HOW TO BUILD A HIGH ACCURACY, 100 CHANNEL, PCM ENCODER FOR $29.95*

David G. Powell
Branch Head, Code P6441
Naval Air Warfare Center
Weapons Division
Point Mugu, CA 93042

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ABSTRACT

Pulse Code Modulation (PCM) Encoders are extensively used in instrumentation and telemetry systems. Commercially available encoders are available from several sources and vary in complexity depending on the application. Encoders often include analog signal conditioning, a system clock, and one or more digital input ports. Many of these systems also cost several thousand dollars and the cost goes up when high data accuracy of one or two percent is required. This paper describes a low cost approach which has been used in production telemetry applications with great success and which yields a PCM encoder with data accuracies of better than 2%.

*per channel

INTRODUCTION

Modern instrumentation systems require the collection of large amounts of data from many different sources. The sources can be any number of different devices such as strain gauge sensors to high voltage power supply outputs, computer data, etc. Sampling requirements may vary from less than one sample per second to several thousand samples per second. Multiplexers have been used for years to sample and combine many inputs into a single output.

Twenty years ago analog multiplexing was used in conjunction with Pulse Amplitude Modulation (PAM) commutators. The output of the commutator was recorded or transmitted back to a central reception and demodulation site. PAM systems were simple and system data accuracies of 2-5% were easily achieved.

Within the past 15 years Pulse Code Modulation has replaced most PAM systems. Inherent advantages of PCM include simplified computer interface, higher resolution, better signal to noise ratio, and secured data transmission. PCM encoders can be purchased to specific system requirements and used as a building block in system design. Another technique of designing a PCM system is to implement the encoder function into the system sequencer/controller. The integrated approach has the advantage of lower cost, smaller volume, and higher signal accuracies if some very simple design techniques are used. These techniques have been used at the Naval Air Warfare Center-Weapons Division (NAWC-WPNS), Point Mugu, California for several years and successfully transferred to production in airborne telemetry systems.

APPROACH

The Weapons Instrumentation Division of NAWC-WPNS has had the opportunity to develop several warhead compatible telemetry systems over the past 20 years. When miniaturization is required, the entire design has to be evaluated carefully to determine where the circuitry can be simplified and which manufacturing technology lends itself to the lowest cost at a given production level. Since these designs were good candidates for hybrid microcircuit technology, several techniques were available to the design engineers which would have been difficult to implement using other packaging technologies.

The signal conditioning in a basic PCM telemetry system, Figure 1, consists of an analog buffer, a multiplexer, an analog to digital (A/D) converter, and a system sequencer to generate control signals and output a serial data stream with appropriate PCM synchronization codes inserted. It is important to realize that although each section of the system performs a separate function, an integrated design approach leads to the best solution.

DISCUSSION

State-of-the-art circuitry for signal conditioners has provided the design engineer with greater resources to improve accuracy while reducing costs. Since the input signal levels from instrumentation data sources can vary from less than one volt to over 100 volts, a method of adjusting these levels to the input range of the A/D converter must be used. One method is to use an operational amplifier to adjust the gain and offset of each input signal to be compatible with the A/D converter. This buffer amplifier may not be needed but is often used to scale the input voltage to the operating range of the programmable section or to provide a low input impedance to the source. This method is well known but has two major drawbacks. Every channel requires several resistors and the absolute values of the components are unique. For the circuit shown in figure 2 the output voltage is given by:

$$V_{out}=-V_{in}(R_{fb}/R_{in})-V_{ref}(R_{fb}/R_{os})$$

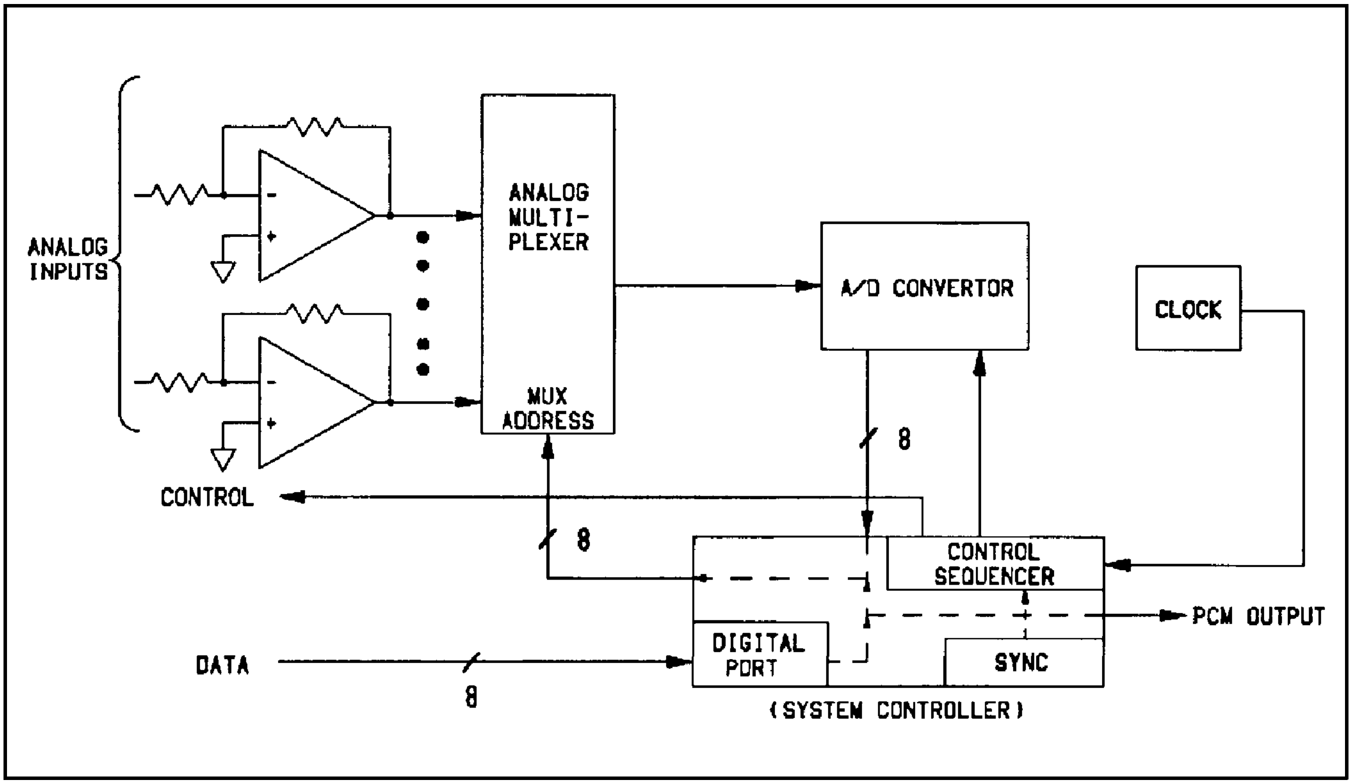

Figure 1. BASIC PCM SYSTEM

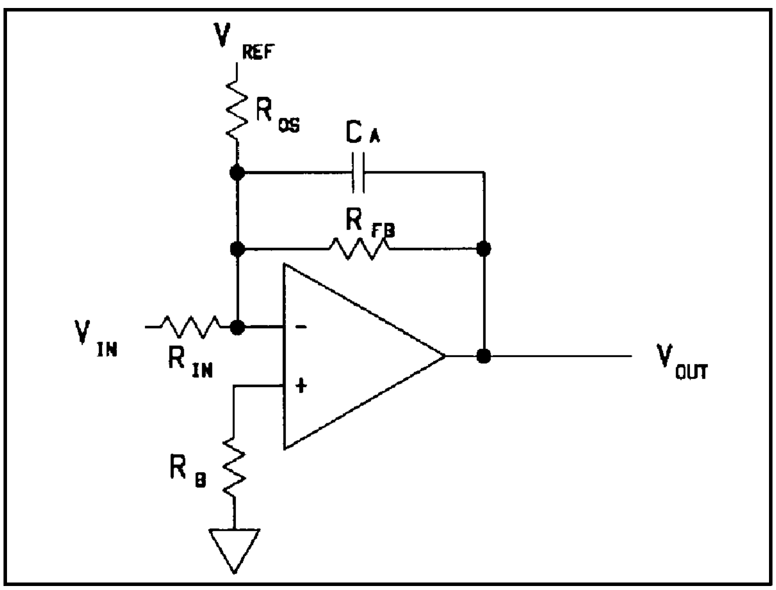

Figure 2. SIGNAL BUFFER

This equation does not take into account the component tolerances which must be considered in high accuracy systems. Several computer programs are available to help the designer determine the worst case variation of the output based on component tolerances. If the components in figure 1 have a 1% tolerance, then the worst case gain error could be as high as 2%. Another way of evaluating errors is by using the square root of the sum of the errors squared or root sum squared (RSS). This method works well for analysing circuits containing large numbers of components because the probability of all components having worst case values is small.

A programmable signal conditioning approach has some interesting advantages over the unique signal conditioning solution. The first is that because gain and offset can be changed by simply changing control codes, engineering modifications can be very easy to implement. Another advantage is more subtle and involves the circuit implementation of the buffer amplifier. In most signal conditioning situations the absolute input impedance is not critical and a 5% tolerance is acceptable. It is the ratio of R_{fb}/R_{in} which is critical in maintaining high signal conditioning accuracy. Thin film resistor chips used in hybrid microcircuits are available from a variety of vendors that have two or more resistor elements on a single chip. The ratio between elements can be held to 0.1% accuracy. Ratios of 1:1, 2:1, 3:1, and 4:1 are typical with an input resistance of up to 1 megohm. The resistor ratios may also be implemented using low cost SIP packaging for standard through-hole technology. Although the specification tolerance for SIPs is listed at 1 to 2%, the matching between elements is typically 0.1 to 0.2%.

