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THESIS

THE DESIGN AND IMPLEMENTATION
OF A POSITION MEASURING SYSTEM FOR
A REMOTELY CONTROLLED VIDEO CAMERA

by

Peter D. Lloyd

June 1989

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A position measuring system for a remotely controlled video camera was designed and built. The camera is intended to be used with the modified Advance Development Model of the AN/SAR-8 Infrared Search and Target Designation System (IRSTD) in use at the Naval Postgraduate School. The video data collected by the camera will be correlated with the infrared data from the IRSTD to develop a background data base that will be used in the development of signal processing algorithms. The measurement system uses two Hewlett Packard HEDS-6000 incremental optical encoders, two Motorola MC68705U3 microprocessors and two digital display devices to measure and present the camera's azimuth and elevation angles to an operator at a remote location. The azimuth can be measured over a range of 360° with a resolution of $\pm 0.0213^\circ$ and the elevation can be measured over 24° with a resolution of $\pm 0.138^\circ$. The resolution is limited primarily by hysteresis, which is due to the backlash in the gears between the transducers and the axes of interest.					
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The Design and Implementation
of a Position Measuring System
for a Remotely Controlled
Video Camera

by

Peter D. Lloyd
Captain, United States Marine Corps
B.S., United States Naval Academy, 1979

Submitted in partial fulfillment of the
requirements for the degree of

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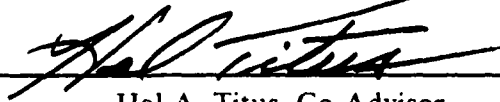


Peter D. Lloyd

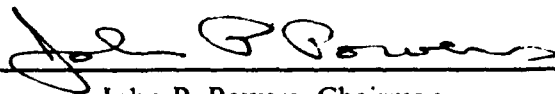
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ABSTRACT

A position measuring system for a remotely controlled video camera was designed and built. The camera is intended to be used with the modified Advance Development Model of the AN/SAR-8 Infrared Search and Target Designation System (IRSTD) in use at the Naval Postgraduate School. The video data collected by the camera will be correlated with the infrared data from the IRSTD to develop a background data base that will be used in the development of signal processing algorithms.

The measurement system uses two Hewlett Packard HEDS-6000 incremental optical encoders, two Motorola MC68705U3 microprocessors and two digital display devices to measure and present the camera's azimuth and elevation angles to an operator at a remote location. The azimuth can be measured over a range of 360° with a resolution of $\pm 0.0213^\circ$ and the elevation can be measured over 24° with a resolution of $\pm 0.138^\circ$. The resolution is limited primarily by hysteresis, which is due to the backlash in the gears between the transducers and the axes of interest.

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THESIS DISCLAIMER

The reader is cautioned that computer programs developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

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I. INTRODUCTION

A. BACKGROUND

The old saying that "every solution breeds new problems", while somewhat pessimistic, quite often rings true in today's increasingly technical world. One such example is the use of infrared (IR) sensors for the detection, tracking and/or identification of targets in a combat environment. IR sensors are ideally suited for use on today's battlefield. They are passive, i.e., they do not need to emit energy in order to detect the presence of potential targets. This allows them to operate during times of emission control when many other target detection systems are useless. They have the ability to "see through" many forms of camouflage and concealment, dust, clouds, smoke, etc., that might otherwise afford an enemy target a safe haven. Additionally, because almost everything on today's battlefield generates some degree of infrared energy, IR sensors can be used to locate and identify a wide variety of targets.

The extent to which a particular IR sensor is useful depends primarily on its ability to detect and identify targets reliably and accurately. Detection of the target is primarily a function of the IR sensor's sensitivity. The classification of a received IR signal as a potential target or as background noise, while still dependant on the sensitivity of the sensors, is primarily a function of the quality of the signal processing algorithms being used to process the received signals. In addition to being reliable these algorithms must be able to process the received signals in "real time" if the system is to be an effective weapons system.

