

# Applications and Circuit Design for the HEDS-7000 Series Digital Potentiometer

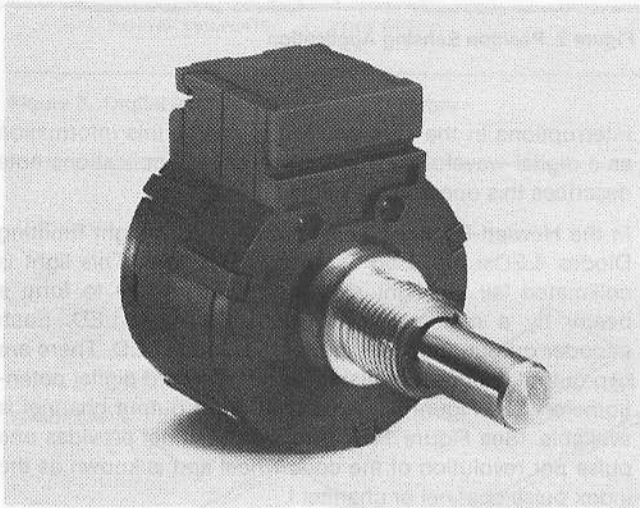


Figure 1. The Digital Potentiometer

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## INTRODUCTION

A digital potentiometer is a component which translates the rotational movement of its shaft into a digital electrical waveform. Digital potentiometers are often referred to as rotary pulse generators. Figure 1 shows the Hewlett-Packard HEDS-7000 series digital potentiometer.

Hewlett-Packard's HEDS-7000 series digital potentiometer has many features to offer both equipment designers and the end user:

- The HEDS-7000 series digital potentiometer has no end limits on its rotation. This allows the digital potentiometer's shaft to make an unlimited number of turns in one direction with complete continuity of the potentiometer's output.
- Hewlett-Packard's digital potentiometer offers high rotational position accuracy (linearity) over large temperature and humidity ranges. This means that the digital potentiometer will always provide the same number of digital pulses on its output for the same change in position of its shaft.
- The HEDS-7000 series digital potentiometer's output is directly compatible with all TTL circuitry.
- Hewlett-Packard's digital potentiometer offers long cycle life and high reliability for the user. The standard HEDS-7000 series digital potentiometer is rated for over 1 million turns of its shaft. Longer cycle life digital potentiometers, with special lubricants for extended bushing life, are available. The HEDS-7000 series digital potentiometer offers high reliability due to its non-contacting optical system for detecting the position of the potentiometer's shaft. This system eliminates all electrical contacting parts which wear and become electrically "noisy" with age and dust.
- One HEDS-7000 series digital potentiometer can be multi-tasked to perform many functions when used in a microprocessor based system. The digital potentiometer provides a digital output when its shaft is turned. A microprocessor can directly read this output and use it to change any parameter that the microprocessor controls.

For example, in a microprocessor controlled oscilloscope, the microprocessor could first use the output of the digital potentiometer to control a voltage level. The microprocessor could then be told by the user, via a front panel switch, to use the output of the digital potentiometer to control an internal clock frequency. Using this method, one digital potentiometer can be used in place of many knobs on a front panel.

The HEDS-7000 series digital potentiometer has several advantages over standard resistive potentiometers.

- The output of the device is directly TTL compatible.
- The device has no contact wiper to become electrically "noisy" with wear and age.
- The number of turns in the clockwise or counterclockwise direction is unlimited.
- The digital potentiometer has a longer cycle life than most standard resistive potentiometers.

The purpose of this applications note is as follows:

- To demonstrate some of the uses for a digital potentiometer
- To explain how a digital potentiometer works
- To explain some of the advantages of a digital potentiometer over a standard resistive potentiometer
- To provide some examples of circuitry which will interface the digital potentiometer to a microprocessor
- And to provide mechanical design considerations and available options for the HEDS-7000 series digital potentiometer.

## DIGITAL POTENTIOMETER APPLICATIONS

Digital potentiometers are most often used in front panel applications. In this application the shaft of the digital potentiometer is manually turned. A knob is usually placed on the end of the shaft. This knob facilitates the manual turning of the shaft as well as covers the bushing where the shaft attaches to the body of the potentiometer. Rotational movement of the shaft by hand is translated to digital pulses which can be read by a microprocessor using an interface circuit like those shown in the following sections of this applications note. The microprocessor can be programmed to perform a number of operations using the same digital potentiometer, such as to change a value shown on a display, to move a cursor on a CRT, or to change an audio level. The HEDS-7000 series digital potentiometers are well suited for front panel applications in devices such as medical equipment, electrical test equipment, computer terminals and peripherals, and CAD/CAM systems.

The HEDS-7000 series digital potentiometer may also be used in position sensing applications. In this type of application a gear might be placed on the shaft whose teeth match that of a strip along a table edge. As the table is moved in a plane tangent to that of the shaft, the gear would turn and the potentiometer could be used to send position information to a microprocessor. Figure 2 shows a diagram of this type of application.

## THEORY OF OPERATION

A HEDS-7000 series digital potentiometer operates by translating rotation of its shaft into interruptions of a light beam using a slotted code wheel. Photodetectors sense these

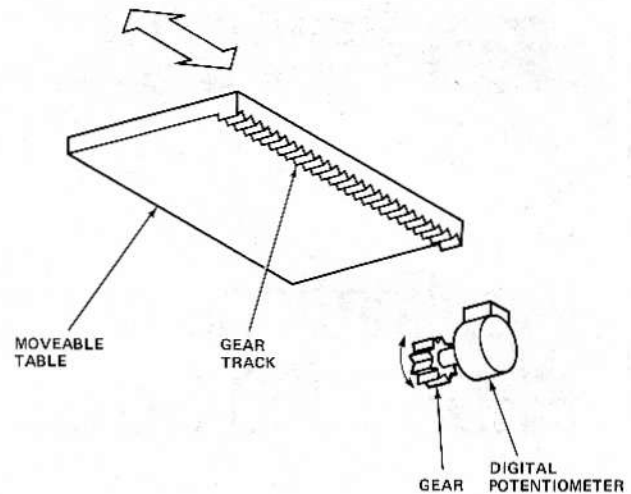


Figure 2. Position Sensing Application

interruptions in the light beam and output this information as a digital waveform. This section of the applications note describes this operation in detail.

In the Hewlett-Packard digital potentiometer Light Emitting Diodes (LEDs) are used as a source of light. This light is collimated (all the light rays are made parallel to form a beam) by a molded plastic lens over each LED. Each encoder output channel requires a separate LED. There are two output channels available on the standard digital potentiometer (See Figure 3.). A optional third output channel is available. (See Figure 13a.) This third channel provides one pulse per revolution of the code wheel and is known as the index pulse channel or channel I.

A shaft is mounted on the body of the digital potentiometer using a bushing which allows the shaft to rotate. A slotted code wheel is mounted on the end of the shaft that is inside the digital potentiometer body. The standard code wheel is a metal disc which has N equally spaced slits around its circumference. As the shaft is turned the code wheel interrupts the beams of light emitted by the LEDs. (See Figures 4a and 4b.) The standard count available for the HEDS-7000 series digital potentiometer is 256 pulses per revolution.