Figure 3 shows a 40 channel hybrid microcircuit which is presently in production and can accommodate single-ended input voltage ranges of ±2.5 to ±40 volts depending on which resistor ratio is used. One MΩ resistors were used for all input resistors. The layout can accommodate a single pole anti-aliasing filter for each channel by adding a capacitor of appropriate value. Input ranges of less than ±2.5 volts can be conditioned but the input impedances must be lower than 1 MΩ; i.e. 250 kΩ. (this is a limitation of the maximum resistance which can be implemented on a 30 mil chip). Input buffer ratios were chosen to attenuate the signal voltage range to not more than ±12 volts. Buffer output voltages should be kept as high as the power supply limits allow to maximize signal-to-noise-ratio. The absolute values of the resistors are not critical and were purchased with a tolerance of ±5%. The ratios between elements are maintained to ±0.1%. The production costs of these hybrids are less than $700 in quantities of 100 or $17.50 per channel. The channels are multiplexed in groups of 16 using CMOS (Complimentary Metal Oxide Semiconductor) analog multiplexers. Each multiplexer output is conditioned separately in the programmable gain stage to alleviate switch capacitance problems encountered in high speed analog multiplexing.

The configuration for the programmable amplifier is shown in figure 4. CMOS switches were used to short all multiplexer outputs to ground except for the one being addressed. This technique dramatically reduces the interference between adjacent channels. Eight multiplexers can be accommodated with the present design for a total of 128 channels. Again the absolute values of the resistors in the summing amplifier are not critical, only the ratios. A high performance operational amplifier was used for the summing amplifier because the offset voltage error is $V_{os}R_{fb}/R_{in}$ where $R_{in}=R_{fb}/8$ (there are eight inputs) and V_{os}, must be low to start with.