Creation of a background data base that can be used to test some of these algorithms has been one of the tasks being performed by the Naval Academic Center for Infrared Technology (NACIT) located at the Naval Postgraduate School (NPS). The Advanced Development Model (ADM) of the AN/SAR-8 was sent to the NACIT in January of 1984 from the Naval Surface Weapons Center (NSWC) at Dahlgren, Virginia. The ADM was modified, calibrated and placed in service at NPS in December, 1987. The modified version of the ADM, the Infrared Search and Target Designation (IRSTD) System, is currently operational at NPS. [Ref. 1: pp. 8-12]

One way to enhance the usefulness of the IR data being collected at NPS would be to collect video data concurrently with the IR data. A video image of a portion of the horizon would permit visual identification of IR sources in that region. This additional

tional information could be an aid in the development of the signal processing algorithms for the IRSTD. Accordingly, a decision to proceed with video data collection was made by NACIT, and a camera system was purchased. Components of the system include;

- RCA (TC1005/01), Closed circuit video camera.
- PELCO (AI700), Automatic iris servo.
- PELCO (F1.5X), 1.5 times range extender.
- PELCO (MLZ6DT), Desk top lens remote control module.
- PELCO (PT1250DC), Heavy duty Pan/Tilt servo.
- PELCO (MPTV1510DT), Pan/Tilt remote control unit.
- Panasonic (WV-5410), Video Monitor.

In Ref. 1 Ayers describes the IRSTD's detectors:

The IR detectors consist of two vertical arrays of sensing elements in the focal plane of the Schmidt telescope. The telescope is rotated so as to sweep the image across the detector arrays. Each array incorporates a column of 90 indium antimonide photovoltaic linear detector elements. These two arrays are independent of each other and are covered by filters which pass selected wavebands of IR radiation in the 3 to 5 micrometer range. Each element has the angular dimensions of $2 \times .3$ milliradians with the larger being its height. Designated as the lead and the lag, these two arrays are separated by about one-half degree in azimuth. [Ref. 1: p. 17]

Thus, as the IRSTD scans the horizon the resulting IR image has a resolution of approximately 10^{-4} radians (0.00573°) in the horizontal plane and 0.23° in the vertical plane. The video system's smaller field of view can be remotely controlled using the control units listed above. Thus, for the video data to be of any use in the development of the signal processing algorithms, the camera's orientation must first be known, and, in order to determine the pixel-to-pixel correlation between the IR image and the video image, the position of the video camera needs to be known with the same kind of accuracy as the IR image. The design and implementation of a position measuring system for this remotely controlled video camera is the subject of this thesis.

B. DESIGN SPECIFICATIONS

The design specifications for this problem were relatively straight forward. The position measuring system needed to meet the following criteria.

- The system should be able to measure the elevation angle (tilt), above and below the horizontal reference plane of the camera over a range of $\pm 12^\circ$.
- The measured elevation angle should be accurate to within $\pm 0.23^\circ$.

- The system should be able to measure the bearing (pan), left or right of some arbitrary reference, of the camera over a range of 360° .
- The measured bearing should be accurate to within $\pm 10^{-4}$ radians.
- The output should be displayed in a convenient form. The display should be collocated with the camera servo remote controls, an indoor site approximately 200 meters away from the camera.
- Portions of the measuring system required to be collocated with the camera should be weatherproofed.
- The system must be reliable and should be simple to operate.

II. DESIGN STRATEGY

A. GENERAL

A position measuring system, like any system, is a combination of devices interconnected to perform a certain function. The most basic position measuring system (see Figure 1) consists of only four such devices: a transducer, a signal conditioner, a display device and a power supply. More complicated position measuring systems include those designed to take a number of different measurements either simultaneously or consecutively. Still more complex systems multiplex these various measurements over a single channel to some distant location where they can be processed and displayed. [Ref. 2: pp. 2-14]

The design specifications for the camera position measurement system (subsequently referred to as the "measurement system") required that two measurements, pan and tilt, be taken simultaneously and transmitted some distance to a remote display. Two separate transducers, capable of independent operation, were therefore required. In order for both the azimuth and the elevation to be displayed simultaneously two display devices were also required.