The photodetectors and a phase plate are located in the encoder body on the opposite side of the code wheel from the LEDs. The phase plate is held in a stationary position between the code wheel and the photodetectors. Apertures with a pattern matching the code wheel slits are located in the phase plate directly over the photodetectors. Two photodetectors are required for each output channel. The apertures in the phase plate are located in such a way that for each pair of photodetectors one of the detectors is darkened while the other one receives light. The output of each of the photodetectors is amplified and then fed to a comparator. As the code wheel is turned the light level that each photodetector receives changes until the first photodetector receives more light than the second one. When this change takes place the comparator changes state and provides a TTL logic level signal.

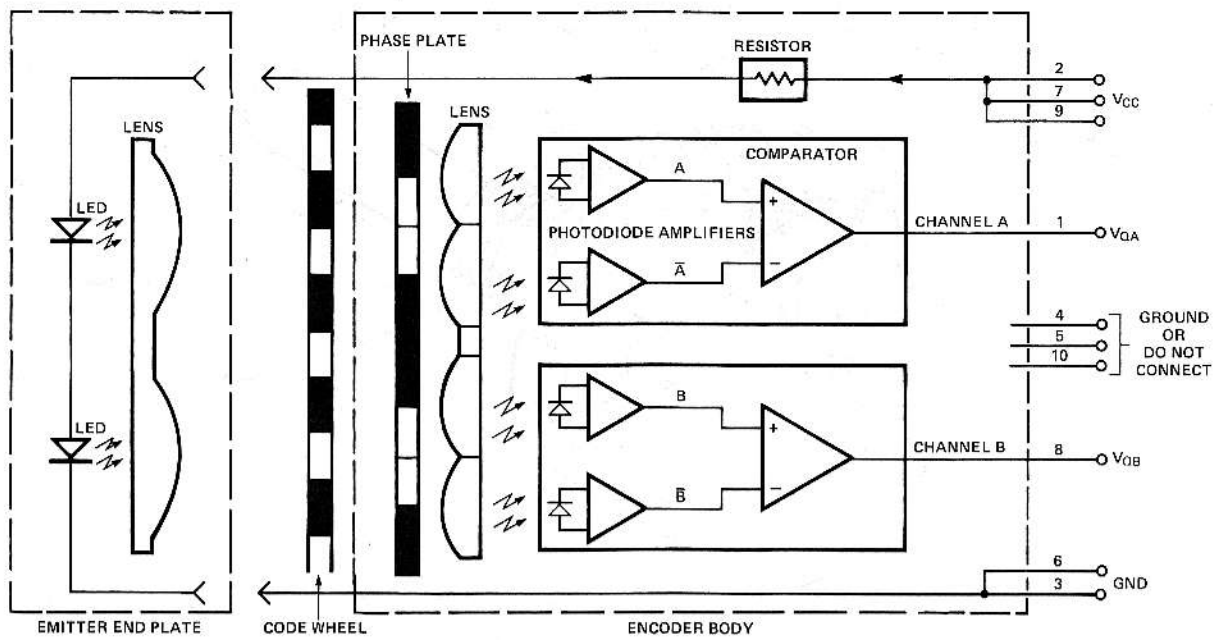


Figure 3. Digital Potentiometer Block Diagram

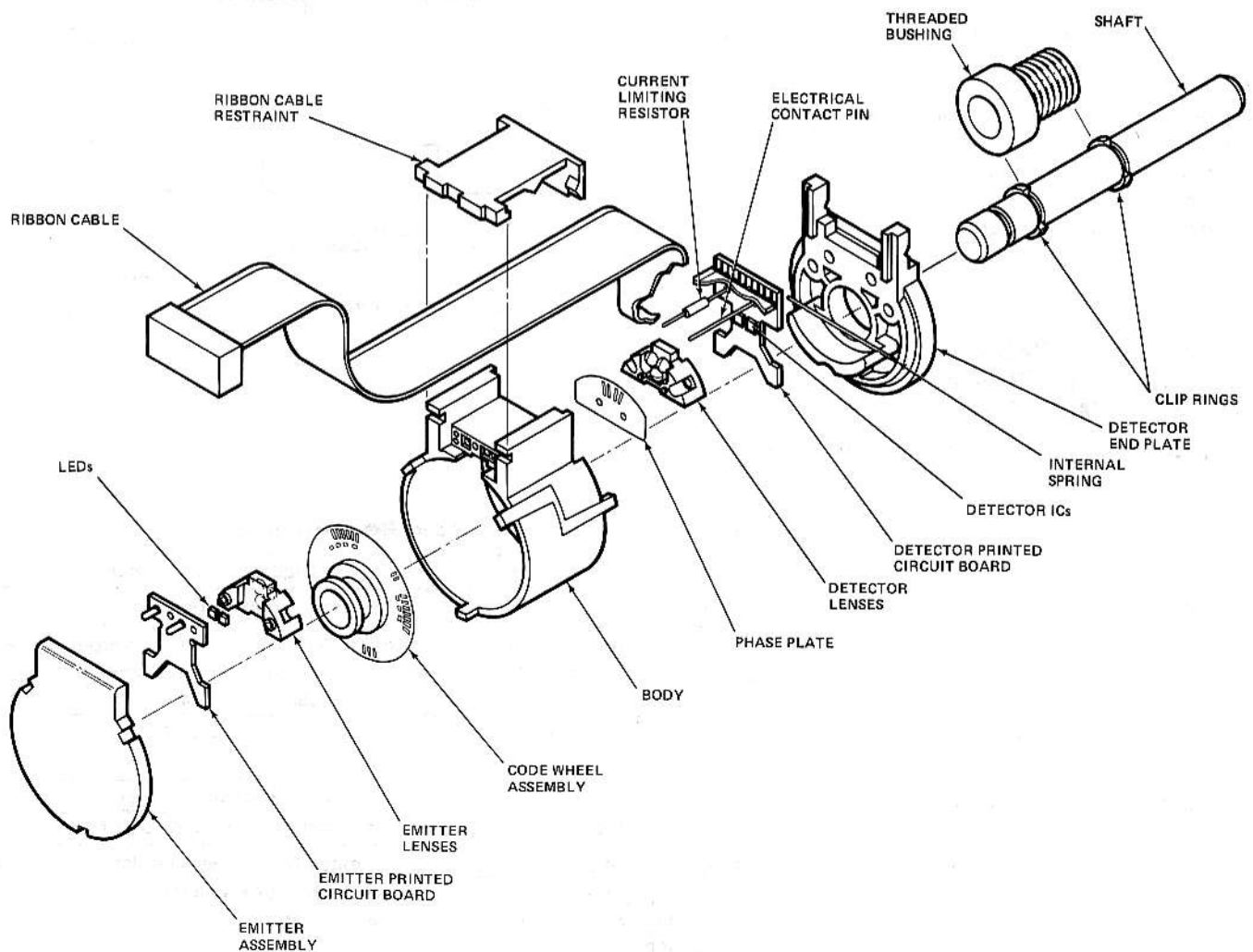


Figure 4a. Digital Potentiometer Exploded View

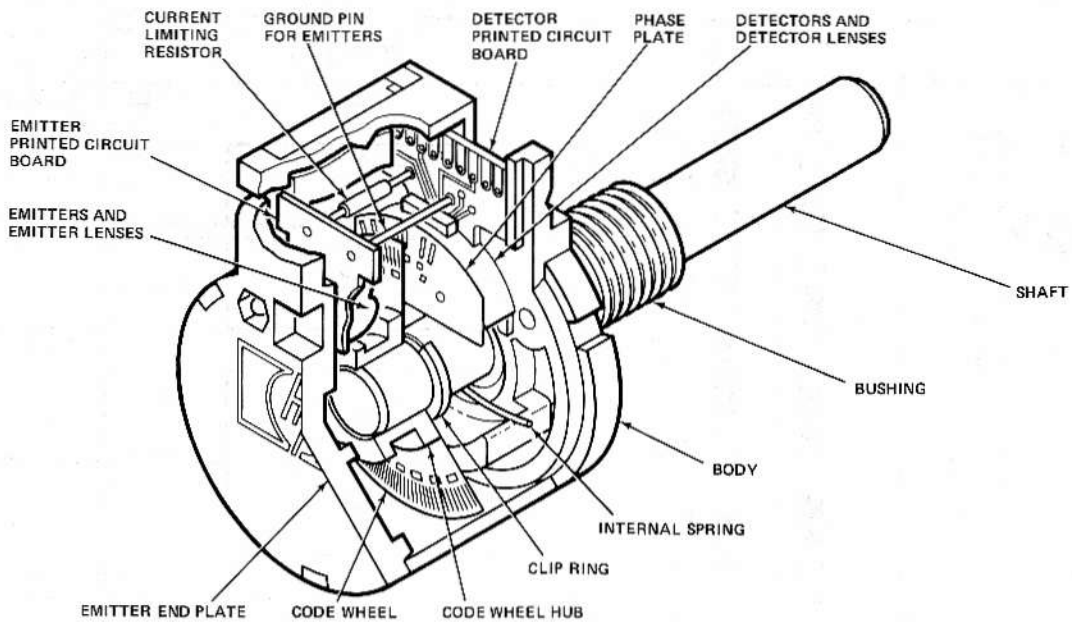


Figure 4b. HEDS-7000 Series Digital Potentiometer Cut Away View

The output of the digital potentiometer is shown in Figure 5. The A and B output channels are in quadrature. This means that they are out of phase by 90 electrical degrees. The phase of output channel A leads channel B by 90° when the potentiometer's shaft is turned in the clockwise direction. Similarly, when the shaft is turned in the counterclockwise direction, output channel B will lead channel A by 90°. Note that the number of pulses which occur on channels A and B is determined by the number of slots in the code wheel. Therefore, the number of pulses which occur for each revolution of the code wheel is fixed.

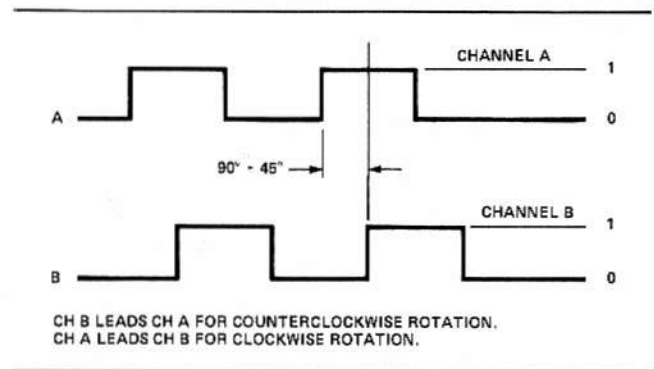


Figure 5. Output Waveforms

### HEDS-7000 SERIES DIGITAL POTENTIOMETER vs. RESISTIVE POTENTIOMETER

The following chart compares the major characteristics of resistive and digital potentiometers.

Table 1. The HEDS-7000 Series Digital Potentiometer vs. a Standard Resistive Potentiometer.

	Resistive Potentiometer	Digital Potentiometer
Output	Analog	TTL compatible - digital
Contact Wiper	Yes; and the wiper <u>will</u> become electrically "noisy" with time	No; the potentiometer is coupled optically and <u>will not</u> become electrically "noisy" with time
Number of turns in either direction	Usually <u>limited</u> to one turn	<u>Unlimited</u> number of turns
Retention of position information with power loss to system	Position information is <u>saved</u> if power to the system is lost	Position information is <u>lost</u> if power to the system is lost
Resolution Limitations	Limited by the <u>analog to digital converter and resistive surface nonlinearities</u> when used in a digital system	Limited by number of pulses per revolution or visual display as appropriate
Typical Cycle Life	50,000 to 100,000 cycles	Greater than 1 million revolutions

