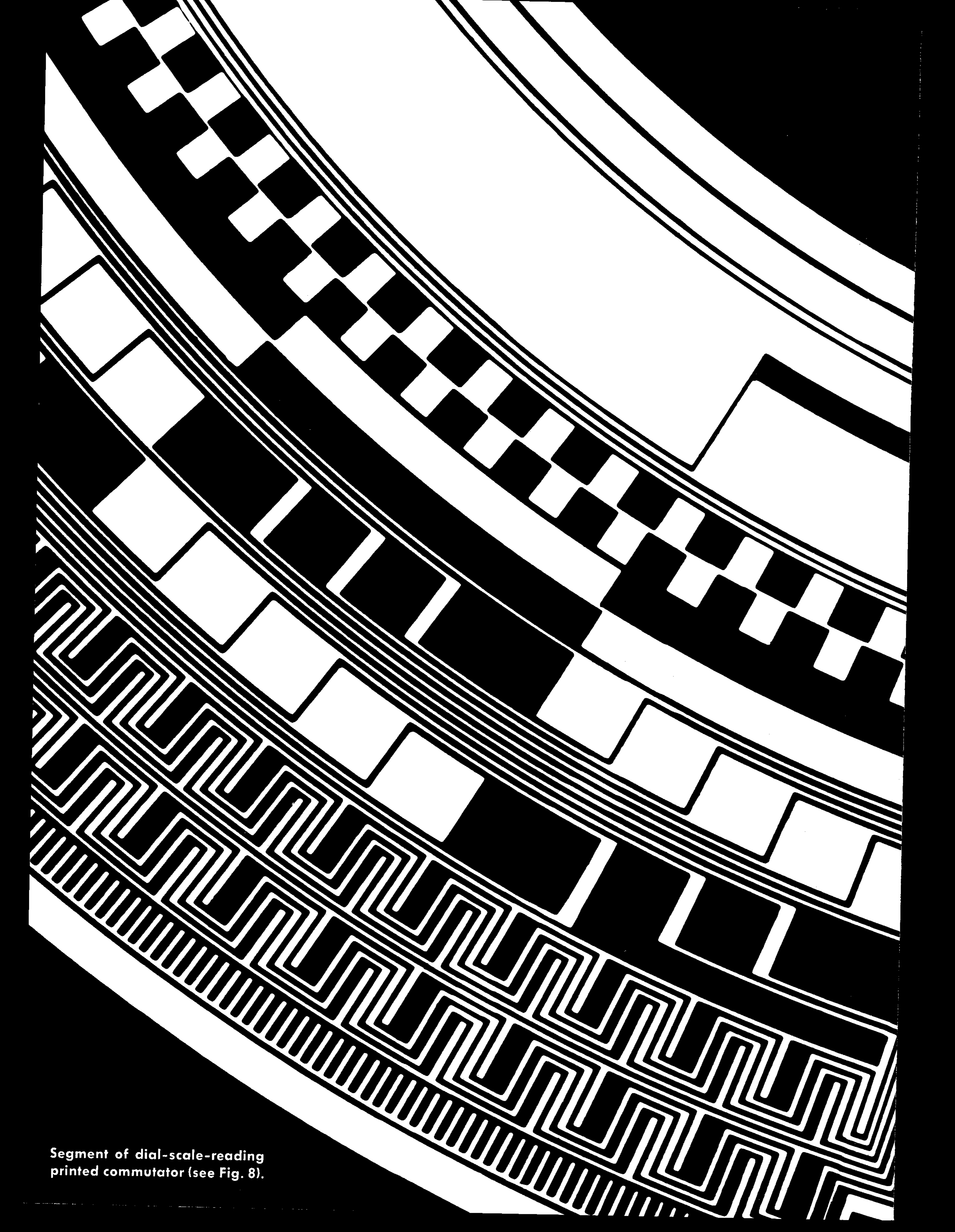


Segment of dial-scale-reading printed commutator (see Fig. 8).

C. A. Walton

A Direct-Reading Printed-Circuit Commutator for Analog-to-Digital Data Conversion

Abstract: A novel direct-readout printed-circuit commutator has been incorporated in the design of a shaft-to-digital converter system for analog-to-digital data conversion. The design avoids the use of supplementary coding or additional translation circuitry required to operate other shaft-to-digital converters. Methods are described for ensuring logical progressions of numerical data despite gearing errors and the analog nature of the input-shaft position. Some applications of the commutator are discussed.

Introduction

The conversion of analog to digital data is the necessary link between the expanding area of real-time measurement and its use in digital computing and control systems. Transformation of such physical quantities as position, weight, pressure and temperature into the common denominator of shaft displacement permits the conversion of analog quantities to the digital language of computers.

The heart of shaft-to-digital conversion systems is the shaft-mounted rotary commutator. Modern printed-circuit techniques allow the design and fabrication of complex conducting patterns which can be *read* with metal brushes to indicate relative angular position.

The actual layout of a printed-circuit-commutator pattern on an insulating board with 100 or more possible positions is, however, quite complicated. There must be a minimum of connections through the mounting board, a practical pattern line and space resolution, and a logical numerical progression.

The last requirement must be met even though, as multiple brushes gradually move over the various paths of the commutator, it is impossible to ensure that at points of simultaneous digit change, such as 19 to 20 or 299 to 300, the different brushes associated with the different-order digits will all simultaneously change their electrical connections. This failure to change simultaneously is known as the *ambiguity* problem.

Several methods have been used to resolve this occurrence of ambiguous errors in gang switching. One method is to fabricate a digital pattern on the commutator which, when read out, gives a modified binary notation known as a *reflected code.* Such a code has the unique property of changing only one bit as the commutator moves from any number to an adjacent number. Figure 1 gives an example of reflected binary coding. (Reflected decimal coding is also used.)[1,2] If all mechanical errors (brush alignment and gearing) are kept to less than one bit, incorrect number progression is impossible. Although reflected codes are usually employed only in single-disc, single-brush systems, their application has been extended to multiple-speed geared systems at the cost of an extra brush or two.

The greatest disadvantage of reflected-code output is the necessity of translating it into a straight binary or decimal code before it can be used in subsequent operations. The rule for translating the reflected-binary code in Fig. 1 to straight binary coding is: For each digit, if the sum of all the more significant bits is even, the bit in question remains the same; if the sum is odd, the bit

DECIMAL	BINARY	REFLECTED BINARY	COMMUTATOR SEGMENT
0	0 0 0 0 0	0 0 0 0 0	
1	0 0 0 0 1	0 0 0 0 1	
2	0 0 0 1 0	0 0 0 1 1	
3	0 0 0 1 1	0 0 0 1 0	
4	0 0 1 0 0	0 0 1 1 0	
5	0 0 1 0 1	0 0 1 1 1	
6	0 0 1 1 0	0 0 1 0 1	
7	0 0 1 1 1	0 0 1 0 0	
8	0 1 0 0 0	0 1 1 0 0	
9	0 1 0 0 1	0 1 1 0 1	
10	0 1 0 1 0	0 1 1 1 1	
11	0 1 0 1 1	0 1 1 1 0	
12	0 1 1 0 0	0 1 0 1 0	
13	0 1 1 0 1	0 1 0 1 1	
14	0 1 1 1 0	0 1 0 0 1	
15	0 1 1 1 1	0 1 0 0 0	
16	1 0 0 0 0	1 1 0 0 0	
17	1 0 0 0 1	1 1 0 0 1	

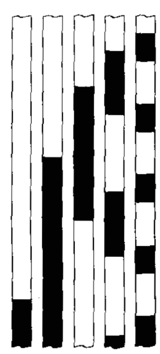


Figure 1 **Use of reflected binary code.**

is changed. Means for accomplishing this translation are an involved and expensive part of a reflected-code shaft-to-digital converter.

Another method of avoiding switching ambiguity is to read the higher-order digits with two brushes following the same physical or electrical path.[3] One brush will lag behind the other, establishing a lag-lead relationship between them. With two brushes there are, in effect, two possible higher-order digits; the lower-order digits are then able to change the higher-order value in accordance with their own transition from 9 to 0 or 0 to 9. Switching between brushes is usually accomplished by diode or relay circuitry.[4]

The disadvantage of diode or relay switching for this type of data translation is that a number of diodes or relays are required for each commutator digit. Also, since there is inadequate output current from the diode circuits, amplification is required before the commutator can drive conventional output means.

To avoid the drawbacks imposed by reflected codes or diode-relay switching, a unique direct-readout printed commutator has been designed in which the pattern of the commutator supplies the digital signal required for output-equipment operation without any supplementary circuitry. Design innovations include magnetic detenting and a lag-lead lead circuit which is an integral part of the pattern.

The commutator will be described in terms of the logic and design considerations of the final method.