Several pairs of RG-178 coaxial cable were available to transmit signals between the camera servo and the remote control site. Since the cable was available and it was desirable to reduce the system complexity, a decision was made not to multiplex the data over a single channel. Instead, each measurand would have a separate transducer, a dedicated signal processor and a unique display device. Position information for each axis would be transmitted over a dedicated channel.

The physical locations of the transducers and the display devices were dictated by the design specifications; however, there was some flexibility in deciding where to locate the signal conditioner. Site selection was based on an attempt to maximize total system performance and simplicity while ensuring the maintainability and environmental integrity of the signal conditioner. The only advantage to locating the signal conditioner with the camera servo and the transducer would have been to limit the distance that the transducer's output signal would have to be transmitted to the processor. On the other hand, separating the signal conditioner and the transducers would limit the distance over which the conditioned signal would have to be transmitted to the display device. The trade-off here was not clear cut and would probably depend on the specific hardware

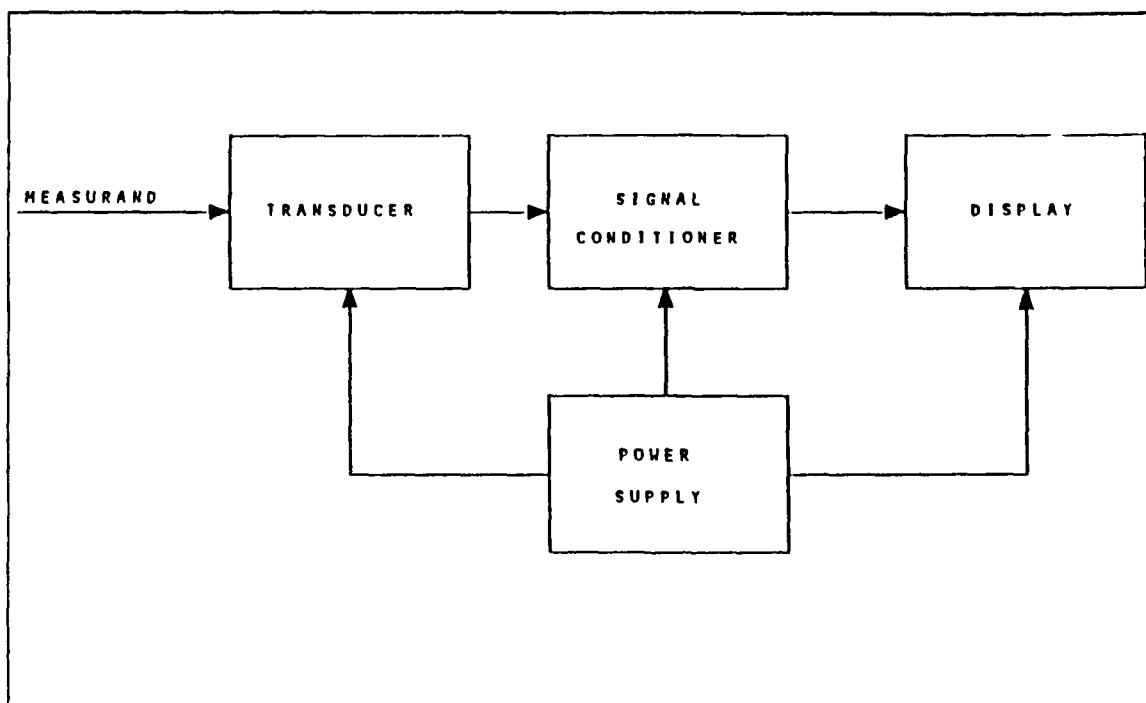


Figure 1. Basic Electronic Position Measuring System: From Ref. 2: p. 2

used and the speed of rotation of the camera servo. There was one significant advantage, however, to collocating the display and the signal processor; since they would both be indoors, the need for weatherproofing the signal processor would be eliminated.

Power was available at both ends of the system, there was therefore no requirement to have a common power supply for the entire system. One supply could be used to provide power to the two transducers, collocated with the camera servo, and a second supply could power the signal conditioner and the displays.

