A High-Speed Transistorized Analog-to-Digital Converter

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Synopsis: With an increase in the use of digital techniques in the fields of instrumentation, data handling, and control, there has been an ever-increasing need for high-speed high-precision, analog-to-digital and digital-to-analog converters.

This paper describes a fully transistorized, reversible, high-speed data converter using the programmed successive approximation technique. Accuracy of 0.05% is obtained in an 11-bit binary encoder, 0.03% in the corresponding decoder. This technique is outlined in some detail as it pertains to the transistorized system.

Conversions are performed at 5 microseconds per bit or 16,000 conversions per second for an 11-bit binary code. Sign is automatically determined and the absolute value of the voltage encoded. A low-voltage reference is used and is electronic-chopper stabilized. The digital-to-analog conversion problem and high-accuracy high-speed techniques using transistor switches are discussed. A number of converter applications are shown.

Finally, over-all system performance of transistorized converters are compared with available vacuum-tube equipment. These techniques are outlined in some detail as it pertains to the transistorized system.

This paper describes a high-speed solid state converter having a conversion rate of 5 microseconds (usec) per bit or 16,000 analog-to-digital conversions per second at an accuracy of ±0.05%. The converter can operate at an 11-bit binary or 13-digit binary coded decimal (3 decimal digits and sign) by simple interconnection of one card. Stability of all circuits obviates need for zero adjusts or calculation knobs. Both internal and external reference voltages are provided for, and any conversion rate, up to the internal 200,000 bits per second, allows synchronization of the serial output to external tapes, drums, or data transmission systems. After a discussion of the problem the converter will be described, then review a few of its many applications.

The many techniques for analog-digital conversion can be classified into three basic types, a sweep, step counter, and successive approximation method. All these basic techniques are widely covered in the literature, so only a brief summary will be given here. The sweep technique compares the unknown voltage with a linearly varying voltage and stops a counter when the two are equal. The step counter approach utilizes a forward-backward counter which incrementally adjusts a known voltage to match the unknown. The third basic method the successive approximation technique in which the unknown voltage is compared first with one half full scale, then with one quarter full scale, and so forth.

The sweep technique has the apparent advantage of minimum equipment, but its speed is greatly limited. The step counter has advantages when examining

Mr. Glasses: What speed is available on the high speed digitizer?

Mr. Marker: Three units can be used for various speeds. One is the Epsco Transicon, which operates at 16,000 readings per second. There are two other designs which operate at 100 and 1,000 readings per second for a 10 per cent change of the input voltage. The accuracies for these two latter types are 0.1 and 1.0 per cent respectively.

Mr. Bills: Are there any provisions for dynamic testing, for example, a response to a step function?

Mr. Marker: A module is being developed for waveform digitizing using an analog sample-and-hold technique where analog storage of the samples is employed.

W. Brandt (International Business Machines Corporation): What is the character rate of the paper tape input and output?

Mr. Marker: Most generally, mechanical readers and punches are employed whose reading and punching rates are 20 and 10 per second, respectively. The programmer is adaptable to photoelectric reading at a rate of 600 characters per second. It is possible, although there is no existing requirement, to use commercial high-speed punches for output tapes whose punch rate is 800 per second.

C. S. Lin (M.I.T. Lincoln Laboratories): Is the 20-ke clock rate, the clock rate or the operating rate?

Mr. Marker: It is the average speed of the flip-flops and other logic circuits in APAR. The device is asynchronous, so it is difficult to specify an operating rate that is meaningful.

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incremental changes or following a slowly varying voltage but suffers greatly in terms of speed when operating on multiplexed or discontinuous inputs. The successive approximation technique is able to handle the highest rate of independent conversions; every conversion requires a precisely known period of time, and when all is considered, seems competitive in amount of equipment required. A transistorized successive approximation technique was selected as offering an optimum combination of reliability, low cost, and speed of operation.