Units-digit arrangement

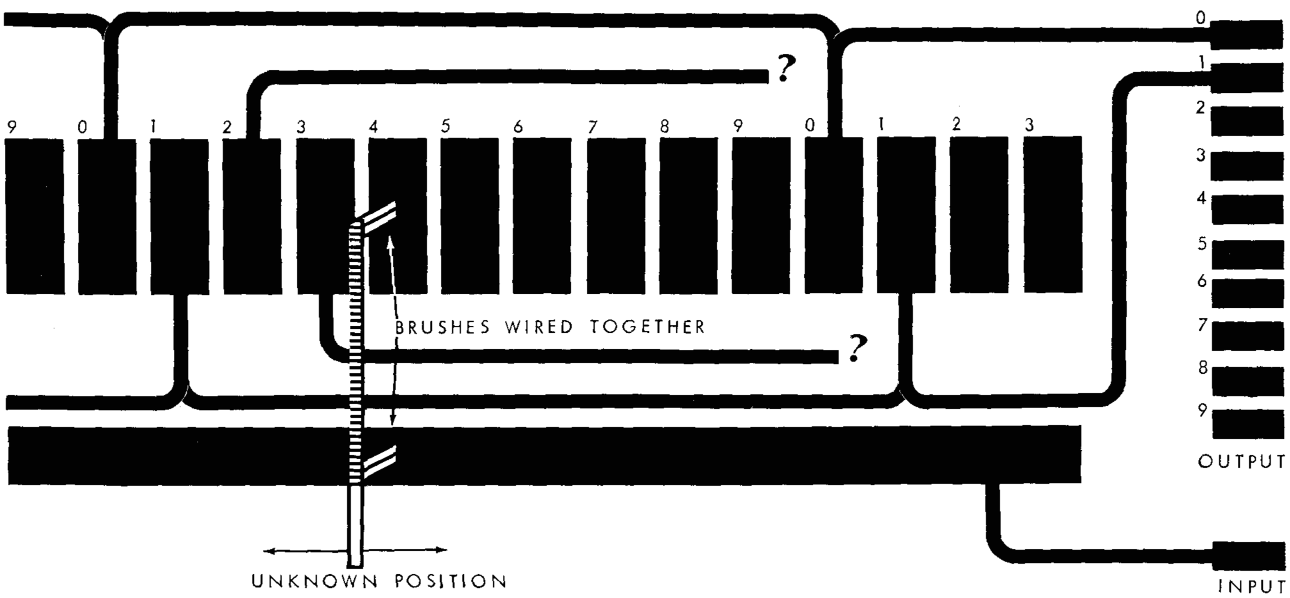
For one rotation of the converter's input shaft (or full travel of a linear-position reader) there may be typically 100 or 1000 positions. Assuming that the straight decimal code is used, then, for 100 positions around the shaft, the units 0 will occur in ten different locations, the units 1 will occur in ten different locations, the units 2 will occur in ten different locations, and so forth for all units digits. Also, all 0's must be connected to the 0 output circuit, the 1's must connected to the 1 output circuit, the 2's must connect to the 2 output circuit, and so forth.

When only two connected metal brushes are used, one for the input *common,* which is solid or always connected, and the other for making contact with all the position sectors, the above such connections are impossible in two dimensions unless one uses impractically slender connectors placed between contact points. Figure 2 shows the problem. (One solution would be to have 100 through holes and patterns on the other side of the commutator; such a scheme, however, is economically impractical.)

Any number of brushes may be used to read the printed-commutator pattern. Figure 3 shows how 11 brushes could be used to solve the problem of Fig. 2. This method obviously requires increasing the radial dimension as well as adding considerably to the brush structure. An improvement on the design of Fig. 3 is shown in Fig. 4; here a single brush does the work formerly done by two.

It is possible to read five different output conductors with only two brushes, using the arrangement of Fig. 5. Conductors 0 to 4 are read in the manner indicated by Fig. 2, and the interconnection problem is solved by returning the conductors in the 5 to 9 interval. To avoid making circuits to the 0 to 4 conductors when the brushes are in the sector where the 5 to 9 conductors should be read, the common, or input conductor, usually solid, is made blank in this sector. This input conductor is also called a *switching common,* because it

Figure 2 **The problem of interconnecting 100 segments in groups of 10 in two dimensions.**



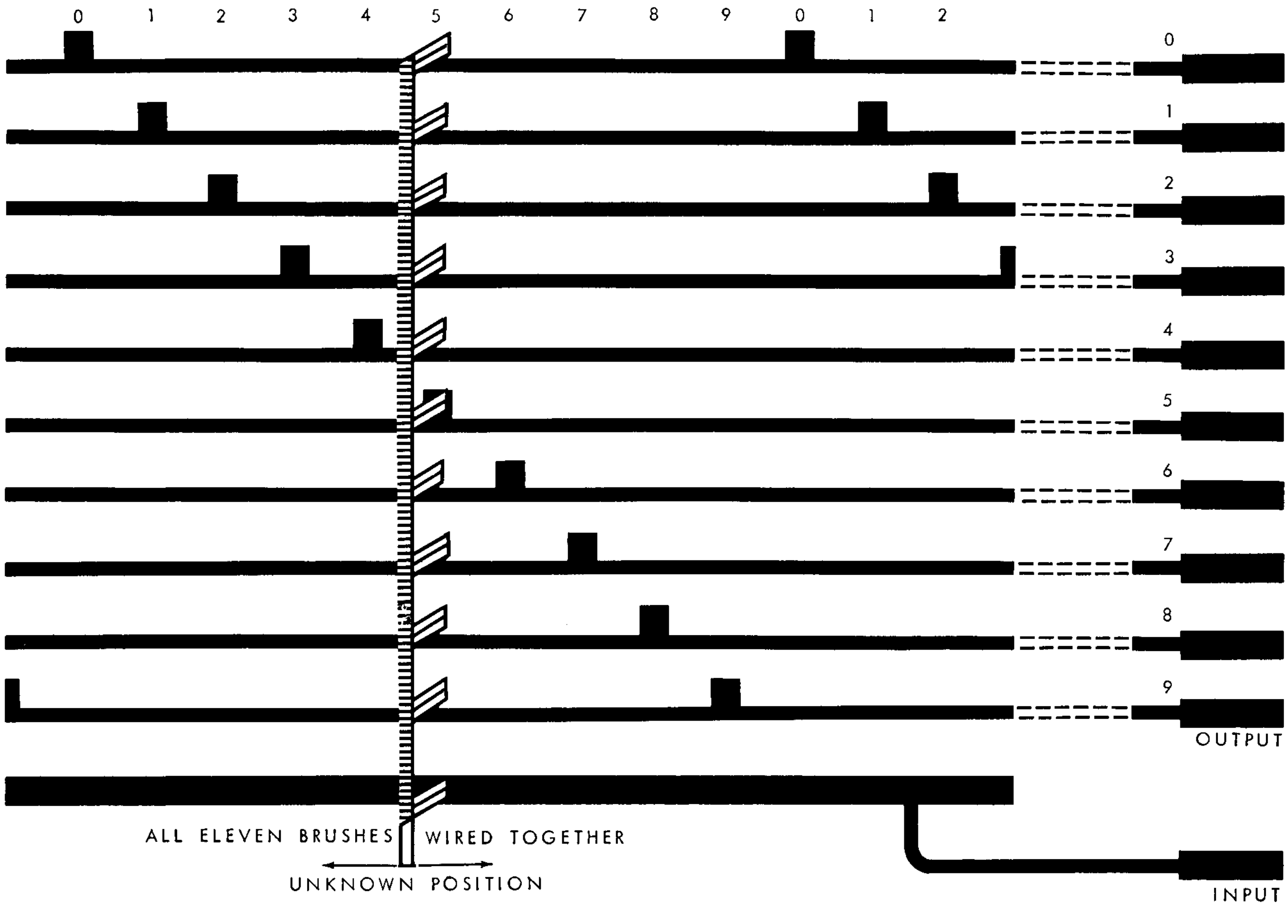
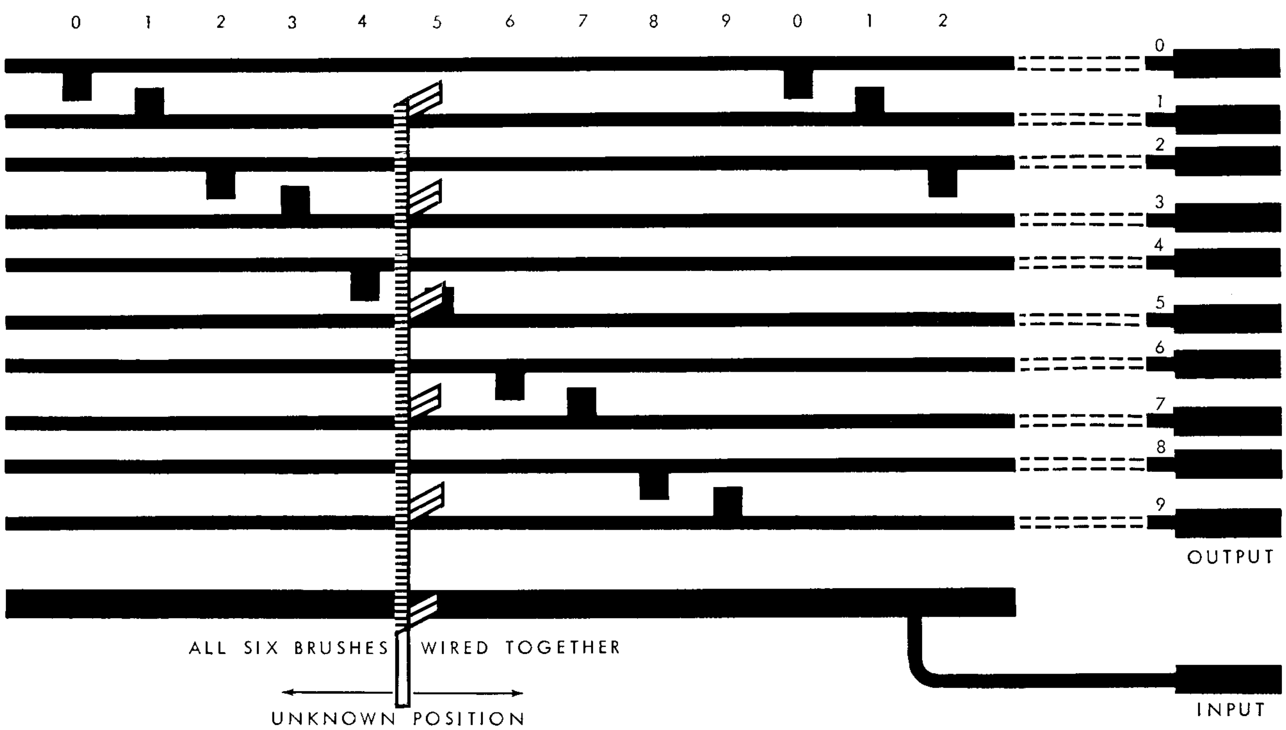


