The term conversion equipment is used here to denote devices which either express analog quantities in pulse-coded digital form or express pulse-coded digital data in analog form. These devices are called coders and decoders, respectively.

Conversion devices may handle a variety of variables which can represent such quantities as force, displacement and its time derivatives, angular rotation, pressure, pH, etc. Direct conversion between these quantities and their pulse-coded digital equivalents is frequently not feasible. By use of suitable transducers, all analog quantities are usually expressed either as a shaft rotation, a linear displacement, or a voltage. These are the only three forms of analog quantities to be considered here.

Problems in the design of conversion equipment arise from two areas. The first area consists of the usual over-all system requirements pertaining to reliability, size, environmental conditions, available power supplies, etc. The second area includes the following considerations which are peculiar to the conversion equipment: type of pulse coding, complexity of equipment, conversion time, accuracy of conversion, and holding ability. The discussion to follow will be restricted to the second area and will outline possible solutions to problems arising from it.

Type of Pulse Coding

The type of pulse coding used in a conversion device is either binary or decimal. Binary representation is more advantageous when the amount of equipment is to be kept to a minimum, but leads to more difficult interpretation when human observation is required. For example, when the problem is to design a converter which measures the ordinates of a curve and tabulates them through use of a typewriter, it is hardly practical to use binary representation. When, on the other hand, the problem consists of designing conversion equipment for a fully automatic control system, binary representation is indeed more practical.

In some cases, it is very helpful to use a modified binary code in which only one digit changes in the transition from one number to the adjacent number. For discussions of modified binary codes, also called cyclic or reflected, and translating circuits between modified and natural binary codes, the reader is referred to papers by members of the Bell Telephone Laboratories and the Moore School of Electrical Engineering.

Regardless of the number base used, the pulse-code pattern may be of serial or parallel form. Which one of the two forms to select for design is not necessarily determined by whether a serial or parallel computer is used. Well-perfected shift registers are now available which can be inserted between the conversion equipment and the computer, so that serial-to-parallel
translation can be reliably accomplished. The use of shift registers does, however, add to the system complexity and can be justified only if an overall improvement in performance results.

**Complexity of Equipment**

When many conversion devices are used in the same system, equipment complexity can be reduced by time-multiplexing techniques. The conversion process is then carried out in two steps, with the equipment necessary for one of the steps common to several of the conversion devices.

As an example of a multiplexed system, consider the shaft-to-digital converters shown in Figure 1 in block diagram form.\(^3\) Only four inputs are drawn, but many others could be added.

The first step in the conversion consists of generating a pulse pair, the time interval between which is a linear measure of the shaft rotation. Consider Shaft 1, which is connected to Control Transformer 1 (CT1). Its stator is excited by three sinusoidal voltages displaced 120 degrees in phase. The resulting rotating flux field in the air gap induces a rotor voltage, \(E_R\), the phase of which, with respect to one of the stator voltages, \(E_S\), is linearly related to the shaft rotation. PG1 and PG5, which are pulse generators, give an output when positive-going zero crossings of \(E_R\) and \(E_S\) occur. Just as the interval between zero crossings is linearly related to the shaft rotation, so is the time interval between output pulses from PG1 and PG5. The desired pulse pair is thus obtained.

The second step in the conversion consists of measuring the time interval between the two pulses. This is done by counting clock pulses. Pulse Generator 5 starts the flow of clock pulses to the counter and whichever of the Pulse Generators 1, 2, 3, or 4 has been selected by the switch stops the counting action. The contents of the counter indicate the shaft rotation and are read by the computer. The equipment common to all the channels consists of the three-phase sinusoidal voltage generator, one pulse generator, the switch, and the counter and its associated flip-flop and gate.

The design of the switch poses no unusual problems since it handles only pulses. This would not be the case if the control-transformer voltages were to be switched and explains why it is considered preferable to use one pulse generator in each information channel.