The main advantage of a resistive potentiometer is that if power is lost to the system position information will be retained.

Both the resistive potentiometer and the digital potentiometer have a limited resolution when used in a digital control system. The digital potentiometer's resolution is limited by the number of slots and bars in the code wheel. The resistive potentiometer is limited by the analog to digital converter's resolution and by nonlinearities in the resistive contact surface.

Hewlett-Packard's HEDS-7000 series digital potentiometer has many advantages over a standard resistive potentiometer to offer both equipment designers and the end user:

- Hewlett-Packard's digital potentiometer offers more ease of design in a digital system than a standard resistive potentiometer. Standard resistive potentiometers require an analog to digital converter for interface to a microprocessor or other digital logic. The HEDS-7000 series digital output allows it to be connected directly to a microprocessor.
- The HEDS-7000 series digital potentiometer is more stable than a standard resistive potentiometer. A standard potentiometer has a "wiper" which contacts with a surface whose resistance varies over distance. This wiper and the resistive material will wear with usage and may become electrically "noisy" if dust or other material contaminates these contacting surfaces. The digital potentiometer uses a non-contacting optical system for sensing shaft position which eliminates this electrical "noise" problem.
- Often standard resistive potentiometers are limited to less than 360° of angular movement. This results in a "deadband" region which cannot be used. Hewlett-Packard's digital potentiometers can be turned over an unlimited range in either direction of rotation and hence have no useless "deadband" region.
- The HEDS-7000 series digital potentiometer is more accurate than standard resistive potentiometers. When used in a digital system, a resistive potentiometer suffers from errors in the analog to digital conversion process and from nonlinearities in the resistive contact surface. As a result, the output of the analog to digital converter may not always change by the same count when the resistive potentiometer's shaft is turned a specified angular distance. (For example, the count might not always change by 15 when the resistive potentiometer's shaft is turned 15 angular degrees.) The HEDS-7000 series digital potentiometer offers excellent linearity when used with the circuits shown in this application note.
- Hewlett-Packard's digital potentiometer offers a longer cycle life than most standard potentiometers. The standard HEDS-7000 series digital potentiometer is rated for over 1 million turns of its shaft. Higher cycle life digital potentiometers, with special lubricants for extended bushing life, are available. Standard resistive potentiometers are usually rated for 50,000 to 100,000 cycles.