Figure 3 **Solution to commutator-design problem requiring eleven brushes.**

Figure 4 **Solution to commutator-design problem requiring six brushes.**



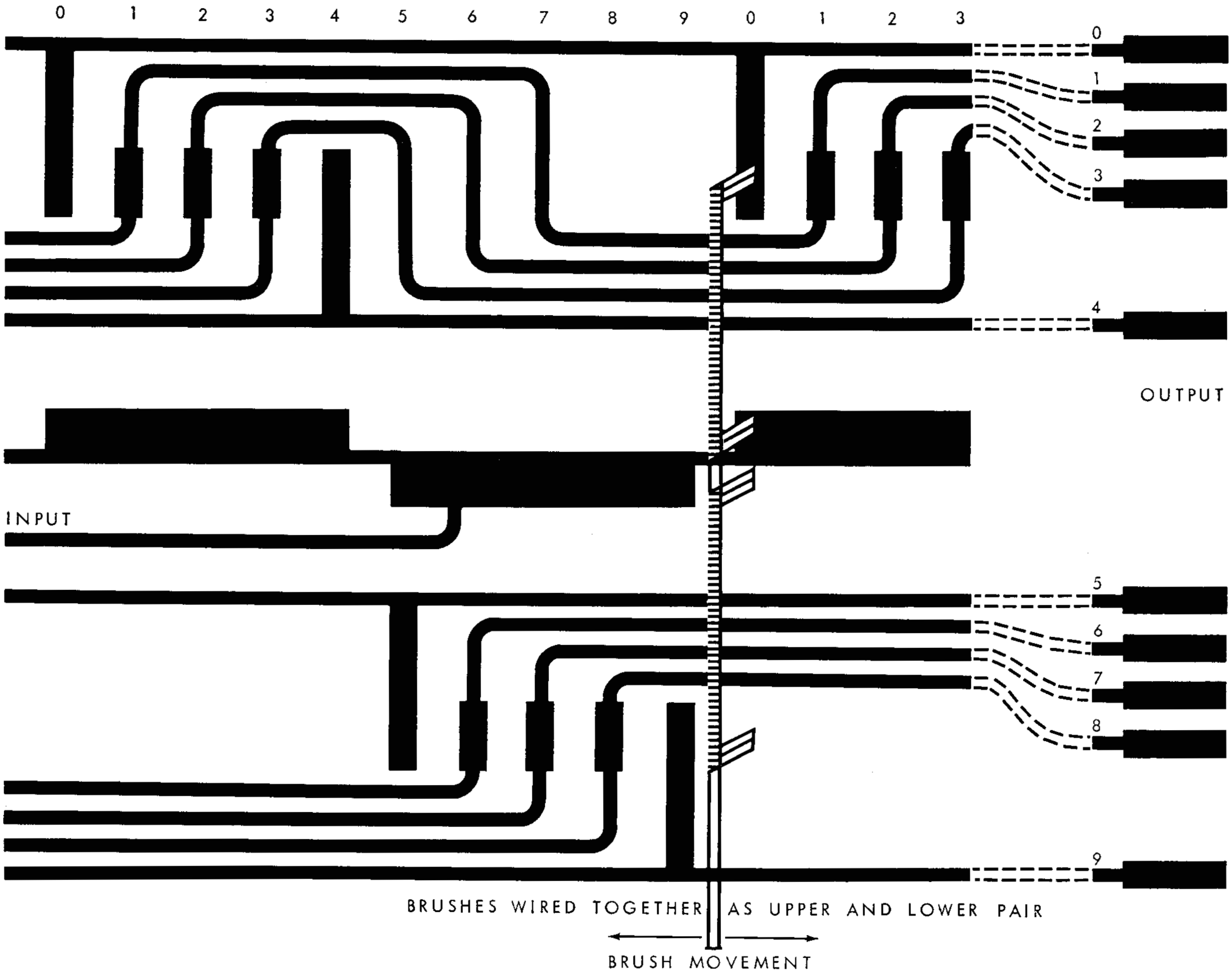


Figure 5 **Solution to commutator-design problem requiring four brushes in four tracks.**

switches off the brush-pair when the pair is in a non-working sector, that is, in a sector where the conductors are simply returning to a position where they may repeat their count.

A further refinement of the design allows a reduction of the over-all pattern radius. The units pattern repeats ten times around the shaft. It is possible to put the 0 to 4 conductors in the first 180 degrees of the units path and the 5 to 9 conductors in the second 180 degrees, and allow two pairs of brushes, riding in the same paths but 180 degrees apart, to read all the units-digit positions. The units-digit switching-common track ensures that only the proper pair of brushes is working at one time. Figure 6 illustrates this operation. Note that brush-pair *A* first reads 0 to 4 and then is cut off, while brush-pair *B,* 180 degrees opposed, reads 5 to 9. Continuity of readout is assured, since *either* brush-pair *A* or *B* may be making the 0 to 4 or 5 to 9 circuits at any time. The gain with this scheme is that only the single radius is required for one brush-pair, due to the diametral symmetry of the units digits.

Tens-digit arrangement

The tens digit is obtained by placing ten sectors adjacent to the perimeter of the units-digit configuration. Only two brushes are needed to read the tens value. The tens-digit brush track is shown at the top of Fig. 7. The tens-digit common is a simple, solid, input track and is not shown. Note that the 0's of the units track connect to the 00 sector in the tens track, the 1's connect to the 10 sector, the 2's to the 20 sector, the 9's to the 90 sector, and so forth; the other sides of the tens sectors may be connected to an external plug. It is through this electrical path that voltage applied to the units conductors finds its way through to the outer rings of the pattern and to the output terminals or plugs.

Hundreds-digit arrangement for dial-scale reading

The hundreds digit can be located around the same shaft as the units and tens digits. The tens arrangement must then be made repetitive in the same manner as the units arrangement, but with a cycle ten times longer. (See Fig. 8.)

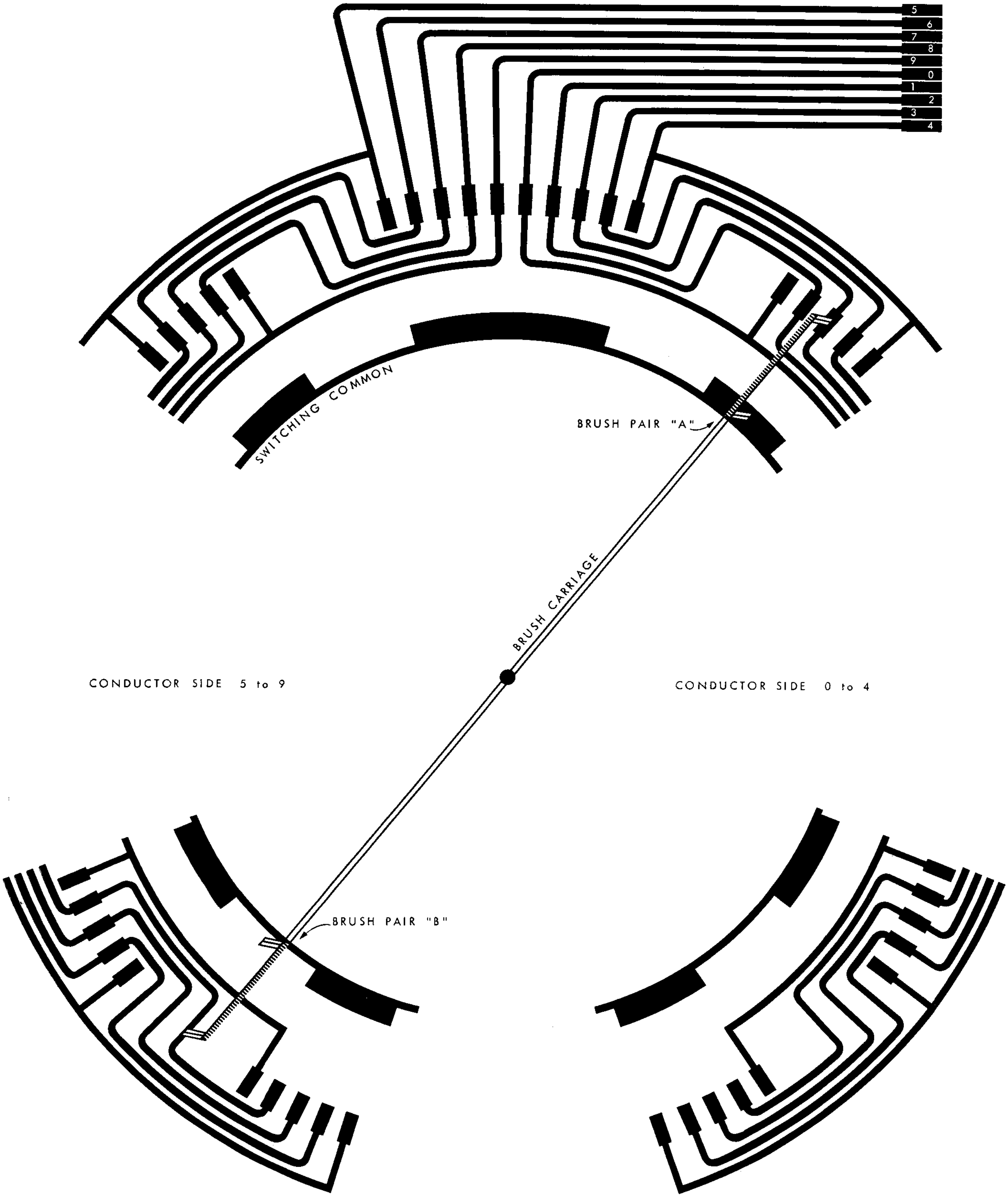


Figure 6 **Solution to commutator-design problem requiring four brushes in two tracks.**