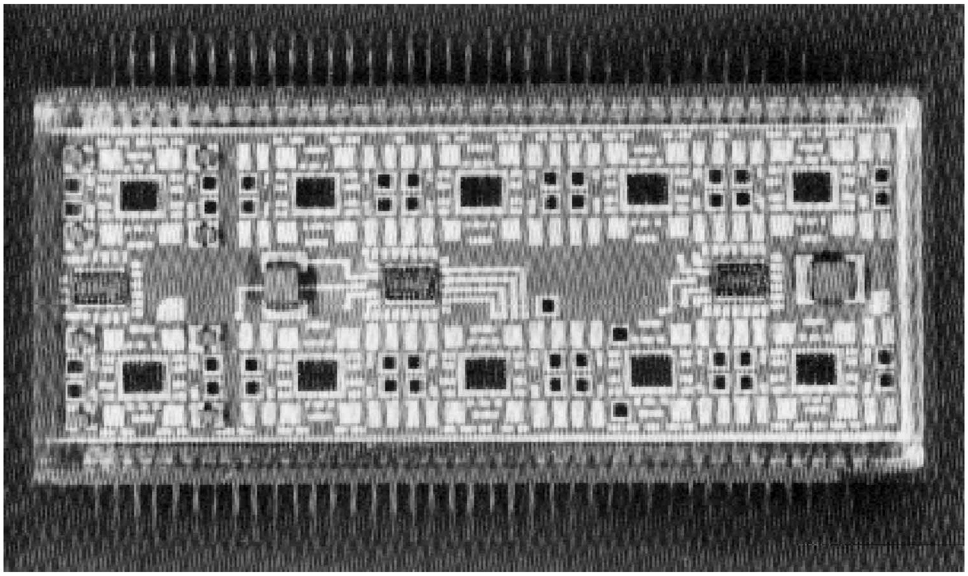

Figure 3. HYBRID 40 CHANNEL BUFFER/MULTIPLEXER

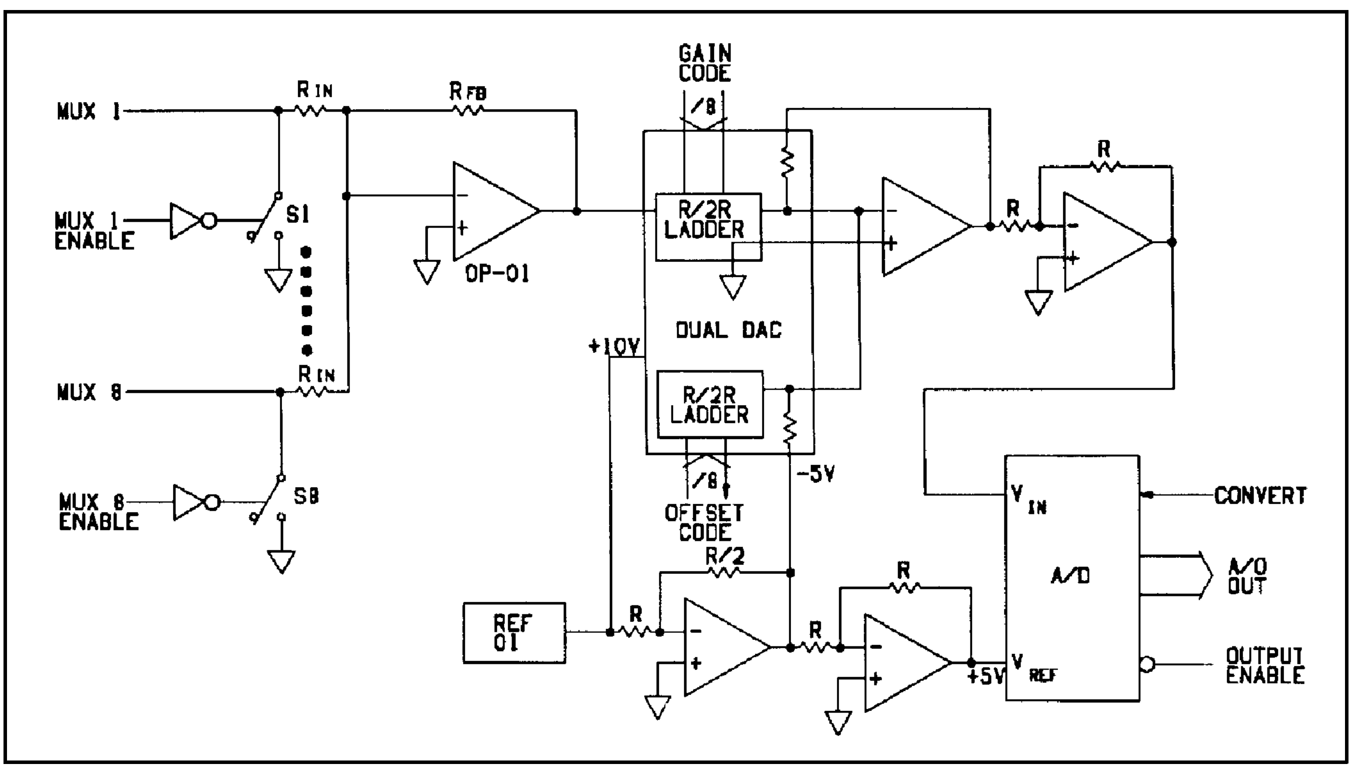

Figure 4. PROGRAMMABLE AMPLIFIER

A dual Digital to Analog converter (DAC) was chosen to adjust offset and gain. Because the DAC is a CMOS multiplying type, it is possible to connect both sections together with one amplifier and use DAC 1 to adjust gain and DAC 2 to adjust offset voltage. The DAC has a worst case gain error of ±0.2% full scale. Connecting both ladder networks together into one amplifier is possible because the thin film ladder networks are side by side on the die and are geometrically identical. Positive and negative offsets can be obtained by using the extra internal feedback resistor of DAC B and connecting it to $-V_{ref}/2$ as shown in figure 4. The output of the DAC is a voltage which has been conditioned in offset and gain to match the input range of the A/D converter (the gain of the signal is adjustable from 0 to .996 in 255 steps and the offset is adjustable from -5.0 to +4.96 volts). Inexpensive half-flash 8-bit A/D converters are available with a worst case gain conversion error of ±½ LSB. The total end to end system error is the combination of all sections as listed below:

Buffer amplifier	0.1%
Multiplexer and amplifier	0.1%
Gain and Offset amplifier	0.2%
A/D converter	0.2%

The total system signal conditioning error due to component tolerance variation can be estimated as follows:

$$E_c=[(0.1)^2 + (0.1)^2 + (0.2)^2 + (0.2)^2]^{1/2} * 100\% = 0.\ 316\%$$