**System Description**

Fig. 1 illustrates the Transicon Datrac converter. A block diagram of this converter is shown in Fig. 2. An absolute value input amplifier buffers the input to an impedance level suitable for matching into the comparator. The comparator always sees a positive voltage independent of actual input polarity except during the sign decision interval. An external or manual start pulse clears the register of the previous number and starts the conversion process. An analog voltage is generated by a programmed sequence of events determined by the control circuitry, the programmer, and the register. These set analog current switches which stimulate the analog signal into the comparator. These current switches form a digital attenuator, accurately attenuating the reference supply to the appropriate digital representation of the code in the register. The comparator is interrogated by the control circuitry at a 200-kc rate and a reject pulse is generated if the input current from the switches is greater than the current from the input amplifier. At the end of a conversion, the control circuitry is turned off and an end of conversion pulse is provided at the output.

The basic internal reference is a IN430A Zener diode controlling a 0.015% high-precision solid-state voltage regulator. An external reference can be substituted if desired. Both serial and parallel digital outputs are provided which are capable of driving external loads without buffers.

**Digital Attenuator**

Since the digital-analog converter is the heart of this equipment and strongly influences the design of its other components, it will be discussed first. Prior to discussion of the specific technique used, a discussion of semiconductor switching is in order.

Two basic methods of switching are shown in Fig. 3. For purposes of discussion, they have been called current and voltage switching.

In simplest terms, current switching implies a constant current in the resistors of the digital attenuator (D-A) network, the switching function only determines which of the available currents are selected as the output and which are shunted into a current sink. Voltage switching is the term applied to the case in which the voltage applied across the summing resistors is switched, while the resistors themselves remain tied permanently to the output.

The current switching method is the one most commonly used with vacuum tubes. If points A, B, C, and D are high with respect to the summation point, current is drawn from each leg according to the ratio of the resistors. If any of the inputs A, B, C, or D, are negative with respect to the summation point, the current in that leg is shorted out and that switch is opened. This is a simple switching scheme although it necessitates the careful selection of diodes or the use of trimming resistors.

A severe disadvantage appears when this scheme is used with solid-state switching devices. The dependence on temperature of the voltage drop across semiconductor diodes, together with their changes in life result in a high reference voltage requirement. Assuming a temperature coefficient of 2 millivolts per degree centigrade (C) and a temperature differential of 40 C, the total uncertainty in voltage drop is 80 millivolts. For 0.05% accuracy, this necessitates a reference supply of 160 volts. Even with the best commercially available silicon diodes, temperature plus life changes imply a reference voltage awkwardly high for a solid state regulator to handle.

If the diodes in Fig. 3B are replaced with germanium transistors in order to improve the quality of the switch, new problems arise. Assuming a leakage current of 0.3 microampere (μa) at 25 C and a maximum operating temperature of 50 C, for 0.05% accuracy, full scale current must equal 30 milliamperes (ma). If used in an A-D converter, this would place severe requirements on the comparator and on the input buffer, and would set impractically high power levels in all the associated circuitry.

Voltage switching, on the other hand,
allows a much smaller reference supply voltage to be used. The drop across the switching transistor can be made very small; for example, it is practical to design switching circuits in which the drop from emitter to collector is less than 2 millivolts essentially independent of temperature. This allows use of a 20 volt reference with switching accuracy of 0.01%. Because of the use of two transistors in push-pull, the summing resistor is clamped either to ground or to the reference supply, depending on whether the switch is “on” or “off.” As a result, leakage current in the off transistor ceases to be a problem since the cutoff transistor always leaks into a conducting transistor. Comparing the impedance of the conducting transistor to that of the summing resistor, it can be seen that the leakage current is attenuated by a factor of at least $2 \times 10^4$. The principal limitation of the voltage switching scheme seems to lie in the breakdown voltage of the transistors used as the switches (they must stand the full reference voltage plus a margin) and their minority carrier storage characteristics which determine maximum switching rate. Both these factors prove to be tolerable with several available transistor types.

A voltage-switched network of the type shown in Fig. 3(D) is also a digital voltage attenuator with respect to the reference voltage, and obviously displays a constant output impedance. Fig. 4 shows the Thevinin equivalent of switch. Fig. 4(C) shows the valid equivalent circuits for a network of this type. When operated into a short circuit or low impedance load, the Thevinin transformation of Fig. 4(D) may be a more useful equivalent.