## CIRCUITRY EXAMPLES FOR THE DIGITAL POTENTIOMETER

Four circuits for interfacing the digital potentiometer to a microprocessor are examined in this section. The first circuit provides digital pulse information directly to a microprocessor.

The second and third circuits employ counters to interface the digital potentiometer to a microprocessor. The advantage of using counters is that the microprocessor need only interrogate the counters when it requires information from the potentiometer. The counters keep track of the present position of the potentiometer's shaft and will count up or down depending on whether the shaft is turned in the clockwise or counterclockwise direction. These circuits free the microprocessor from the task of recomputing the position of the potentiometer's shaft each time the shaft is turned. This allows the microprocessor to spend more time performing processing functions other than monitoring the output of the digital potentiometer. The disadvantage of the second and third circuits is the added parts count and cost over the direct interface circuit.

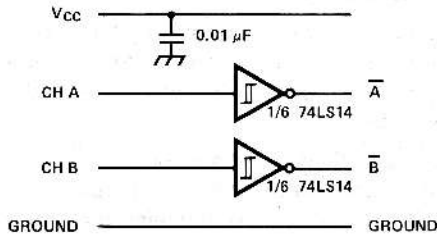
The last circuit is an example of a digital potentiometer decoding scheme which should be used in applications where visual feedback is available, direction of shaft rotation and relative shaft movement are important, but absolute shaft position is not critical.

### Direct Interface Circuit

The output of the digital potentiometer can be fed directly to a microprocessor using the circuit shown in Figure 6. 74LS14 inverters are used in this circuit to provide more current to drive the microprocessor input ports. The 74LS14 inverters also help to "square up" the digital output when the output lines are loaded down by the microprocessor. Output channels A and B of the digital potentiometer can be treated as the most significant bit and least significant bit of a two binary number by the microprocessor. As the shaft of the digital potentiometer is turned, the binary number will change. The microprocessor can be programmed to determine when the shaft is turning clockwise or counterclockwise by decoding the binary output. To decode the output of the potentiometer, the microprocessor must compare the present binary number on the potentiometer output with the number that was last on the output and use the following table.

Table 2. 74LS14 Output Logic Table

Present number on the 74LS14 output.		Previous number on the 74LS14 output.		Direction of rotation of the potentiometer's shaft.
A	B	A	B	
0	0	1	0	Clockwise
0	0	0	1	Counterclockwise
0	1	1	1	Clockwise
0	1	0	0	Counterclockwise
1	0	0	0	Clockwise
1	0	1	1	Counterclockwise
1	1	1	0	Clockwise
1	1	0	1	Counterclockwise



STANDARD 74 SERIES COULD ALSO BE USED TO IMPLEMENT THIS CIRCUIT.

Figure 6. Direct Interface Circuit

**Advanced Micro Devices AM25LS2569 Counter Circuit**

This circuit employs AM25LS2569 counters. These counters require one data line to provide potentiometer output pulse (clock) information and another data line to provide the direction of rotation of the potentiometer's shaft. The pulse and direction of rotation information is decoded from the digital potentiometer's quadrature output using three HEX inverters, three NAND gates, and a D-type positive edge-triggered Flip-Flop with preset and clear. The implementation of these gates for quadrature decoding is shown in Figure 7.

A timing diagram for the quadrature decoding logic is shown in Figure 8. The first four waveforms on the diagram represent the quadrature output of the digital potentiometer (A, and B) and their inverse (A-bar, and B-bar). The waveforms C, D, and E represent the outputs of the three NAND gates and the U/D and CP waveforms represent the direction and clock pulse data lines respectively.

Output channels A and B are fed into 74LS14 Hex inverters to provide A-bar and B-bar. The clock pulse information is decoded by feeding A-bar and B-bar into a NAND gate that is connected to an inverter. The CP line goes to the high state only when both output channels A and B are low. Since both A and B are simultaneously low only once every 360 electrical degrees, this logic supplies clock pulses to the counters which are equal in number to the number of lines on the potentiometer's code wheel.

The direction of rotation information is decoded from the quadrature output using two NAND gates and a D-type positive edge-triggered Flip-Flop. Output channels A-bar and B-bar are fed into a NAND gate which is connected to the PRESET of the Flip-Flop. The output of the NAND gate is normally high and goes low only when A is low and B is high. Output channels A and B-bar are fed into another NAND gate which is connected to the CLEAR of the Flip-Flop. This NAND gate is normally high and goes low only when channel A is high and channel B is low. When the output of the NAND gate goes low, the output of the Flip-Flop is cleared. The Q out-