This calculation assumes ideal operational amplifiers. In practice the offset current and voltage must be taken into account. The RSS offset voltage error for the system shown which used MC 34184 quad amplifiers for the signal buffers, MC 34182 amplifiers in the DAC section and an OP-01 for the multiplexer buffer is given by

$$E_{os}= \{[(0.004)^2 + (0.004)^2 + (0.0004*8) + (0.001)^2 + (0.001)^2]^{1/2}\}*100$$

or 0.665% referenced to one volt (one volt was the smallest input voltage range for the system). The total system error is the RSS of the tolerance and offset errors or

$$E= [(0.316)^2 + (0.665)^2]^{1/2} = 0.736\%$$

The entire analog system was designed without using any unique resistor values. Since each of the ratio elements were part of the same die, the resistance ratios are stable with changing temperature.

The system controller can be implemented in several ways. A block diagram for a typical controller is illustrated in figure 5. A design capable of controlling an analog subsystem, a parallel digital input port, a sync code generator, and a serial PCM output register can be implemented using less than 20 off-the-shelf 54HC type parts or a programmable gate array such as an Altera or Xilinx device. The encoder is just a sequencer which provides control signals to the individual sections. Typical strobes could include PROM counter increment, PROM enable, offset, gain, multiplex channel, A/D convert, and parallel digital input. The encoder must also include a parallel to serial shift register to output the PCM data at a constant rate.