A block diagram of the prototype measurement system is shown interconnected with the camera positioning system in Figure 2. Once this basic system layout had been determined, proper selection of the actual hardware was necessary. The design criteria were the primary consideration in the initial stages of the hardware selection. Final selection of the specific components, however, involved balancing additional factors, such as availability and cost against the system requirements.

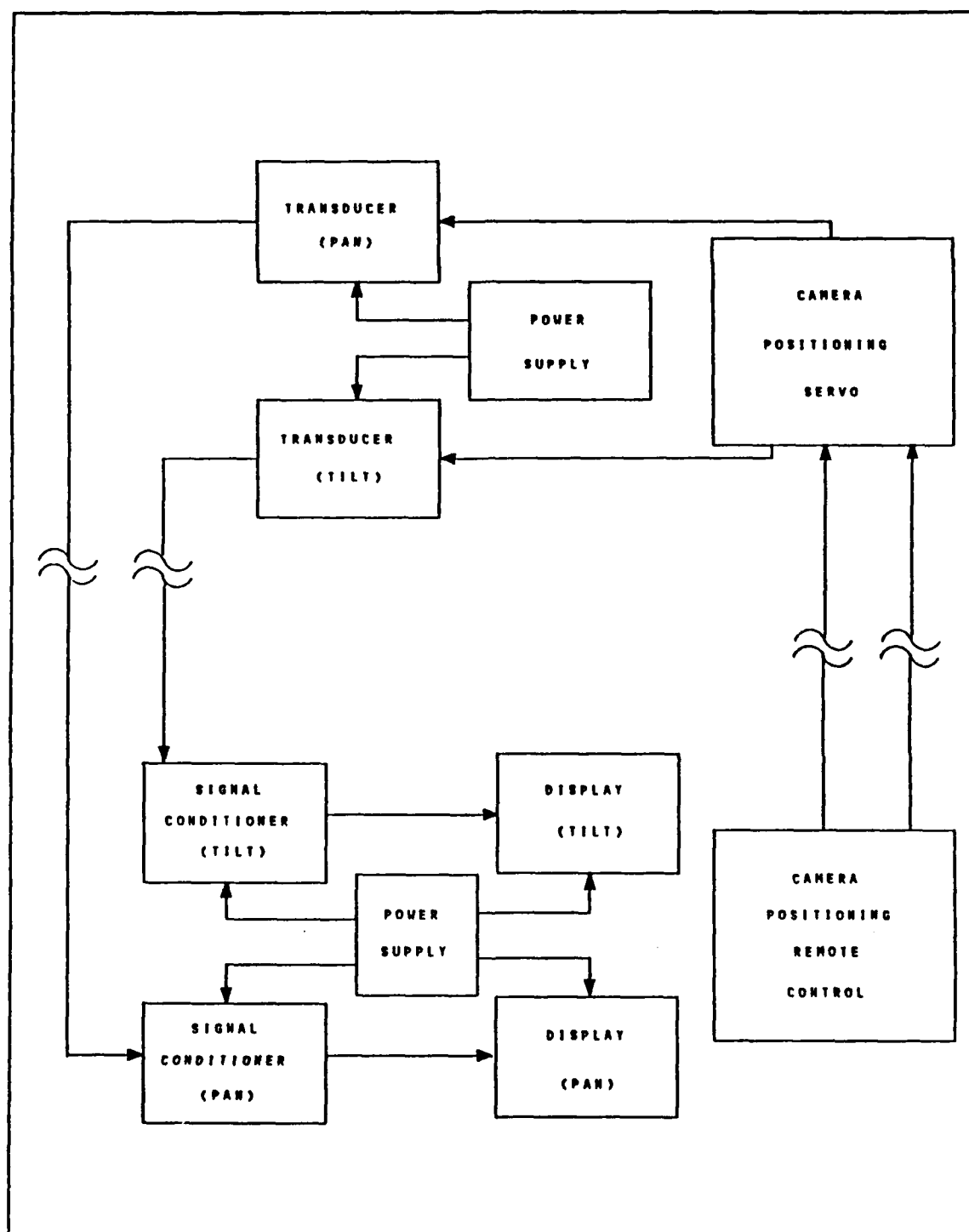


Figure 2. Camera Position Measuring System

B. TRANSDUCERS

1. General

Since in practice most measurement systems do not have the ability to respond directly to the measurand, transducers are used to convert one physical quantity (e.g., angular position) into another, more usable quantity or signal (e.g., an electrical signal) [Ref. 3: p. 1-4]. The transducer is therefore a vital part of any measurement system, and although none of the components of this system could have been chosen independently of the other elements, proper transducer selection appeared to be the key to meeting the design specifications. Thus, selection of a transducer was the next step in the design process.

Using the selection guidelines given by Norton on pages 51-53 of Ref. 2 and the design criteria stated previously, several observations and decisions were made which significantly reduced the number of transducers considered feasible for use in the measurement system. The fact that the servo was capable of rotating the camera left or right, and up or down suggested that the transducer should be capable of detecting both increasing and decreasing angles on both axes. Additionally, since the servo was anticipated to rotate the camera through one 360° arc in the horizontal plane, the transducer used to measure this angle (subsequently referred to as the "pan transducer") needed to have a comparable range capability. The range requirement for the "tilt transducer" (used to measure the elevation angle) was much less restrictive. These factors, angular bidirectional capability and full scale range, eliminated a great number of transducers from the list of candidates.

The list was further narrowed by the accuracy requirements previously specified. Again the accuracy in the horizontal plane placed a much more severe limitation on the selection of a transducer than the accuracy requirements for the vertical plane. The following paragraphs in this section outline the logic used in the selection of the transducers. The factors considered in the selection process included the following;

- The accuracy requirements given in the specifications.