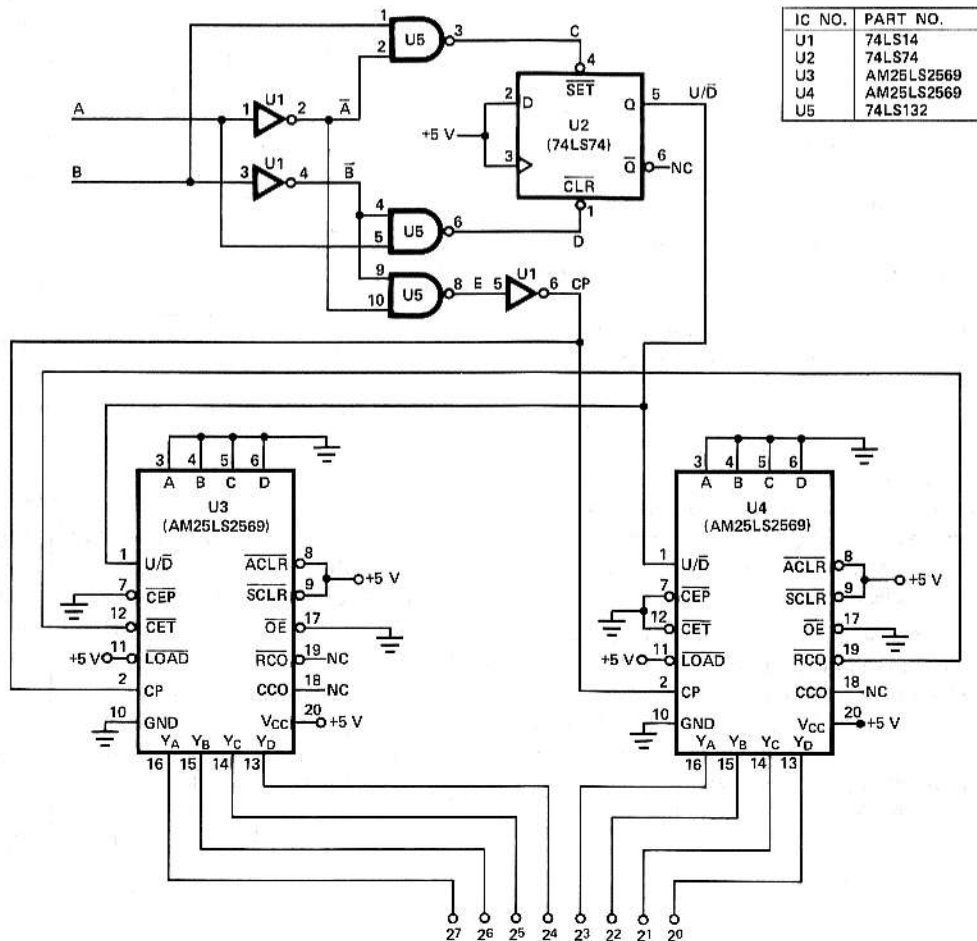


Figure 7. Advanced Micro Devices AM25LS2569 Counter Circuit

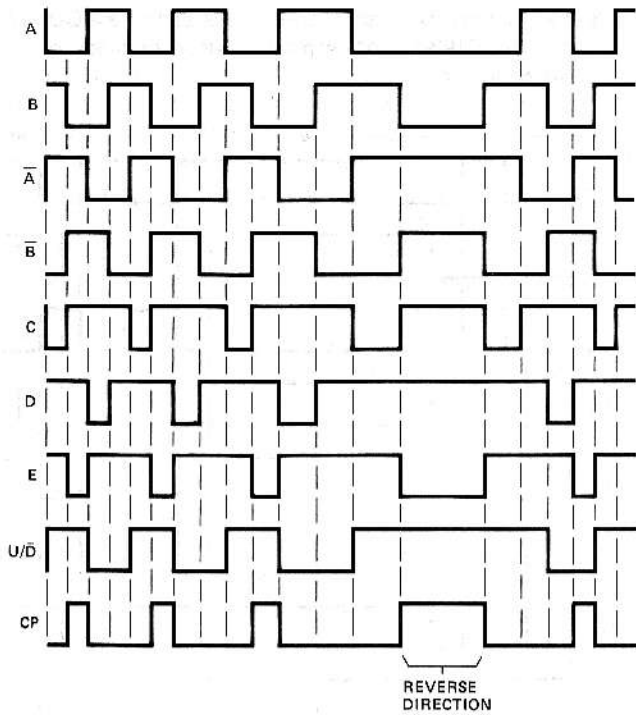


Figure 8. Timing Diagram for the AM25LS2569 Counter Circuit

put of the D-type Flip-Flop is connected to the counters' U/D line. By looking at the PRESET and CLEAR entries on a Flip-Flop logic table, or at the output waveforms in Figure 8, it can be seen that the U/D line follows the  $\bar{A}$  channel when the shaft is turning in the counterclockwise direction and channel B when the shaft is turning in the clockwise direction. The AM25LS2569 counters determine whether a pulse on the CP line should increment or decrement present count by interrogating the U/D line when the clock pulse occurs.

The U/D line can be attached to the  $\bar{Q}$  output of the D Flip-Flop to change the direction shaft rotation to increment the count. AM25LS2569 counters provide a binary output; if a BCD output is required AM25LS2568 counters may be used.

#### 74LS192 Counter Circuit

74LS192 BCD decade up/down counters are used in this circuit. These counters require two data lines for counting operations. The CPU data line provides pulses when the digital potentiometer's shaft is turned in the clockwise direction. Similarly, the CPD data line provides pulses to the counter when the shaft is turned in the counterclockwise direction. Clock pulse and direction of rotation information is decoded from the digital potentiometer's quadrature output using four-two input NAND gates, two-three input NAND gates, and a D-type positive edge-triggered Flip-Flop with preset and clear. Implementation of these gates for quadrature decoding is shown in Figure 9.

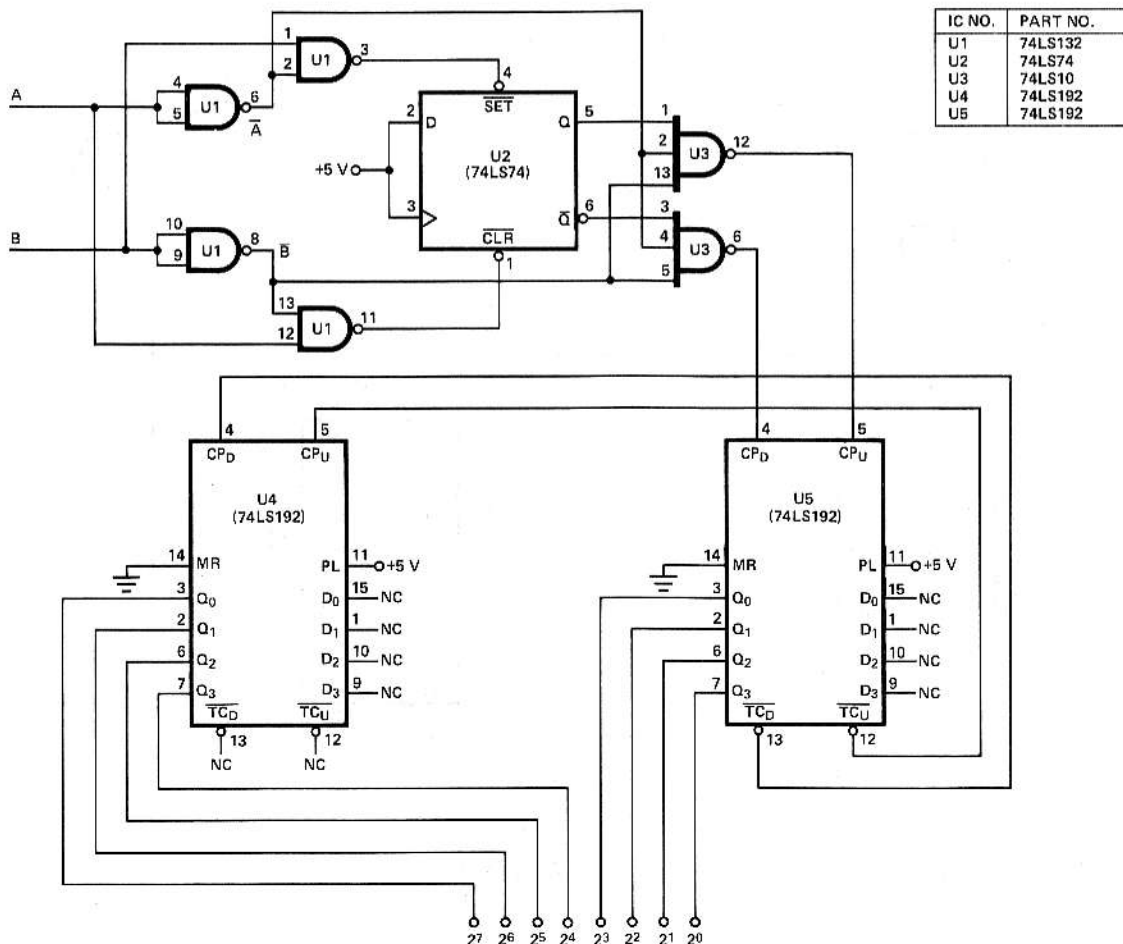


Figure 9. 74LS192 Counter Circuit

A timing diagram for the quadrature decoding logic is shown in Figure 10. The first four waveforms on the diagram represent the quadrature output of the digital potentiometer (A, and B) and their inverse ( $\bar{A}$ , and  $\bar{B}$ ). The waveforms Q, and  $\bar{Q}$  represent the outputs of the D-type Flip-Flop. The CPU and CPD waveforms represent the clockwise and counterclockwise clock pulse data lines which are the outputs of the three input NAND gates.