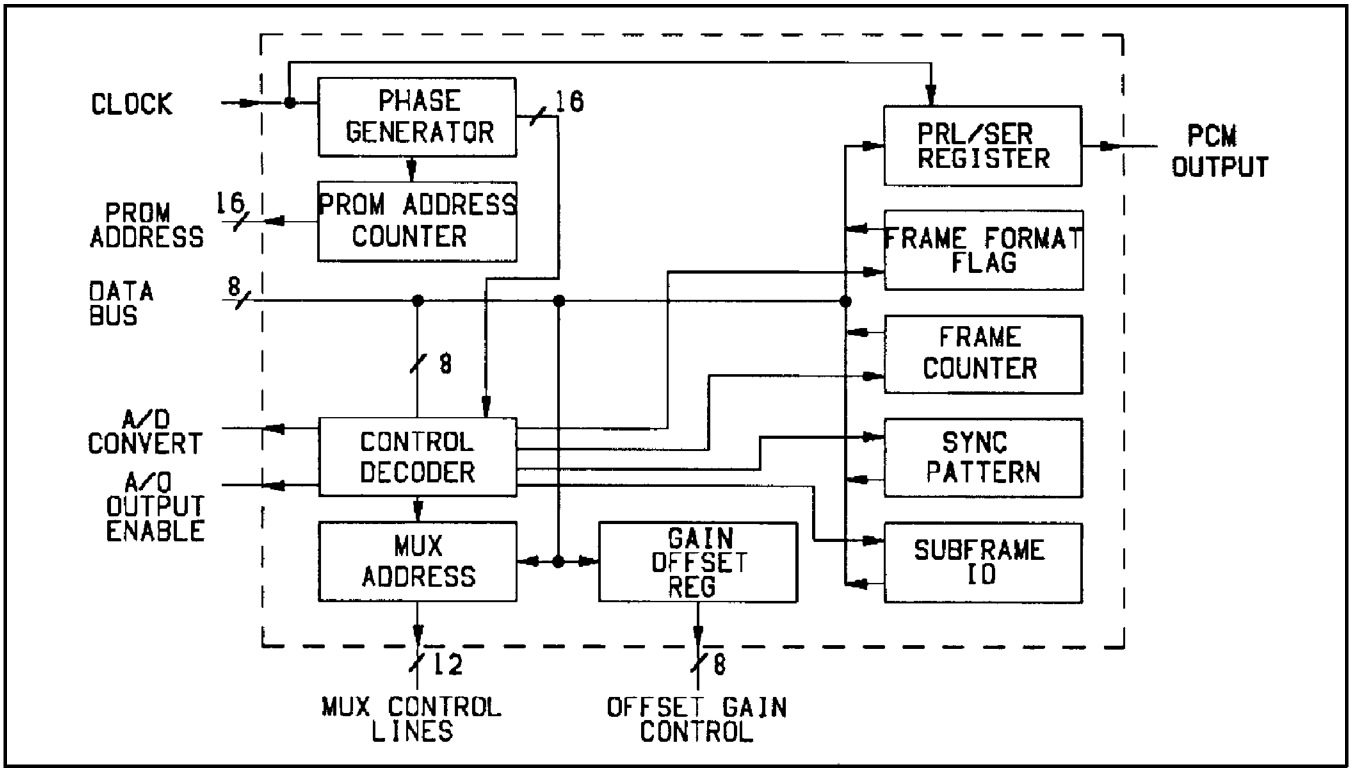

Figure 5. SYSTEM CONTROLLER

One of the greatest advantages of this type of system is its programmability which is very useful during early R&D testing where data sample rates, input signal ranges, and types or quantities of signals tend to change.

The following characteristics can be easily changed with a PROM driven system:

- FRAME LENGTH
- SAMPLE RATE
- SUBFRAME LENGTH
- SUBFRAME ID
- SIGNAL GAIN
- SIGNAL OFFSET
- WORD ARRANGEMENT
- FRAME FORMAT
- SYNCHRONIZATION WORD

The Weapons Instrumentation Division at Point Mugu has used the Metal Oxide Semiconductor Integration Service (MOSIS) design tools to implement several PCM controllers with high speed CMOS technology. MOSIS offers participating members several advantages in developing custom Application Specific Integrated Circuit (ASIC) systems including public domain design tools and quick prototype foundry services (usually less than 6 weeks). These controllers have the capability of inserting sync patterns, frame format indicators, subframe ID, frame count, and new/old data flags into the PCM stream as well as controlling the analog, discrete, and digital subsystems. The devices cost about $100 in small untested quantities and much less in large quantities. In one application, a 94 analog channel, ±2% accuracy, 2.4 Mbit/sec PCM system was implemented for a production cost of less than $3000. The entire system occupies less than 5 cubic inches.

CONCLUSION

High accuracy, low volume, inexpensive PCM encoder systems can be produced by integrating the encoder function into the system digital design. The system can be easily tailored to satisfy changing input sample rates or voltage range requirements by making use of PROM driven gain, offset, and multiplex address techniques. High analog accuracies are obtained by controlling resistor ratios without using high precision unique values.