The constant source impedance property of the digital attenuator makes it a particularly desirable digital-to-analog converter. When the Transicon Datrac converter is operated in the reverse mode, D-A, the digital attenuator may drive the output directly, without buffering, and delivers a current which is exactly proportional to the digital setting of the register regardless of the magnitude of the resistive load. For bipolar outputs, the absolute value amplifier is used as an output buffer. Digital-analog accuracy is ± 0.05%.

The Transicon digital attenuator, Fig. 5, was set to operate with a reference of 16 volts for binary systems. In decimal systems, $16^{-1/3}$ volts is used, giving a Thevinized 10-volt full scale. The digital attenuator is summed with the input into the comparator.
The solid state comparator is of the pulse amplifier type having a sensitivity of a fraction of a millivolt. When interrogated, it supplies a reject pulse if the sum of the input voltage and its internally generated analog is less than zero. Long term drift of this comparator is ±1 millivolt without any calibration or adjustment. Freedom from calibration is an essential feature in any equipment which must operate in a large system over a long period.

**Programmer**

A specially designed magnetic programmer was used in the converter. Essentially, it is a magnetic ring counter using a square-loop blocking oscillator per stage. It has two principal advantages. One is low cost due to the use of only one core and one inexpensive transistor per bit. The second is the use of magnets which permit permanent storage. This enables the converter to operate at any repetition rate from 0 to 200kc. This feature is particularly useful when the serial pulse output is required to be synchronous with the users clock, as for example, in a magnetic drum or tape system.

The reference supply, Fig. 6, is a ±0.015%-precision, solid-state chopper stabilized operational amplifier having an output impedance less than 100 milliohms. In addition to providing current to the encoders, the reference is available externally. If desired, an external reference supply may be switched in for ratiometer measurements.

**Absolute Value Amplifier**

Several methods of achieving bipolarity in an essentially unipolar converter are shown in Fig. 7. One method is to offset the input amplifier so that ground-in equals half full-scale output. With this method, plus and minus full scale input equal full scale and ground output. This results in complementary outputs for negative inputs and proves disadvantageous for some applications.

Another method of bipolar operation is to switch the polarity of the reference supply, depending on the sign of the input. One means of doing this is shown in Fig. 7(B). This involves diode switching with the associated stability problems. Other schemes are available but all involve the use of two reference supplies with the associated switching problems.

In this, unit bipolarity is achieved by the use of an absolute value amplifier. This involves two cascaded stages of chopper-stabilized operational amplifiers, with the output of the first or second switched to the comparator according to the sign of the input. Use of a transistor switch allows the comparator input to be stabilized within 10 usec after a change of amplifier input polarity.

**Modular Construction**

The Transicon Datrac is modular in design. Fig. 8 provides an interior view of one standard model. The use of standard printed-circuit building blocks enable the user to expand his system as the need develops. An 11-bit binary converter can be converted to a 3-decimal digit converter in a matter of hours.

**Transicon Datrac System Applications**

The modular and flexible basic design of the Transicon Datrac converter allows...
it to perform a wide variety of arithmetic control, and data processing functions as well as the normal digital-analog and analog-digital conversions. Four examples are blocked out in Figs. 9 through 12. They are "limit monitoring," "square root generation," "span control and linearization," and "analog multiplication."

In the limit monitoring operation, Fig. 9, the digital attenuator is slaved to a digital signal representing the desired limit, and continuous comparisons at 100 kc are made between the number and the input. An alarm pulse is provided when the input exceeds the specified value. A single converter could monitor 100 independent signals at 1,000 samples per second, using multiplexed inputs and plugboard or toggle switch stored constants.

Fig. 10 illustrates a square root generation technique. A feedback analog voltage is generated which is proportional to the square of the number in the register by cascading two digital attenuators both of which are identically controlled by the register. Since the operation of the converter forces the feedback to agree with the input, the number generated during conversion in the register (x) must be proportional to the square root of the input (x²). This mode of operation may be alternated with normal conversion by switching the additional digital attenuator.

Fig. 11 shows a combined setup for span control and linearization. Zero suppression and scaling are performed in the converter input amplifier. Linearization is accomplished by a two-pass conversion. On the first pass, the raw correction increment is selected; the second pass results in conversion of the corrected voltage. The correction is selected by the most significant bits resulting from the first pass. These bits are applied either to a small external memory which yields the correction, or are decoded and applied as a selection voltage in a simple potentiometer or toggle switch "memory." The great advantage obtained from this technique is that the correction for each interval may be independently selected, making linearization of complex functions nearly as simple as that of monotonic functions.