Output channel A is fed into both inputs of a two input NAND gate to provide  $\bar{A}$ . Output channel B is treated in a similar fashion to provide  $\bar{B}$ . Channels  $\bar{A}$  and B are fed into a two input NAND gate whose output is connected to the PRESET of the D-type Flip-Flop. This NAND gate's output is normally high and will only go low when A is low and B is high. When the output of the NAND gate goes low, the Flip-Flop output is set high. Output channels A and  $\bar{B}$  are fed into another NAND gate which is connected to the CLEAR of the Flip-Flop. This NAND gate is normally high and is only set to the low state when  $\bar{A}$  is high and B is low. When the output of this NAND gate goes low the Flip-Flop's output is set low. The Q output of the D-type Flip-Flop is NAND'ed with  $\bar{A}$  and  $\bar{B}$  to provide the CPU waveform. The CPU line is normally in the high state and only pulses when the potentiometer's shaft is turned in the clockwise direction. The  $\bar{Q}$  output of the D-type Flip-Flop is also NAND'ed with  $\bar{A}$  and  $\bar{B}$  to provide the CPD waveform. The CPD line is also normally in the high state and only pulses when the potentiometer's shaft is turned in the counterclockwise direction.

The CPU and CPD lines can be interchanged to reverse the direction of shaft rotation to increment the count. If a binary output is required from the counters instead of a BCD output, then 74LS193 counters may be used in place of the 74LS192 counters.

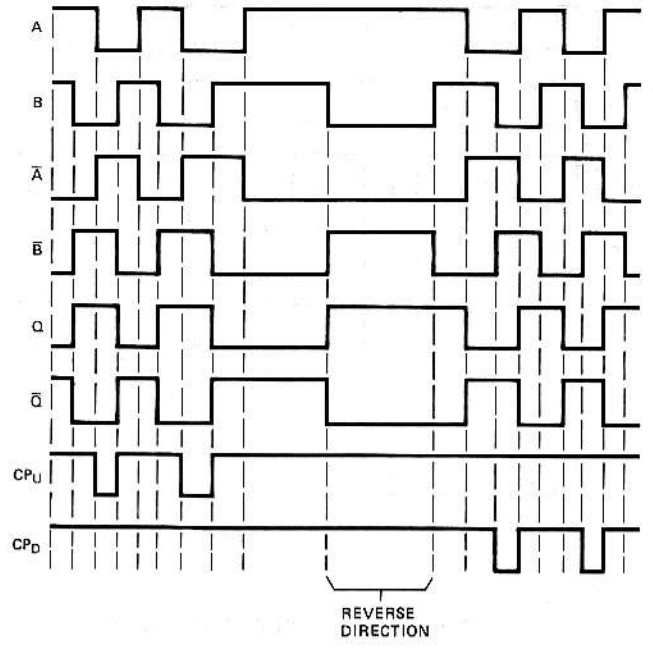


Figure 10. Timing Diagram for the 74LS192 Counter Circuit

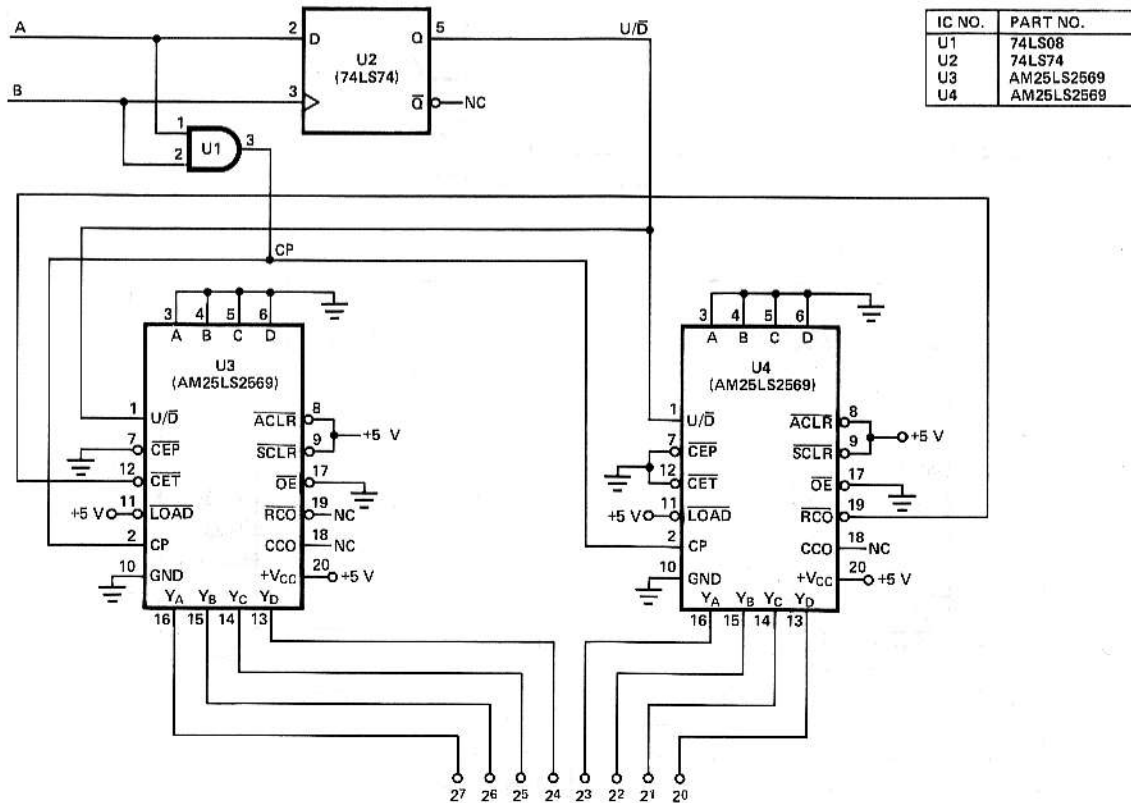


Figure 11. D Flip-Flop Interface Circuit



### D Flip-Flop Interface Circuit

Figure 11 shows a circuit which employs a D Flip-Flop to decode the output of the digital potentiometer. The output of the D Flip-Flop and an AND gate are used to drive two AM25LS2569 counters. The AMD AM25LS2569 counters provide an eight bit binary output which can be read by a microprocessor. Although this circuit appears to be a simple method for decoding the potentiometer's output, it is NOT recommended that the D Flip-Flop circuit be used for this purpose. The reason for not recommending the use of this circuit is that the D Flip-Flop may not read all of the output pulses from the digital potentiometer when the direction of rotation of the potentiometer's shaft is changed. For example, if the digital potentiometer's shaft is first turned in the clockwise direction, then stopped, and turned in the counterclockwise direction, some of the pulses in the output of the digital potentiometer will not be read by the D Flip-Flop. The result is that the digital potentiometer's shaft cannot be moved from an initial position to a new position, then the direction of rotation of the shaft be reversed and the shaft be returned to the initial position, with the same initial count resulting on the AM25LS2569 counters.

