstruction of the data in the exact same time sequence as originally recorded. This permits operation as a high quality analog recorder with highly accurate cross correlation capabilities. It also permits the exact same data to be analyzed by both analog and digital techniques for those laboratory situations where analog and digital processing systems are to be compared.

Direct Digital Recording

In addition to computer tape production and analog reconstruction, digital data may be recorded and reproduced for strict digital recording applications. Any data rate can be used as long as the normal tape densities are not greatly exceeded. As mentioned earlier, any playback speed can be used.

Performance Monitoring

Performance monitoring has been provided at every critical point:

1) input analog signal verification after signal conditioning,

2) verification of encoder accuracy,

3) verification of data to be recorded (at input to recorder electronics),

4) verification of recorded data (read-after-write or field playback),

5) verification of data played back on the laboratory transport,

6) verification of each sample point of computer data, and

7) indication on output of parity errors existing on the original PCM tape.

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Fig. 7. Typical tape formats.

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* The tape recorder drive can be referenced to an external audio oscillator so the playback rate can be precisely matched to the computer processing speed.

* Eight bits are considered more than adequate for our analog laboratory reconstruction work.
All of the above signal checks are made by two types of parity checks on the digital portion of the system, analog signal test points, and “quick look” D/A reconstruction. The first parity type is a subsystem parity, which is generated on each encoded sample point on each subsystem. This parity may be checked in the field before it is recorded, by read-after-write electronics, or by playback in the field. A lighted display continuously shows the parity error rate. The subsystem parity can be treated as a data bit and transferred to the computer tape. This allows a final parity check of the data point in core as part of the computer analysis program.

The second type of parity is a full system parity, which is generated in the field on the sum of all the recorder data tracks. This check is mainly for the PCM tape playback system but may also be checked in the field. Errors are continually counted and displayed on lights to tell at a glance if the system is operating properly or not. Errors on the original PCM tape are flagged on the computer tape, so those particular data points may be deleted or averaged out if desired by the computer program.

Complete analog reconstruction electronics is included as part of the monitoring logic. It may be patched in for “quick look” verification at the output of the A/D converters, read-after-write electronics, or on playback. The analog reconstruction is valuable because it provides a check of the input electronics, patchboards, sampling accuracy, and all timing in the system (especially data synchronization and multiplexing) that is not apparent by a parity check. However, errors in the least significant bits are too small in magnitude to be apparent in a scope display of the analog signal but are apparent in parity checks. Therefore, both parity and analog checks are necessary and complement each other.

Lighted displays to indicate the digital value of any input channel, pin jacks to monitor any analog channel before it is digitized, voltage standards and variables, and test synchronizing signals complete the monitoring facilities of the system.

**Conclusions**

The specifications of this system are for one particular application at Bell Telephone Laboratories but may be of use in planning a similar system. It is interesting to note that the cost of the system per channel for commercial equipment is about 3600 dollars, which includes input signal conditioning, all of the various inputs and outputs, and 6-speed operation. This per channel cost is close to that of a typical FM instrumentation recording system, which does not have the same flexibility. The system is built entirely of commercial components and includes about 400 cards of digital logic. The equipment has been in various states of operation for about a year, and performance has been satisfactory.