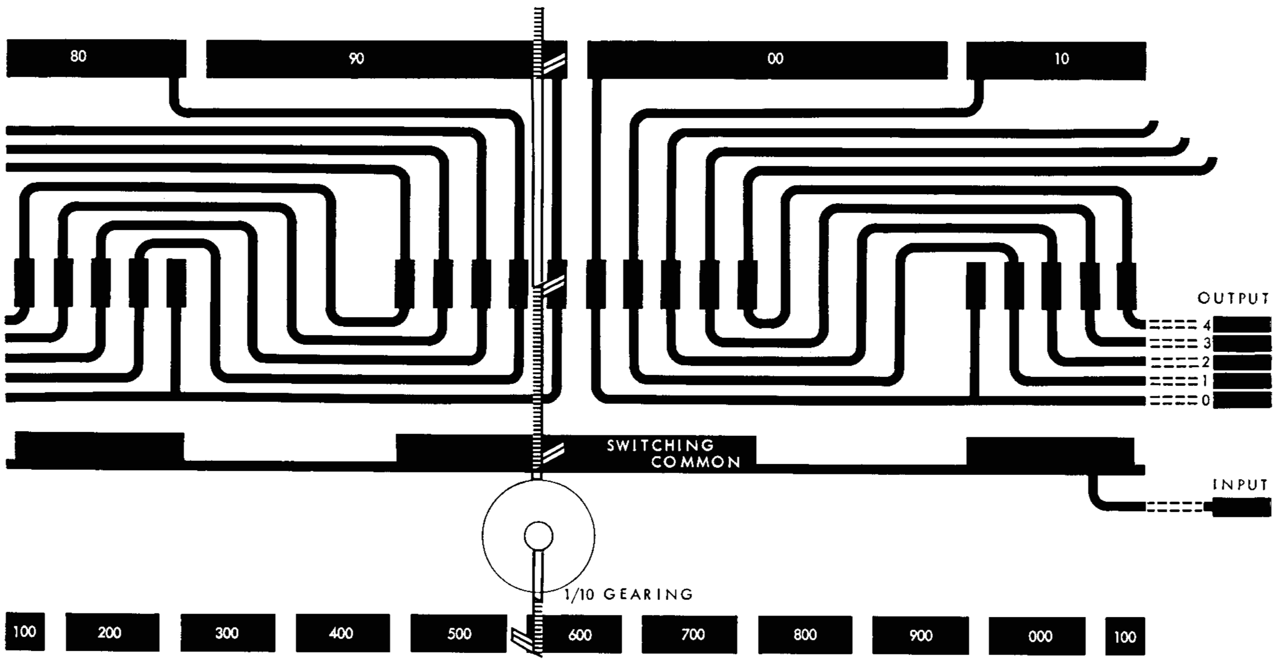


Figure 7 **Addition of hundreds-digit track and attendant ambiguity problem caused by gear-train backlash.**

Figure 8 shows an actual printed commutator used with a dial scale to form the control units of an automatic digital scale-reading device, or *scale take-off.*[5] The commutator pattern and dial scale are rigidly mounted on a common frame. Objects placed on the scale transmit an axial rotation to a shaft supported in fixed bearings. At one end of the shaft, an attached pointer gives a visual indication of the object's weight on the dial scale; at the opposite end of the shaft, an attached brush assembly, moving synchronously with the pointer, traverses the commutator pattern. A digital signal representing the weight of the object is read from the commutator and then transmitted to a recording device, such as a card punch or a solenoid-operated typewriter.

In Fig. 8, Rings 11 and 12 represent the units (or least significant) digits, and the pattern repeats as shown in Fig. 6, with Tracks 5 and 6 serving as the units switching commons. The tens digits repeat in the same manner in Tracks 9 and 10, with Tracks 7 and 8 serving as the tens switching commons. Since the scale's capacity is 1000 increments, there is no need to repeat the hundreds digit in a cyclic manner, and it is read by Brush 4, with Brush 1 serving as a solid common.

Tracks 2 and 3 serve to read a fourth, or thousands digit which in this instance has one of two values, either 0 or 1. Tracks 13 and 14 are read by a brush pair, Track 13 having 1000 identical conducting sectors, each aligned with a valid number on the commutator. These tracks are further described in the section on *Detenting.*

Hundreds-digit arrangement for geared systems

The actual commutator shown in Fig. 8 is too large (10-in. diameter) for a compact instrument-type mechanism. By placing the hundreds-digit track around a lower-speed shaft geared to the original shaft, the device can be made smaller and the units-tens pattern need not be repeated as often (see Fig. 7). In one IBM commutator, a units-tens pattern (Fig. 11) printed on an insulating card is backed up by hundreds and thousands patterns (Fig. 10) printed on the reverse side. This not only allows compact brush gearing between digit tracks but also permits limited use of advantageous through-connections between opposite patterns, as described at the end of this section.

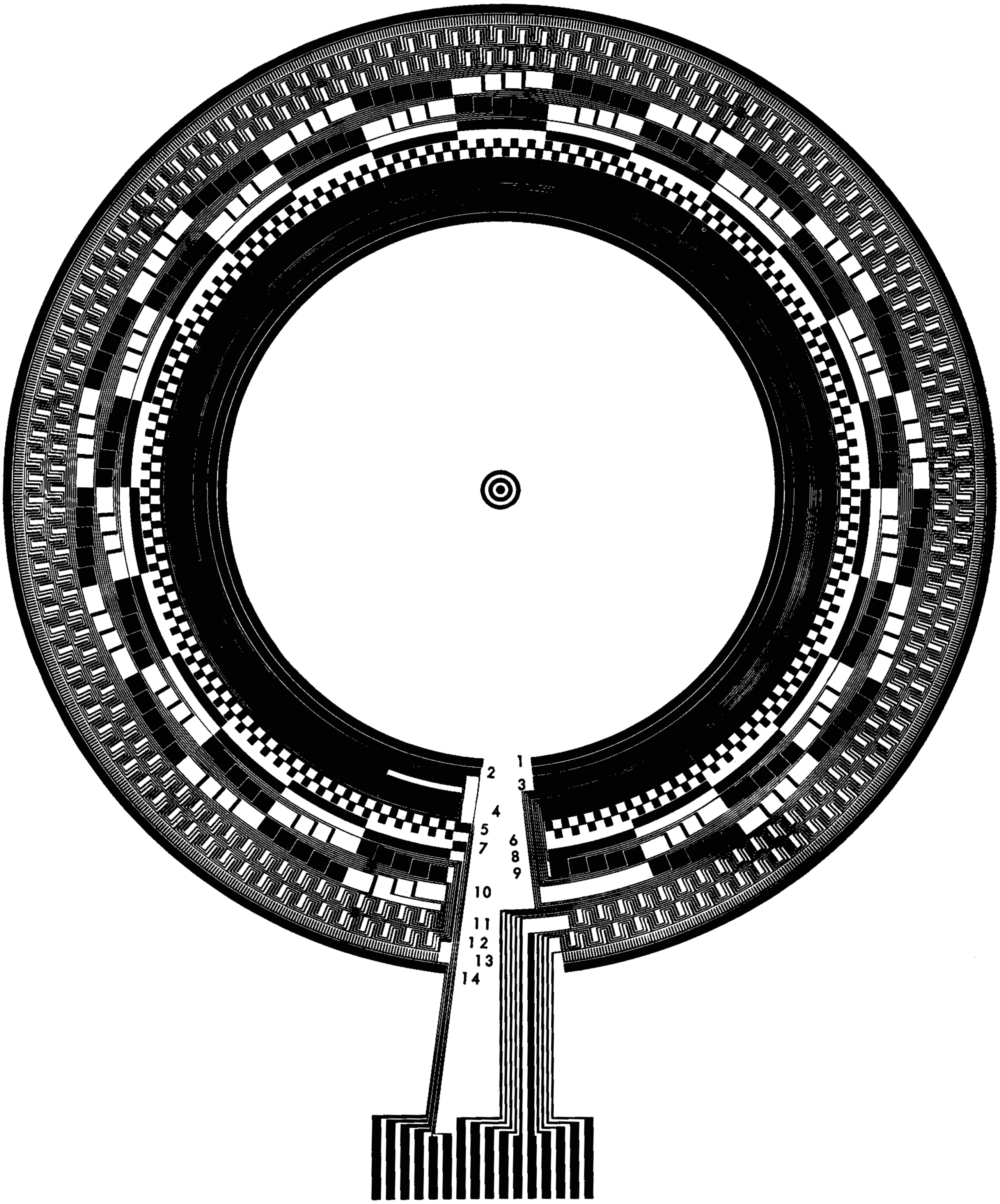
A serious problem is the ensuring of proper coordination between the units-tens and higher-order-digit advances. Errors in gearing, including backlash, and errors in brush and pattern positioning are unavoidably present in geared systems. As Fig. 7 shows, some mistakes in readout, such as 699 or 500, are almost certain to occur at the point where the reading should be 599 or 600. As the units and tens values change from 99 to 00, the hundreds digit must also advance progressively from 5 to 6, 1 to 2, or whatever the value may be.