**Conversion Time**

In a time-multiplexed system such as the one shown in Figure 1, the number of signal channels which can share the common equipment is limited by considerations of conversion time and required sampling rate. The conversion time, \(r\), is the time required to develop the equivalent of the quantity being coded or decoded. In the example of Figure 1, the conversion time may be as long as one period of the sinusoidal control-transformer excitation. (To simplify the discussion, it is assumed that the computer requests a shaft reading in synchronism with the zero crossing of the reference sinusoid.) If it is assumed that each shaft can be sampled at the same rate, \(r\), it follows that the number of channels, \(n\), which can share the common equipment is
A numerical example may be helpful here. Assume that it is required to resolve the shaft rotation in Figure 1 to one part in a thousand. A clock frequency of 2 MC is to be used. Hence it will take 0.5 millisecond to count to 1000, the largest required number. The period of the synchro excitation must then be 0.5 millisecond. Assume that the sampling rate is to be 25 per second. Equation (1) is then satisfied when \( n = 80 \). One may be tempted to increase the number of channels which can share the common equipment by increasing the synchro excitation frequency. But increasing the excitation frequency also requires increasing the clock frequency, if a given resolution of the shaft rotation is to be maintained. The maximum operating rate of practical counters does not permit clock rates much in excess of 2 MC.

Generally speaking, the conversion time required is a function of the elements used in the equipment and the basic conversion techniques employed in its operation. All-electronic converters achieve the lowest conversion time, which may range from microseconds to milliseconds. The upper part of this range is typical of devices in which a counting action is involved. The lower part of the range is typical of devices in which a parallel number is converted into a voltage amplitude. Converters in which electromechanical or mechanical elements are used will have conversion times ranging from tens of milliseconds to seconds.

Accuracy of Conversion

The achievement of high accuracy in the performance of conversion equipment poses the greatest problem to the designer. This is not surprising, since a part of any conversion device consists of analog equipment and is therefore subject to the usual accuracy limitations of analog equipment. These limitations are particularly severe when magnitudes of electrical voltages or currents denote the information. In analog equipment other than laboratory devices, accuracy of a voltage level to one part in 1000 is considered good. Hence conversion devices between voltages and pulse-coded numbers cannot, in practical cases, be expected to have accuracies much better than one part in 1000. Where the system is such that voltage levels represent the information at the input to a coder or voltage levels are required at the output of a decoder, this maximum possible accuracy does not pose a grave limitation, since whatever data processing precedes the coder or follows the decoder will have comparable accuracies.

However, if the system is such that the input to the coder is, for example, a shaft rotation, or the output of the decoder is required to be a similar mechanical displacement, the use of voltage levels in either conversion device may lead to unsatisfactory results. Mechanical displacements are frequently handled with an accuracy at least one order of magnitude better than electrical voltage levels. To achieve the full accuracy which the mechanical units in the system can exploit, properly designed conversion devices cannot involve parts which make use of electrical voltage levels, unless these parts are placed inside a closed loop. Such a loop is illustrated by the block diagram of Figure 2, which depicts a decoder having a shaft rotation as the output. In the feed-forward section of the loop, the error, expressed in
digital form, is converted into a voltage amplitude by the decoder. The amplified output of the decoder energizes the motor which drives the output shaft. In the feedback section of the loop the shaft rotation is expressed in digital form by the coder. The loop is closed by the subtractor which compares the digital command with the digitally-coded response. In this block diagram, the entire burden of accuracy is placed on the coder, and the expected shortcoming of the digital-to-voltage decoder does not limit the accuracy to which the output shaft may be positioned.

Suitable coders for use in Figure 2 have been developed. One embodiment is the well-known coding wheel. A recent design of a coding wheel with a diameter of about 10 inches has an accuracy of better than one part in 30,000. Still higher accuracy could be achieved if larger disc diameters were to be used, but the system would become more unwieldy.