Fig. 12 shows an analog multiplier which simultaneously digitizes the multiplicand. In the form shown, the multiplier is able to digitize large amplitude complex waveforms where frequency components are below half the sampling rate, or 8 kc. If a forward-backward counter is substituted for the registers shown, (a single counter can replace both registers and the gating), signals with frequency components up to 200 kv may be followed. Because the maximum rate of change of the counter is 200 bits per millisecond, a full scale excursion for a counter-multiplier requires 10 milliseconds.

Comparison with Vacuum-Tube Converters

As the use of digital techniques increases, there will be a need for more and better converters. Transistorized converters have advantages which will enable them to capture much of this market.

During the past few months, not only Transicon but also some of the other available equipment have been evaluated. Based on these tests plus information gained elsewhere, a comparison can be made between equivalent vacuum tube and transistorized converters.

At present, the transistorized converters are somewhat slower than the fastest tube converter, the Datrac. However, there is no intrinsic reason why a transistorized converter could not be operated as fast. The accuracies of the two systems are comparable. The Transicon requires approximately 15% of the volume and weight and 10% of the power consumption of its tube equivalent. The reliability of the Datrac has been proved in over 1,000,000 hours of field operation. Transicon is expected to do as well. Finally, there is the question of cost. Despite the somewhat higher cost of transistors, the transistorized converter is substantially less expensive than an equivalent tube converter. This results from savings in power supply, metalwork, assembly, and simplified circuitry which solid state techniques afford. The next year should witness a definite increase in the use of transistorized systems in the converter field.

Discussion

J. A. Gariocchi (Radio Corporation of America): What are the maximum and minimum values of the ladder resistors in the digital attenuator and how accurate are they?

Mr. Bothwell: The smallest resistor is approximately 13,000 ohms. Accuracy is 0.02 per cent.

The largest resistor in the digital attenuator is about 700,000 ohms, and this is about as large as practical to build in the allowed space.

The accuracy required of the precision resistors, of course, decreases in proportion to their binary weight and their decimal significance. The most significant digits require the greatest accuracy, and so forth.

Mr. Gariocchi: How do you maintain accuracy transistor switching for such a large range of ladder load currents?

Mr. Bothwell: The ladder design is such that the range of load current is restricted to approximately ten to one. In addition, the switching accuracy improves as the current is described so that the switch need only be designed for the largest load current.

Mr. Gariocchi: What transistor types are used in the transistor switch?

Mr. Bothwell: Without going into very specific details, a number of transistor types will give reasonable yield. The General Transistor 2N320, the Radio Corporation of America 2N5280 or 2N404, and practically any other high-gain medium-frequency alloy junction types will give switching performance in the order of magnitude that we discussed. The specific transistor we use is purchased to our specification at the moment, in order to be sure that we do not have to select. To get optimum performance, examine the equations of Ebers and Moll, and optimize the ratio of forward to reverse gain.

R. Reichard (Computer Control Company): Can you cite statistics on the reliability of the Datrac?

Mr. Bothwell: I think Mr. Reichard is asking for reliability on the Transicon Datrac. For the Datrac, we have had 300 units in the field for several years, and with the normal life time of vacuum tubes, we believe the reliability of that unit has proven to be extremely high. Definitive statistical data on commercially sold instruments is difficult to compile since the unit becomes the property of the customer after it is sold.

The Transicon Datrac reliability statistics are going to be more difficult to give. This unit has only been in production for 6 months. There is not enough live data available to be really significant there but we expect reliability at least as good as the tube equipment gave.

Mr. Reichard: Are failures largely due to the chopper and is this an electromechanical one?

Mr. Bothwell: The answer is that it is an electromechanical chopper used extremely conservatively. The requirements of it are quite modest. We believe the life of this chopper will be extremely long.

Gerald Smith (Daystrom Instruments): Could you briefly describe the type of circuit used for your "compare" functions?