Logical numerical progression is lacking to some degree in all shaft-to-digital converters, but especially in those which include gearing. Various ingenious solutions have been proposed to correct the deficiency. Use of the reflected code is one solution. A lag-lead brush solution has been adopted by IBM which, unlike the lag-lead method described in the Introduction, does not require diode-switching for operation.

This type of lag-lead control is based on the continuous availability of two adjacent values of the potentially ambiguous digit. For hundreds-digit lag-lead control, one value (the lower of the two possible hundreds digits) is associated with the numbers 50 through 99 of the unit-tens pattern, and the other value (the higher of the two possible hundreds digits) is associated with the numbers 0 through 49 of the units-tens pattern. The two values are read by the lagging and leading brushes.

The choice of the lagging or leading brush is made by two additional etched-in sectors surrounding the units-tens shaft. They are connected through the insulating card to lag and lead common sectors in the hundreds pattern on the opposite side.

Figure 8 **Printed-commutator scale-take-off pattern.**



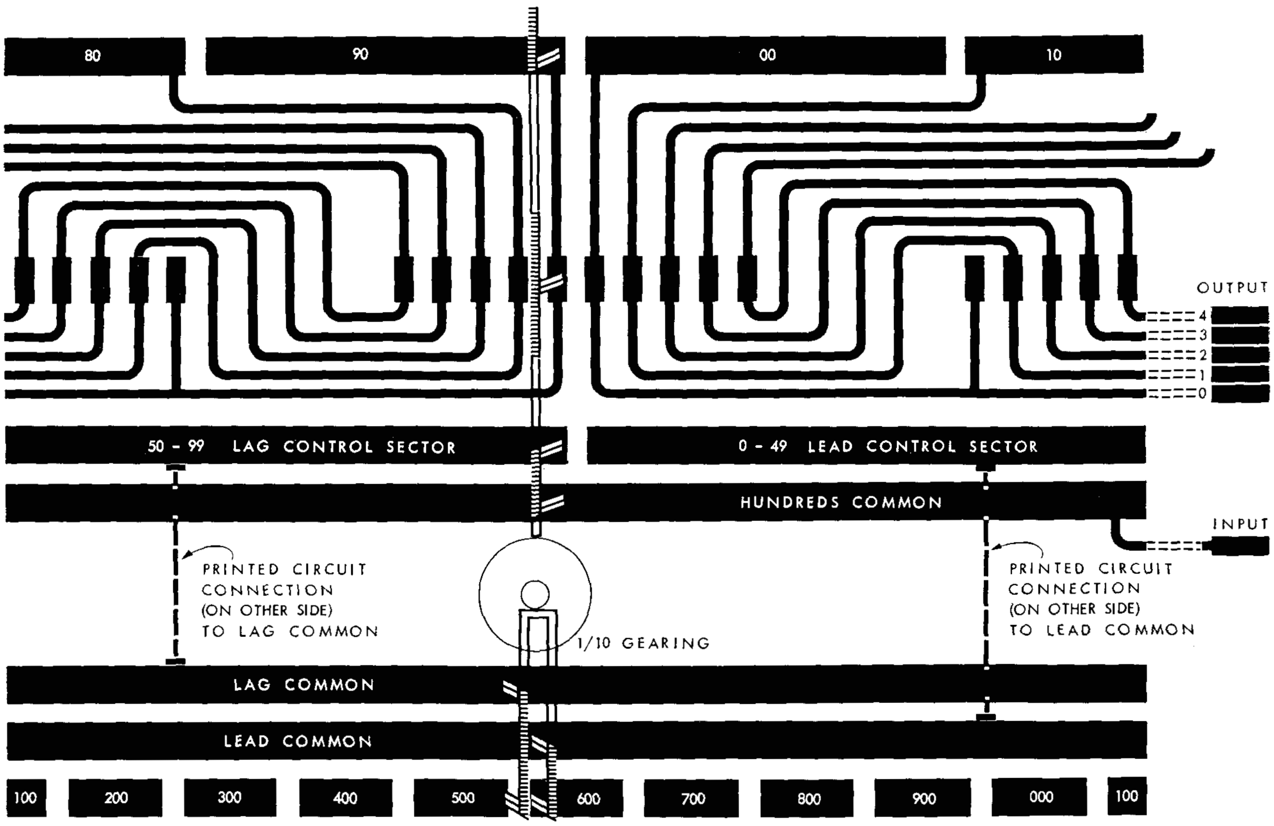


Figure 9 **Schematic solution to ambiguity problem using lag-lead brush configuration.**

Figure 9 schematically illustrates how hundreds-digit lag-lead switching is accomplished within the pattern, without the benefit of relays, diodes, or any external devices. The lag (50-99) sector is in line with the 50-99 digit positions of the units-tens tracks. The hundreds-digit circuit is then: hundreds common to lag-control sector to lag common (a solid ring around the hundreds-pattern shaft) to the 500 sector. The number read out is 599. If the units-tens brushes rest on 00 rather than 99 (intermediate units position prevented by a detent described later), the hundreds-common input is connected through the brushes to the lead (0-49) sector and the hundreds circuit is: hundreds common to lead-control sector to lead common (a second solid ring around the hundreds-pattern shaft) to the 600 sector. The number read out is 600.

Figure 10 is an actual arrangement for accomplishing a lag-lead operation similar to that just described. The combination of patterns (including that of Fig. 11) allows a four-digit readout. The upper-right-hand pattern for the most significant (thousands) digit closely resembles the layout of Fig. 9. Note the two internal solid rings, one for lag and one for lead. The outer data sectors are formed in a continuous repeating interlocking *Z* shape, rather than in the rectangular shape of Fig. 9. The *Z* shape staggers the pattern, forcing the pattern rather than the brushes into lagging and leading positions. In this arrangement, the radial alignment of the brushes simplifies their manufacture. The corresponding brushes in the rectangular arrangement, though located on the same radius, would require an angular displacement of approximately 18 degrees between them.

The fourth and fifth brush paths from the center of Fig. 11 (each split at two transition points, 99 to 00 and 49 to 50) are the thousands lag-lead and hundreds lag-lead control sectors, respectively. The need for duplicate thousands lag-lead paths as shown in Fig. 10 is explained in the next section.

The tabs attached to each solid sector in the patterns of Figs. 10 and 11 provide terminal points for making through-connections to the various sectors on opposite sides of the insulating board. A hole is drilled through the center of each tab, a wire is passed through the hole, folded over, and soldered to the tab. To trace paths through Figs. 10 and 11, note that tabbed connections common to more than one pattern have a common identifying legend:

HLG Hundreds-Digit Lag
HLD Hundreds-Digit Lead
MLG Thousands-Digit Lag
MLD Thousands-Digit Lead.

Thousands-and-additional-digit arrangement

The method just described for placing the hundreds-digit layout on the commutator can be applied to higher-order digits as well.