The output of the D Flip-Flop, during a change in direction of the digital potentiometer's shaft, is shown as the U/D line in Figure 12. The actual change in direction of the shaft

occurs in the time frame indicated on the timing diagram. During this time frame the B output channel is in the high state. The next positive transition of this line occurs only after the "actual change in direction" time frame. The U/D line only changes state with a positive transition of B output channel. Therefore, the U/D line does not change state within this "actual change of direction" time frame. As a result, the counters continue one count in the wrong direction before following the U/D line's command to reverse the direction of counting.

This counting error does not occur every time a change in the direction of rotation of the shaft is made. If the B channel output is in the low state when the shaft's direction is changed, then the B channel and the U/D line will both change state before the counter's LSB changes and no counting error will result.

Because it is not possible to know whether or not an error in the output will occur for any single change in direction of the potentiometer's shaft, it is not recommended that this circuit be used in applications where the position of the shaft must correspond with any particular numerical output of the counters.

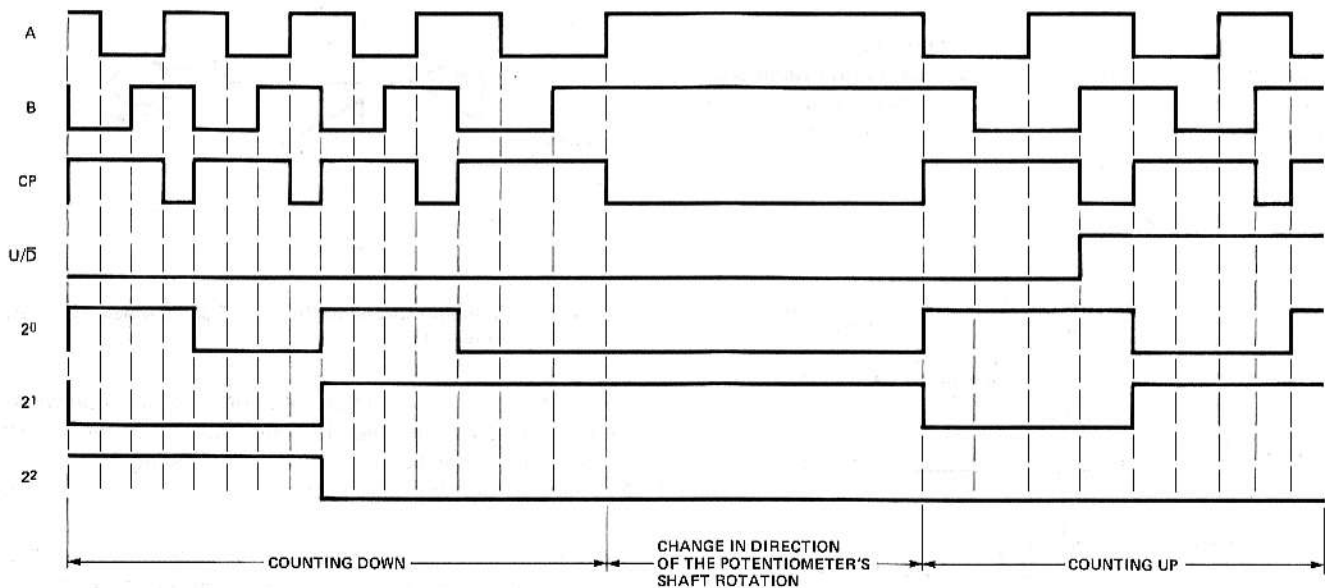


Figure 12. Timing Diagram for the D Flip-Flop Interface Circuit

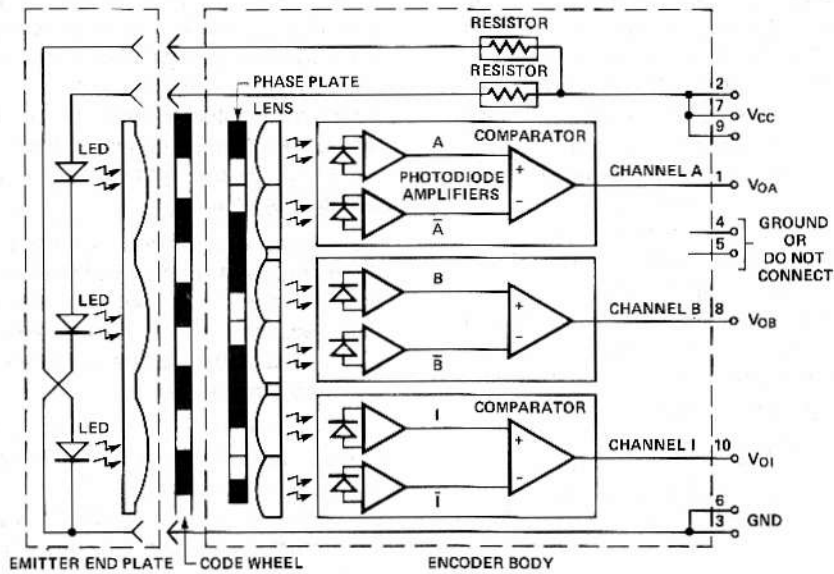


Figure 13a. HEDS-7000 Series Digital Potentiometer Block Diagram Showing the Optional Index Pulse Channel

## DESIGN CONSIDERATIONS FOR THE DIGITAL POTENTIOMETER

### HEDS-7000 Series Digital Potentiometer Options

The Hewlett-Packard HEDS-7000 series digital potentiometers are available with five options. These options are: code wheel counts, an index channel, rotational torque variations, shaft lengths, and cable terminations. Check with the local Hewlett-Packard sales representative for details about cost and availability of these options.

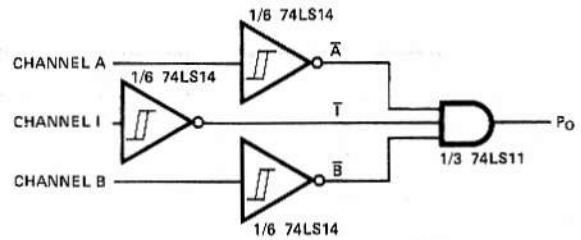


Figure 13c. Summing Circuit to Provide Discrete Index Pulse "P<sub>0</sub>" Shown in Figure 13b.

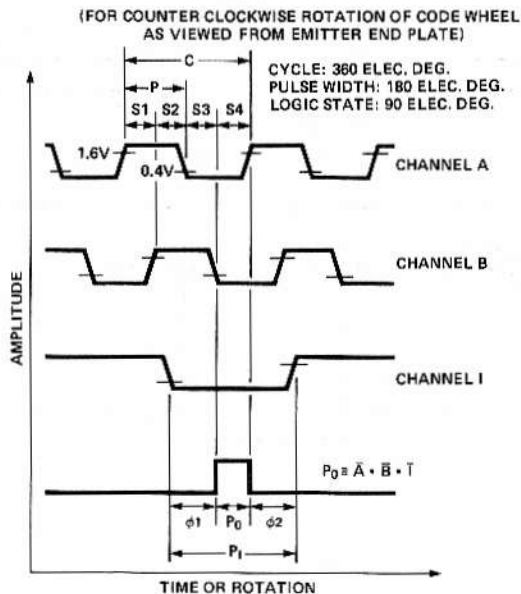


Figure 13b. Three Channel Digital Potentiometer Output Waveforms

The first option is the number of counts on the code wheel. The standard digital potentiometer has a code wheel with 256 counts. Other code wheel counts ranging from 100 to 512 counts per revolution can be ordered from Hewlett-Packard.