Mr. Bothwell: Essentially, an electronic switch device chops the signal at the error junction between our analog feedback and our input signal. If the analog feedback is not equal and opposite to the input signal, a chopped signal results which passes through a high-gain a-c amplifier and a phase sensitive demodulator. The demodulated pulse signal is, then, the decision signal.

M. Garden (Leeds and Northrup): Is the three millivolt area of the reference supply due to drift or to loading?

Mr. Bothwell: With a 100-milliohm source impedance, we get about a tenth of a millivolt shift due to maximum loading.

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The drift which I mentioned is due to two factors. One is temperature drift of the reference Zener diode. The second factor is finite amplifier loop gain and its internal drifts. These factors contribute less than 3 millivolts from 20 to 50 °C.

Mr. Garden: Is the external reference required to have the same impedance and recovery time as the internal reference, or is an amplifier provided to match the external reference to the ADC?

Mr. Bothwell: No amplifier is provided unless specifically requested, but it can be provided.

It is not necessary to have quite so low a source impedance as we have, but it is necessary to have a source impedance of less than approximately 0.3 ohms; otherwise, the accuracy will suffer to some extent. The recovery time is very necessary. This can be obtained by putting a good tantalum capacitor across the terminals of the device or across the terminals of the reference supply voltage. The Transonic is not intended to operate from high impedance reference unless a buffering amplifier is included in the equipment.

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The Trial Translator, An Automatic Programming System for Experimental Russian-English Machine Translation

V. E. GIULIANO

Grammatical and syntactic rules designed for the production of “smooth” automatic translations between human languages will be called translation algorithms. Because of the rigid constraints imposed by automatic machines, the formulation of translation algorithms involves unprecedented problems of a linguistic nature. Much of the existing literature in the field of machine translation consists of theoretical treatments of these problems, or of appropriately simplified abstractions from these problems. Several specific algorithms for the machine translation of Russian to English have been proposed, but none have been tested on a large scale. These rules are apparently based on the intuition and linguistic backgrounds of the individual writers, sometimes aided by the manual analysis of short text samples. Until very recently the use of automatic machines has been confined to the application of ad-hoc computer programs, tailored to the processing of particular sentences or carefully selected texts.

At the present time it is exceedingly difficult, if not impossible, to evaluate most of the schemes which have been proposed for Russian-English translation. This difficulty is due to the absence of any practical means for testing these schemes on large bodies of text. Many of the proposed algorithms will, doubtlessly, work in the majority of cases. There remains, however, the question of whether they are “fail-safe.” That is, do they lead to annoying but safe nonsense when they fail, or do they lead, instead, to smooth but incorrect sentences? It is possible, but highly improbable, that most of the fundamental linguistic problems connected with machine translation are already solved in the literature. At present, however, there is no way of testing the validity of this conjecture.

An automatic programming system, called the Trial Translator, is suggested in this paper for the automatic testing of translation algorithms. This system accepts, as its inputs, a set of experimental translation algorithms expressed in a suitable pseudocode language, and a large body of Russian technical text. The system applies the algorithms to the text and produces, as its output, a readable trial translation, the English text resulting from the application of the given rules to the given text. The Trial Translator contains three main subsystems, the Automatic Dictionary, the Formula Inserter, and the Specifier-Evaluator-Editor (Fig. 1).

The Automatic Dictionary

Suppose that the entries in a Russian to English dictionary are recorded on a medium which can be read by an automatic computer, say on a reel of Univac magnetic tape. A Russian text can be recorded on another reel of magnetic tape from a manual input device, say a Uni­typer. A complex of machine programs can be written for the computer, a Univac I in the example considered, which accepts these two reels of tape as inputs, and which produces a tape containing a word-by-word translation of the text as its output. Such a complex of machine programs, together with the dictionary file, will be called an Automatic Dictionary.

An automatic Russian-to-English dictionary was originally proposed by Oettinger in 1954, as a “linear approximation” to a completely automatic translating system. A concrete system of machine programs for the operation of an automatic dictionary, with Univac I equipment, was suggested by the writer in 1957. This system, forming the operating part of the Harvard Automatic Dictionary, has since been programmed and is currently in operation. A semi-automatic dictionary compilation process has been developed, and has been used for the preparation of a Russian-English dictionary file for the fields of

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*Giuliano—The Trial Translator*