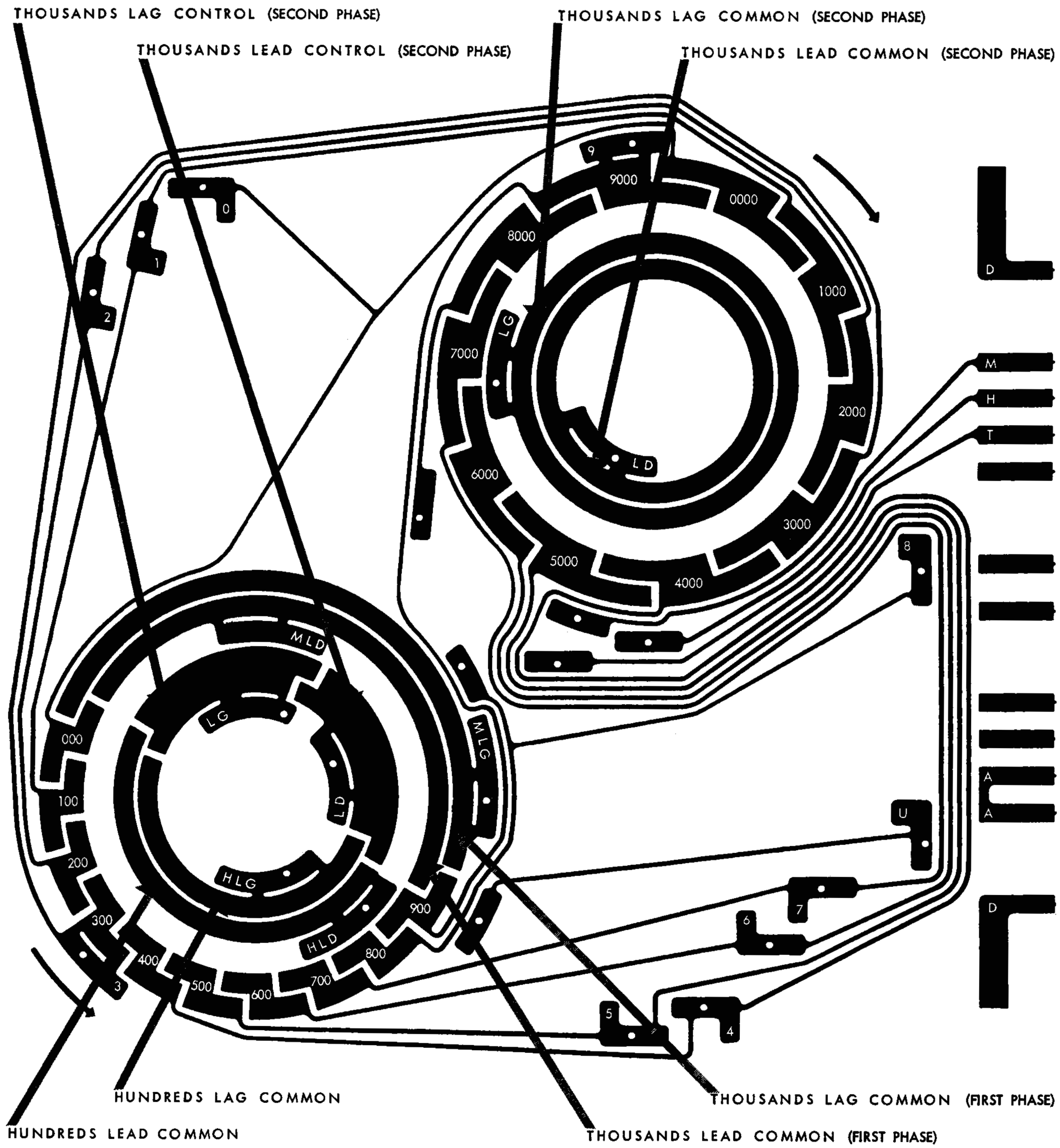


Figure 10 **An actual pattern showing hundreds and thousands digits tracks, and lag-lead tracks for gearing-backlash compensation.**

The upper-right-hand pattern of Fig. 10 is the thousands-digit layout. Because all digits must be referred to the primary (units-tens) shaft in an isolated manner, a thousands lag-lead path is added (fourth brush path, Fig. 11). Direct wiring of lag-lead control from the units pattern to the thousands pattern is not practical due to an excessive buildup of brush tolerances and gear backlash. Thousands lag-lead is therefore accomplished in two phases. The thousands lag-lead control sectors around the units-tens shaft are wired through the insulating board to the thousands lag-lead common sectors around the hundreds-digit shaft (lower left, Fig. 10). Thousands-digit lag-lead brushes transfer the signal to a second thousands lag-lead control sector around the hundreds shaft. The path is completed by through-connection-wiring (since the sector is in the center of the hundreds pattern) to the thousands pattern (upper right, Fig. 10).

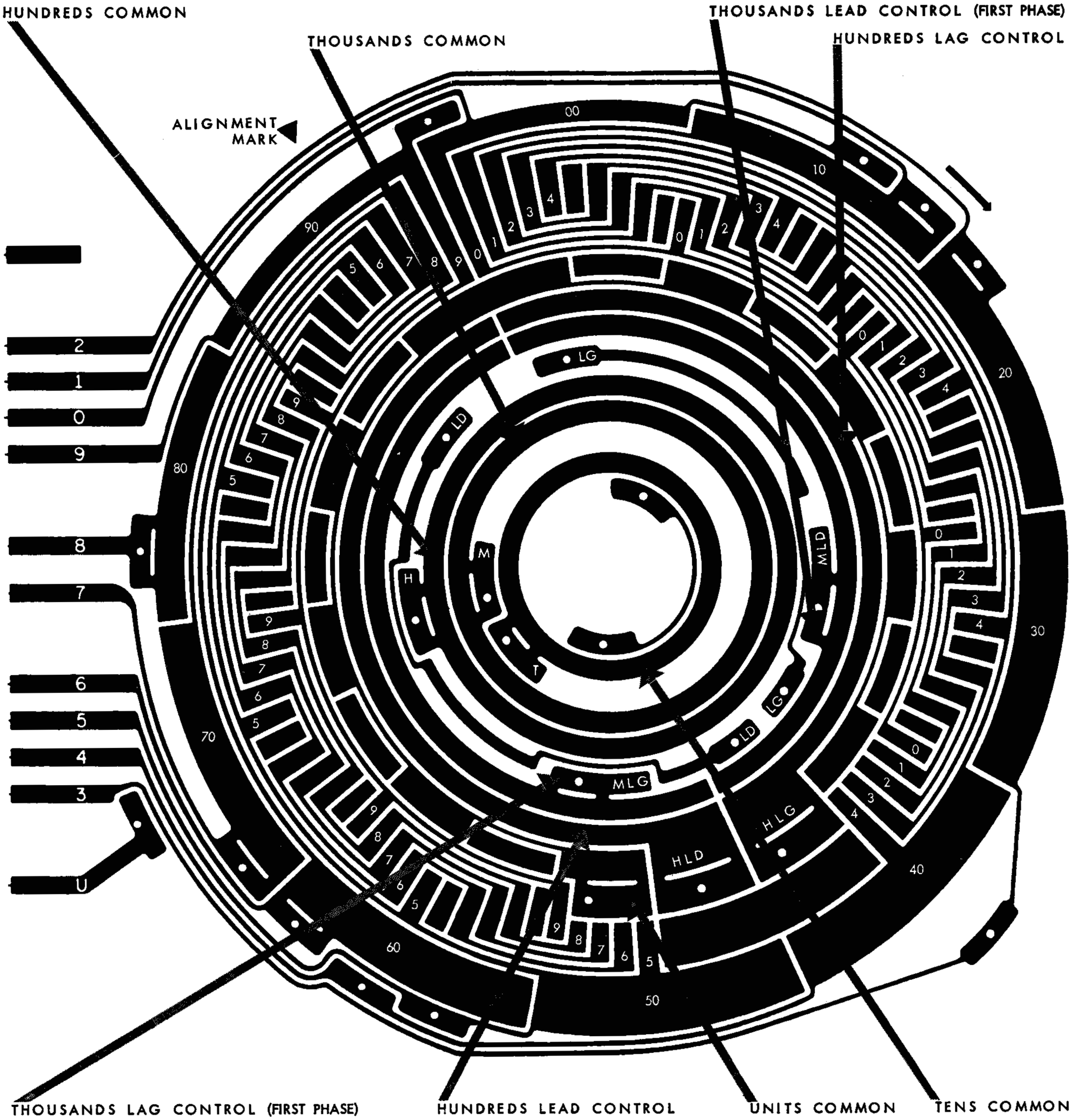


Figure 11 **An actual pattern showing units and tens digits tracks, and control sectors for hundreds and thousands lag-lead tracks of Fig. 10.**

With the addition of the separate hundreds and thousands patterns shown in Fig. 10, a departure from the previous units-tens pattern-layout logic is required for two-dimensional interconnection. Figure 12a shows why it is impossible to connect two separate patterns advancing in the same direction. If they advance in counter-rotating directions, however, as shown in Fig. 12b, continuation of progressive readout while advancing over the thousands pattern is then obtained by proper gearing of the thousands brushes to the main shaft.

Detenting

Detenting is necessary to ensure that the reading brushes do not fall between or upon two conductors. Two detenting methods have been used here, neither of which rely on the conventional approach of a sharp metal finger finding the hills and valleys in a detent wheel. Figure 13 shows how a "check pattern" in one application signals the ambiguity or non-validity of a point on the pattern to a detent magnet. If it is non-valid, a one-half-bit brush motion is used to bring the