At the present state of the art, coding wheels appear to be among the most accurate coders developed. Except for alignment difficulties in the reading equipment, their output is free from drift, and their accuracy is limited only by mechanical tolerances in establishing the code pattern. Through the use of closed-loop systems such as the one shown in Figure 2, coding wheels may be used in the design of decoders as well as coders, leading to devices comparable in accuracy to any but the very highest precision mechanical devices.

The high accuracy of conversion is achieved in a system of the type illustrated in Figure 2 at the expense of substantial complexity of equipment. If accuracy of one part in 30,000 is desired, a fifteen-digit reading system at the code wheel and a fifteen-digit subtractor must be supplied, in addition to the elements in the feed-forward section of the loop.

In some cases a saving in equipment can be achieved by using an incremental system, i.e., a system in which the command does not tell the shaft where to go with respect to an arbitrary reference point, but with respect to the point where the previous command has left it.

An illustration of an incremental system is given in Figure 3, which shows the decoding servomechanism used in the M.I.T. Numerically Controlled Milling Machine. The input to the loop consists of a pulse train containing a number of pulses equal to the number of angular units through which the shaft shall turn. The unit of angular rotation chosen in this illustration is one degree, so that when, for example, the shaft is to turn 90° clockwise, 90 pulses are impressed on the upper command input to the reversible binary counter. Each command pulse is added to the contents of the reversible binary counter. An increase in the contents of the counter from normal, which is a number one-half the capacity of the counter, results in a positive voltage output from the coder and, through the amplifier and motor, in clockwise rotation of the output shaft. For each degree of rotation of the output shaft, a pulse originates from the coder on one of two lines, depending on the sense of the output rotation. For clockwise rotation, assumed in this example, the feedback pulses appear on the lower line from the coder and cause the contents of the counter to decrease. When the number of feedback pulses equals the number of command pulses, the reversible counter returns to normal, the decoder output is zero, and the output shaft comes to rest. When counter-
clockwise rotation of the shaft is desired, the command pulses appear on the lower input line and the feedback pulses on the upper line from the coder. The coder consists of a wheel containing a commutator-like arrangement of alternate conducting and non-conducting segments which, in conjunction with interpreting circuitry, allow one synchronizing pulse to pass to one of the output lines for each degree of shaft rotation. The need for synchronizing pulses, which are arranged never to coincide with command pulses, arises from the fact that the reversible counter cannot add and subtract simultaneously and hence cannot handle command and feedback pulses at the same time.

When the long conversion time inherent in a system like that shown in Figure 3 is tolerable, the use of an incremental system of this type can give a very satisfactory design with moderate amounts of equipment. In the M.I.T. machine, 17-digit binary numbers can be handled, and yet a six-stage reversible counter and a six-stage decoder suffice. The amplifier and motor are of the usual instrument type. The code wheels used in the coders have mechanical pulse pickups, but photoelectric or magnetic pickups of equivalent functional performance can be developed and will probably lead to higher reliability. The interpreting circuitry associated with the code wheels consists of three flip-flops and six coincidence circuits.

A similar incremental system, the output of which is a linear motion, derives its feedback by counting the number of optical grating lines which pass a reference point. Resolution to a fraction of a thousandth of an inch can be readily achieved in a practical system.

It should be noted that, unless special provisions are made, errors in an incremental system are cumulative. Thus if, in Figure 3, the coder fails to give an output pulse for every degree of shaft rotation, the missing feedback pulses will result in misalignment of the output shaft and this misalignment will perpetuate itself until the shaft is reset, either manually or by means of a supervisory circuit.

It has previously been emphasized that where high conversion accuracy is required, voltage levels must not be relied upon as a basic measure. The examples of high-accuracy converters cited have been shown to derive their high performance from optical gratings, coding discs, or wheels. Assuming properly designed and aligned reading circuits, the conversion accuracy depends only on the accuracy with which the lines or code patterns have been laid out. Mechanical tolerances thus determine the conversion accuracy. But while mechanical tolerances can be made to be small, equally small tolerances can be achieved electrically in the control of time or frequency, without recourse to specialized laboratory equipment. Thus designs of conversion devices which use an electrical measure of time as the accuracy-governing factor can be expected to result in high accuracy. No such devices appear to have been announced to date.