An optional index pulse channel is available (channel I). This third output channel provides one pulse per revolution of the code wheel. The index pulse can be used as a reference point which must be passed through each time a full revolution of the code wheel is made. Note that the direction of the rotation of the code wheel can only be determined by decoding the quadrature output of channels A and B. A block diagram with channel I is shown in Figure 13a. Figure 13b shows the output waveforms of a three channel digital potentiometer. Figure 13c shows the circuitry required to give the discrete index pulse logic state "P<sub>0</sub>" shown in the output waveform (Figure 13b).

The standard HEDS-7000 series digital potentiometer has an internal spring to increase the static friction and a lubricant to increase the dynamic friction of the bushing. The lubricant is designed to make the shaft turn smoothly when operated manually. The internal spring is designed to prevent "backlash" when the operator lets go of the potentiometer's shaft. For applications in which static and dynamic friction are not desirable, special lubricants can be provided which reduce the dynamic friction of the bushing. The internal spring in the potentiometer can also be left out of the assembly to reduce the static friction of the bushing.

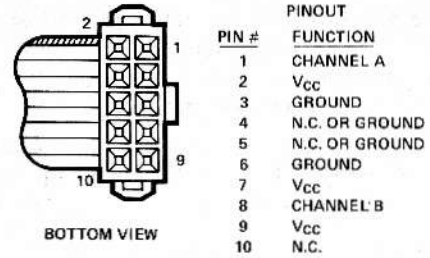
The fourth option is a choice of two different types of cables for electrically connecting the digital potentiometer to the supply voltage (+V<sub>CC</sub>), ground, and to the output channels A, B, and optional channel I. The first choice is a 6 inch, 10 connector ribbon cable which is terminated in a Berg 66900-310 "Quickie II" female connector. The second choice is individual, six inch, color coded leads coming out of the potentiometer with no terminating connector. Figure 14 shows the cabling options for the HEDS-7000 series digital potentiometer. Other cabling options may be available from Hewlett-Packard.

The standard shaft length for the HEDS-7000 series digital potentiometer is 0.50 inches. Other shaft lengths such as 0.31 inches, and 0.81 inches are available. A shaft with a flat side for knob alignment is also available.

#### Dimensions of the Digital Potentiometer

The dimensions of the digital potentiometer are shown in Figure 15.

#### Ribbon Cable Termination



NOTE: REVERSE INSERTION OF THE CONNECTOR WILL PERMANENTLY DAMAGE THE DETECTOR IC.  
MATING CONNECTOR  
BERG 65-692-001 OR EQUIVALENT

#### Color Coded Wire Termination

COLOR	DESIGNATION
WHITE/BLACK/RED	CHANNEL A
WHITE/BLACK/BROWN	CHANNEL B
WHITE/RED	V <sub>CC</sub>
BLACK	GROUND

Figure 14. Digital Potentiometer Cabling Options

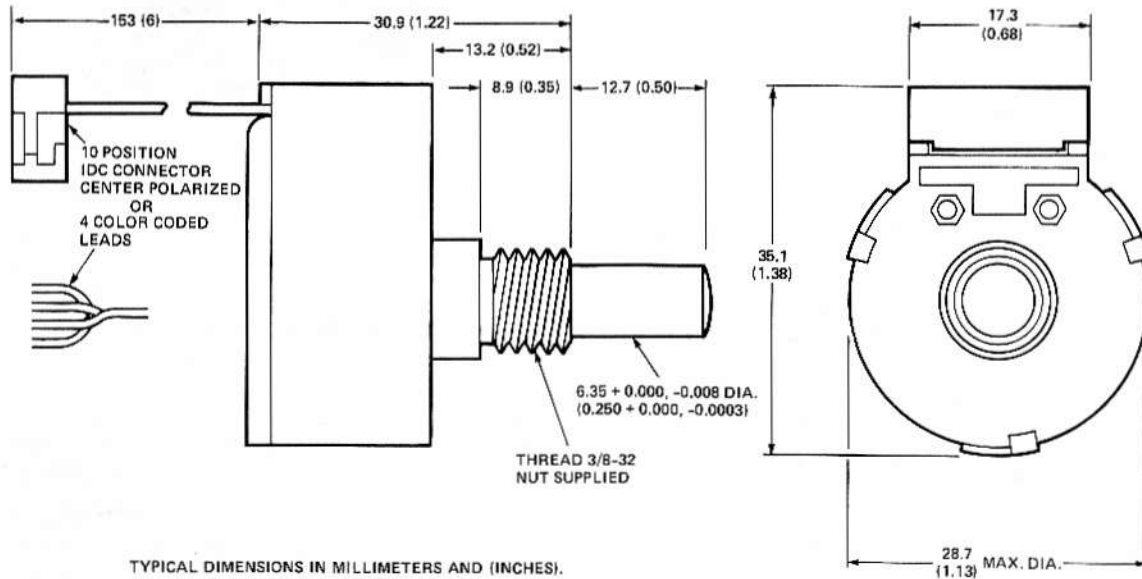


Figure 15. Digital Potentiometer Dimensions

### Assembly Procedure for the HEDS-7000 Series Digital Potentiometer

The procedure for front panel mounting a HEDS-7000 series digital potentiometer is as follows:

1. Drill a 3/8 inch hole in the front panel where the digital potentiometer is to be mounted. Note that on the back-side of the panel, clearances for the digital potentiometer body and ribbon cable are required.
2. Insert the shaft of the digital potentiometer through the hole and tighten the 3/8-32 mounting nut on the threaded section of the brass bushing. **DO NOT PUT**

**MORE THAN 15 IN-LB OF TORQUE ON THE ENCODER BODY WHEN TIGHTENING THE MOUNTING NUT ON THE BRASS BUSHING.**

3. Connect the ribbon cable or wires as shown in the "Termination" diagram (See Figure 14.). Be careful not to connect the output channels A, B, or I to the supply voltage (+V<sub>CC</sub>). If the output channels are connected to the supply voltage the detector ICs will be permanently damaged.



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For more information, call your local HP sales office listed in the telephone directory white pages. Ask for the Components Department. Or write to Hewlett-Packard, U.S.A. — P.O. Box 10301, Palo Alto, CA 94303-0890. Europe — P.O. Box 999 1180 AZ Amstelveen, The Netherlands. Canada — 6877 Goreway Drive, Mississauga, L4V 1M8 Ontario. Japan — Yokogawa-Hewlett-Packard Ltd., 3-29-21, Takaido-Higashi, Suginami-ku, Tokyo 168. Elsewhere in the world, write to Hewlett-Packard Intercontinental, 3495 Deer Creek Road, Palo Alto, CA 94304.