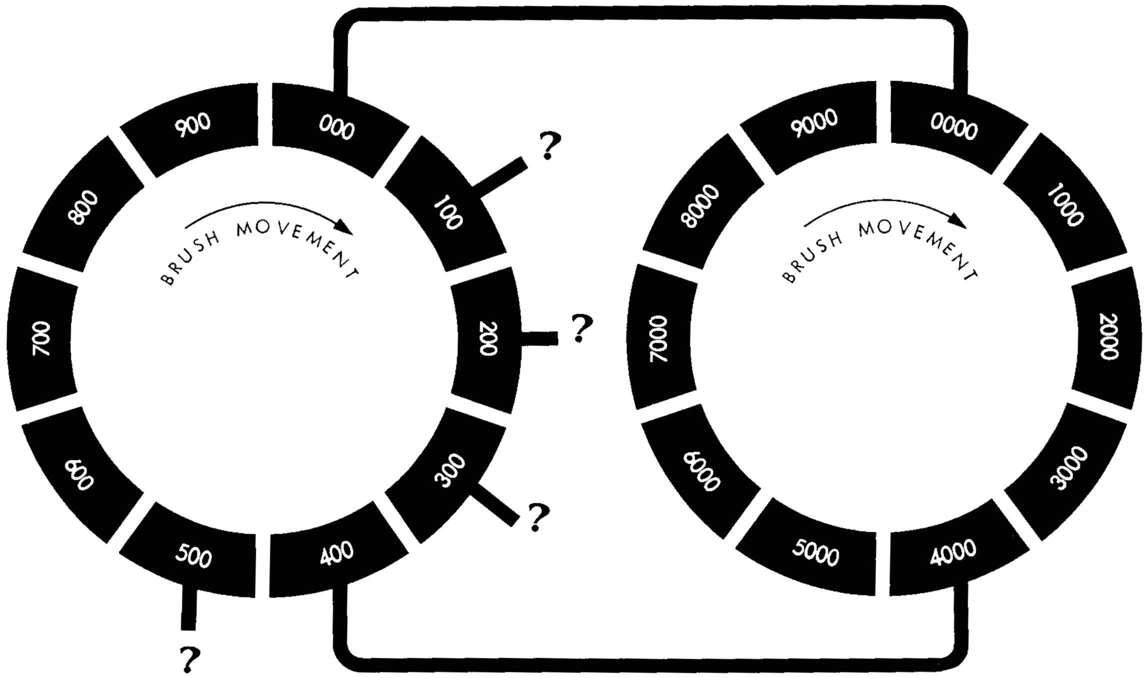
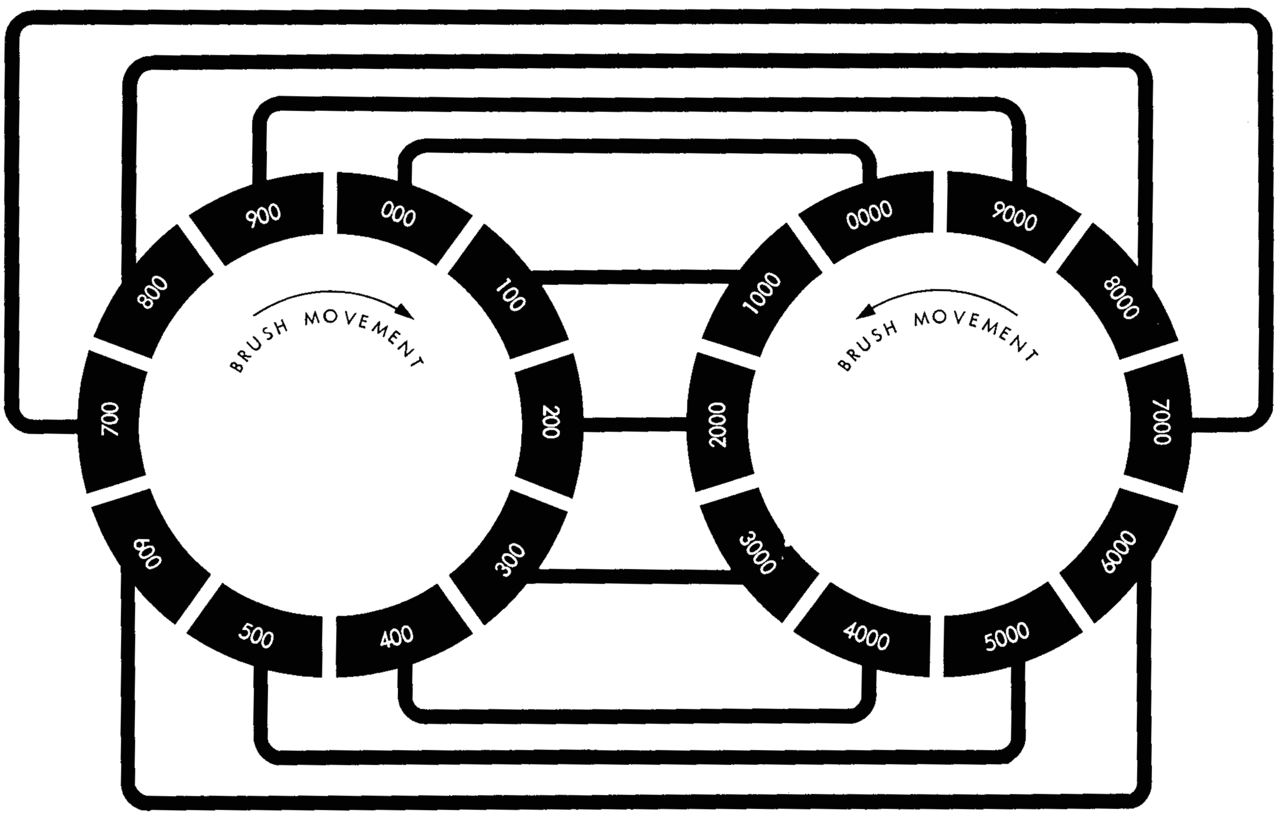


Figure 12a **Impossibility of interconnecting two separate patterns advancing in the same direction.**

Figure 12b **Interconnection of two separate patterns advancing in counterrotation.**



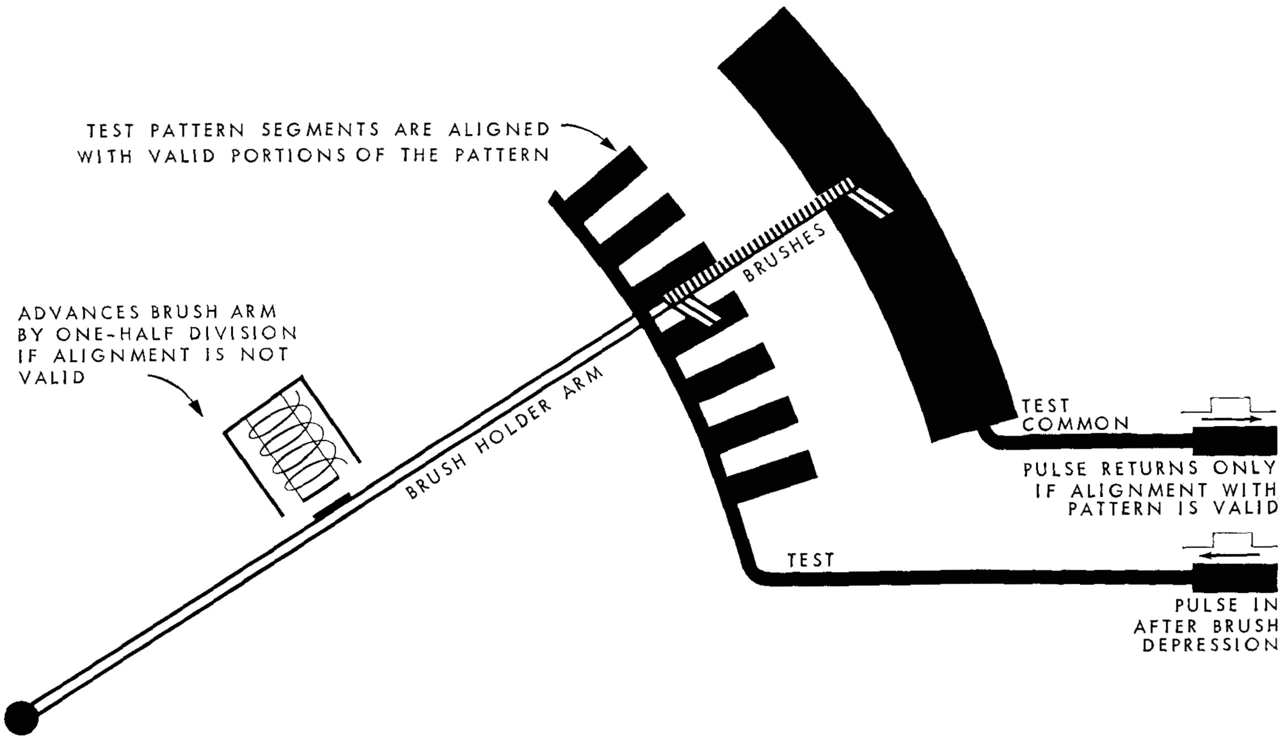


Figure 13 **Use of check pattern to indicate commutator-position validity.**

brushes into a valid area. Because the check-pattern is an integral part of the pattern, it is accurately aligned with other values in the pattern. It has the advantage over other equivalent methods of adding almost nothing to the cost of the pattern. The actual check pattern is shown in Fig. 8 as Tracks 13 and 14.

In another shaft-converter application (see Fig. 11) detent action is produced magnetically as a sector of magnetic gear teeth, or detent magnet, attracts similar teeth on a 100-tooth detent gear. Figure 14 is a sketch of this arrangement. As the detent magnets are energized (immediately prior to a reading), the magnetic gear teeth send flux in and out of the detent wheel, causing tooth alignment. Simultaneously, due to an axial offset between magnets and the detent wheel, an axial motion takes place which brings the brushes down onto the commutator pattern. Brush life is lengthened because the brushes are raised above the pattern during traversing, or *slewing*.

Pattern manufacturing

Some of the more critical considerations in printed-commutator manufacture are line resolution, dimensional stability, and surface smoothness. Where brushes are in continuous contact with the commutator, experience has dictated the necessity of a surface smoothness of better than 10 micro-inches for long life. Since bearing centers are included in most patterns, the dimensional stability of an epoxy-glass base material is needed. A minimum line width and spacing of 0.020 inches has given good resolution for all patterns produced to date.

The procedures for manufacturing printed-commutator patterns are referred to variously as additive, subtractive, or transfer processes, according to the manner of forming the printed pattern. Either photo-etching or silk-screening may serve as the actual printing process. Flushing may be accomplished by high pressure and heat, or may be inherent in the process, as in the transfer method.

IBM has tentatively adopted a procedure of plating a rhodium pattern on a smooth, flat, stainless-steel plate, plating nickel and rhodium over this, then pressing the plastic base against the plate, and finally removing the steel plate.[6] To get the required surface smoothness, the steel is buffed before plating and the rhodium baths must be of high quality.

Brush design and manufacture

An assembly comprising two precious-metal-alloy wires, each about 0.016 inch in diameter, molded into position in the brush holder has proved to be the most successful brush design. Wire-brush assemblies are bent simultaneously in a jig for uniform linearity. The brushes are then ground-off so that equality of length and deflection is obtained. Brushes made in this manner have been run over both raised and flush patterns.

Life tests of such brushes running over a 10-micro-inch flush rhodium pattern indicate that 100 million inches of travel would cause less than four mils wear when the linear velocity is 55 inches per second and the contact pressure is 3-4 g. This is equivalent to more than 10 years of heavy-duty life.

Applications

The assembled patterns of Figs. 10 and 11, and the detent of Fig. 14, together with brushes, gears and back and front plates comprise an analog-to-digital converter capable of measuring shaft positions, or displacements such as length, when converted to rotation. The measured values may be used in subsequent computing and/or control operations, as in the IBM Automatic Production Recorder (APR).