Holding Ability

Whenever a digital computer is used in a control system, a sampled data system results. With respect to the computer output, this means that the results of the computations are available not continuously in time, but at discrete values of time. In the interval between outputs from the computer,
the decoder must be capable of remembering what the last output from the computer has been. We say that the decoder must have a holding ability.

One way to achieve holding ability in the design of a decoder is to incorporate a storage register into which the computer inserts its output. A storage register from which information can be read out continuously is required here. At the present time, such a register is still somewhat difficult to realize when operating speeds are too great for electromechanical devices, and the number of electron tubes must be limited.

Another way to achieve holding ability is to store the output of the decoder in analog form. Where voltage is the analog quantity, one might use a condenser for storage. Where shaft rotation is produced by the decoder, one might mechanically clamp the shaft. But very often storage in analog form is not satisfactory.

A third way to achieve holding ability involves storage in the time domain. The number to be decoded is first converted into a linearly related time interval. This time interval is then remembered. Simultaneously, the time interval is continuously converted into a voltage amplitude.

The block diagram for a decoder in which holding ability is achieved in the time domain is outlined in Figure 4. The upper part of the figure shows how the number is converted into a pair of pulses, the time interval between which is proportional to the number. The computer presets the counter to the nine's complement of the number to be decoded. The computer then starts the flow of clock pulses to the counter through the gate circuit marked G. When the counter has been filled, an end-carry pulse will appear at its output, which stops the further flow of clock pulses. The time interval, T, between the start pulse and the end-carry pulse is linearly related to the number to be decoded. Next, the pulse pair is held and converted into a voltage amplitude. The method involved there is shown in the lower part of Figure 4. The memory function is accomplished by the delay elements which are adjusted to have equal time delays, , and which are closed upon themselves. After the delay elements are cleared by the computer, a start pulse is generated. This pulse emerges seconds later from Delay 1, and every seconds thereafter. Seconds after the start pulse an end-carry pulse appears at the input to Delay Element 2, where it emerges seconds later and every seconds thereafter. Thus at time , , ... there is an output from Delay Element 1, and at time , , ... there is an output from Delay Element 2. For every pulse on its upper input line the flip-flop is set to the 1 position and for every pulse on its lower input line, the flip-flop is set to the 0 position. Thus the flip-flop is in the 1 position for every seconds out of . Since is a linear measure of the number to be decoded, so is the duty-cycle of conduction of the 1 tube in the flip-flop. It only remains to remove the d-c component of the waveform at the plate of the 1 tube, which is accomplished by the low-pass filter. This completes the conversion process. It should be noted that the equipment in the upper part of Figure 4 may be shared by several channels. Each channel contains the equipment in the lower half of the figure and is connected to the common equipment by a switch.

Several devices may be used for the delay elements. In one application of this scheme, tracks on a magnetic storage drum are employed. This is
a particularly useful approach when the basic computer already contains a magnetic drum.

Summary

Some of the remarks made in the previous sections may be summarized as follows:

In designing conversion equipment for systems containing several signal channels, over-all equipment complexity can be reduced by time-sharing part of the converters between several channels. The number of channels which can share the common equipment is limited by the conversion time and the required sampling rate.

Accuracy is easiest to obtain by using time as a reference in an electrical system, or displacement or rotation in a mechanical system. An incremental system employing simple equipment can achieve high accuracy, but long conversion time results. Closed-loop techniques permit the use of a conversion device to its fullest accuracy as either a coder or a decoder.

In the interval between outputs from the digital equipment, decoders need to remember the previous output. This holding ability can be achieved conveniently in the time domain.

References

Fig. 1. Shaft-to-digital converters

Fig. 2. Closed-loop decoder

Fig. 3. Incremental decoder

Fig. 4. Decoder with holding ability