Servo-voltage converter

Voltage-to-digital conversion is accomplished by connecting a precision potentiometer to the output shaft of a servo-driven converter of the type described in the previous paragraph. A great variety of voltage inputs (from thermocouples and other transducers) can be reduced to digital form with such a system (see Fig. 15).

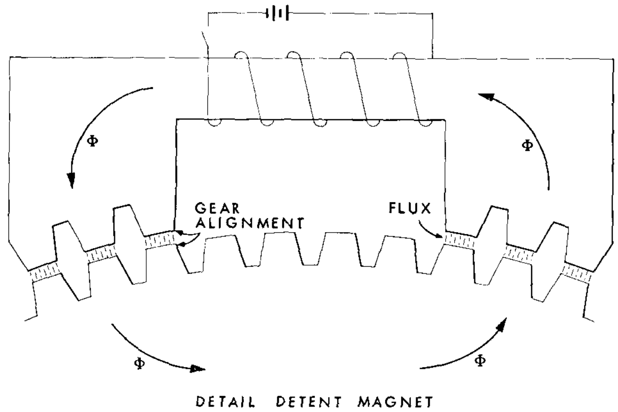
Commutator clock

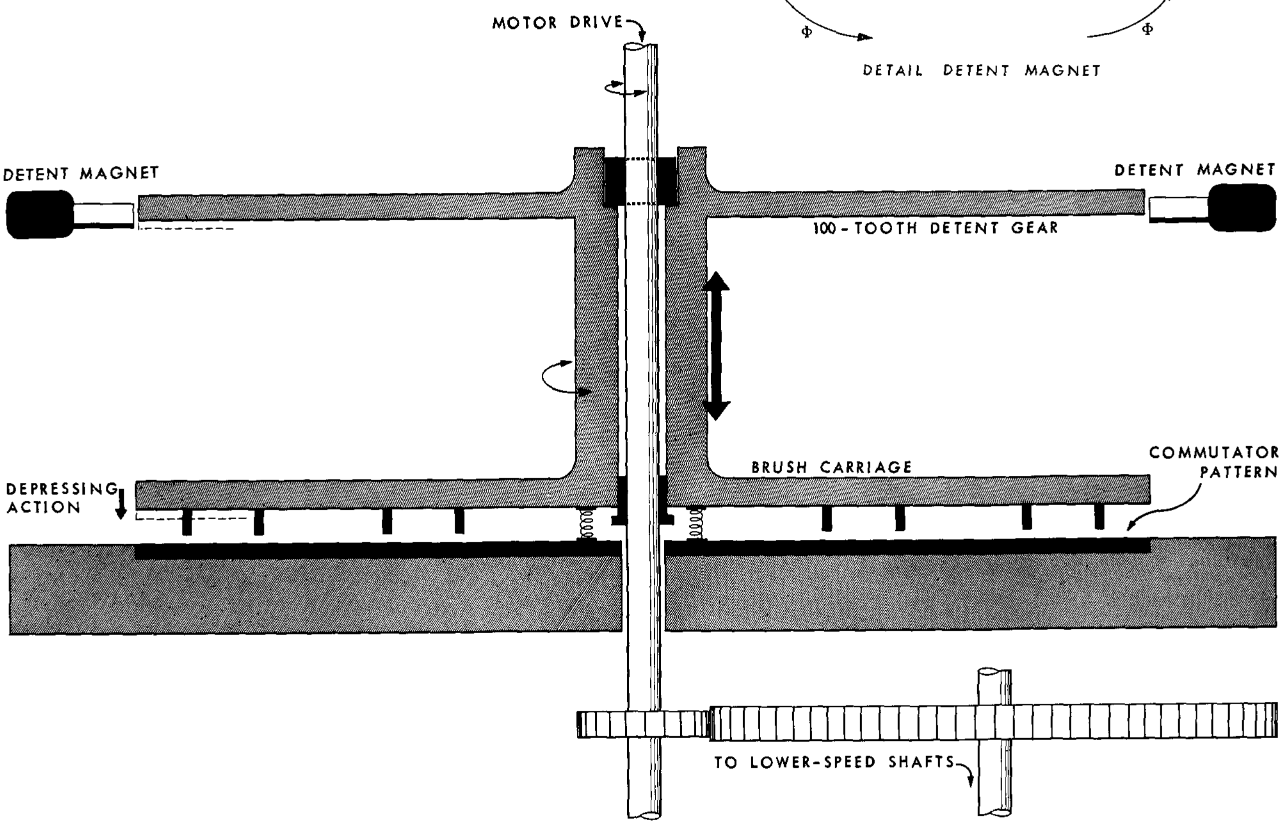
Printed-commutator patterns designed for minutes, hours, AM and PM, tenths of minutes, hundredths of hours, and thousandths of hours readout are used as central elements in the APR commutator clock. Modular construction permits a choice of the type of counting to be used in the least-significant positions.

Other uses

Printed-commutator patterns have been suggested as multipole switches for column-shifting in small electrical calculators, or for mechanical-switch-type multiplication-table lookup. If the pattern controls a digital-to-analog converter, a stable analog function of position can be generated. The function may be exponential, sinusoidal, or logarithmic. With a logarithmic pattern, a servo-driven electrical readout "slide rule" is practical.

Figure 14 **Magnetic detent, showing axial brush-carriage motion on readout.**
Inset: Magnetic circuit for simultaneous angular brush-carriage alignment.





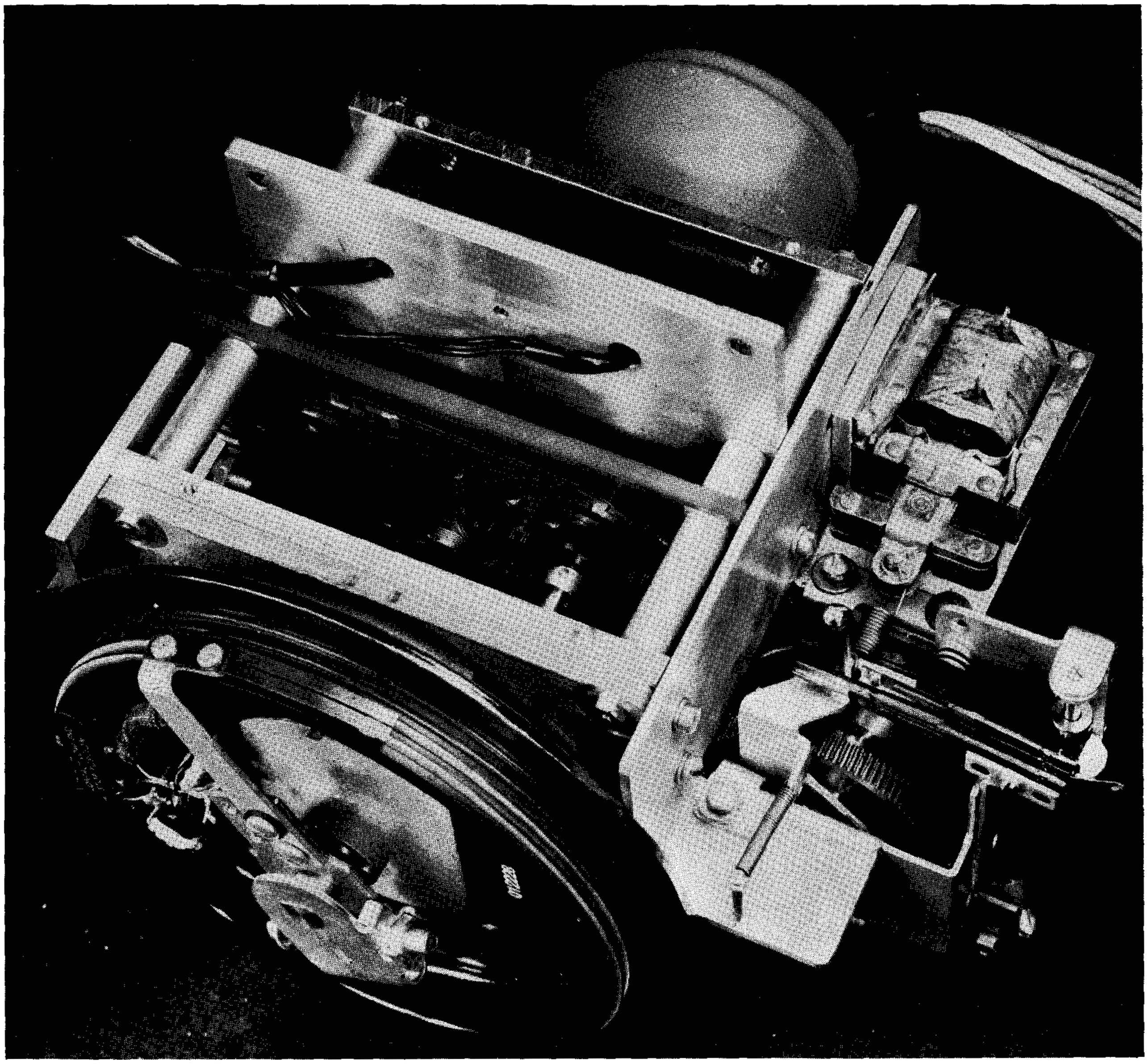


Figure 15 **A shaft-to-digital converter as part of a servomechanism for voltage-to-digital conversion.**

Acknowledgment

The author wishes to acknowledge the assistance of numerous individuals at the IBM Endicott Product Laboratory and at C. D. Lake Consultants, Inc. In particular, the author wishes to thank J. L. Wagner, who first called his attention to the possibilities in printed circuits for shaft-to-digital conversion.

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