- The ease with which a specific transducer could be installed on the servo.
- The ability to weatherproof the servo and the transducer once the transducer was installed.
- The rotation speed of the camera about the servo axes.
- The extent to which a particular transducer/mounting configuration would modify the measurand.
- Cost effectiveness.

- Availability.
- Signal conditioning requirements.
- The extent to which the selection of a particular transducer would simplify or complicate the modification or expansion of the measurement system.

2. Transducer technologies

Displacement transducer technologies fall into three very broad categories depending on whether they are capable of measuring linear or angular displacement, or both. Some technologies could be eliminated immediately since they were clearly not suited for measuring angular position. Strain gauge displacement transducers, inductive displacement transducers and vibrating-wire displacement transducers are examples of such devices. The following paragraphs briefly describe the different transducer technologies which were investigated. Table 1 on page 18 summarizes the salient points of the discussion. [Ref. 2: pp. 90-117].

a. *Reluctive Displacement Transducers*

The rotary variable differential transformer (RVDT), which operates by detecting a change in the reluctance between coils, offers excellent resolution, dynamic characteristics, linearity and life expectancy [Ref.3: p. (2-14)]. Figure 3 shows a schematic diagram and a simplified cross-section of an RVDT. The ferromagnetic, cardioid-shaped core is attached to a shaft as shown. As the shaft rotates, the inductive coupling between the primary and each of the secondary coils changes. When the cam is symmetric with respect to the two secondary coils, their output voltages are equal but opposite in phase which results in a differential output voltage of zero. As the shaft rotates away from this "null" the differential output voltage varies as shown in Figure 4. The linear region of the curve is limited to the angles between $\pm 40^\circ$ of the reference. Thus, the RVDT could not be used on the Pan axis. It was however, initially considered as a candidate for the Tilt transducer. [Refs. 2: pp. 93-99, 3: pp. (9-10)-(9-13) and 4: p. 19]

Another type of reluctance displacement transducer is manufactured by Farrand Controls. Their INDUCTOSYN rotary position transducers have accuracies to ± 1.5 arc sec ($\approx (4 \times 10^{-4})^\circ$). Unfortunately, these devices are 11.89 inches in diameter, and mounting them on the camera servo would have been extremely difficult, if not impossible. [Refs. 2: pp. 89-111, 5]

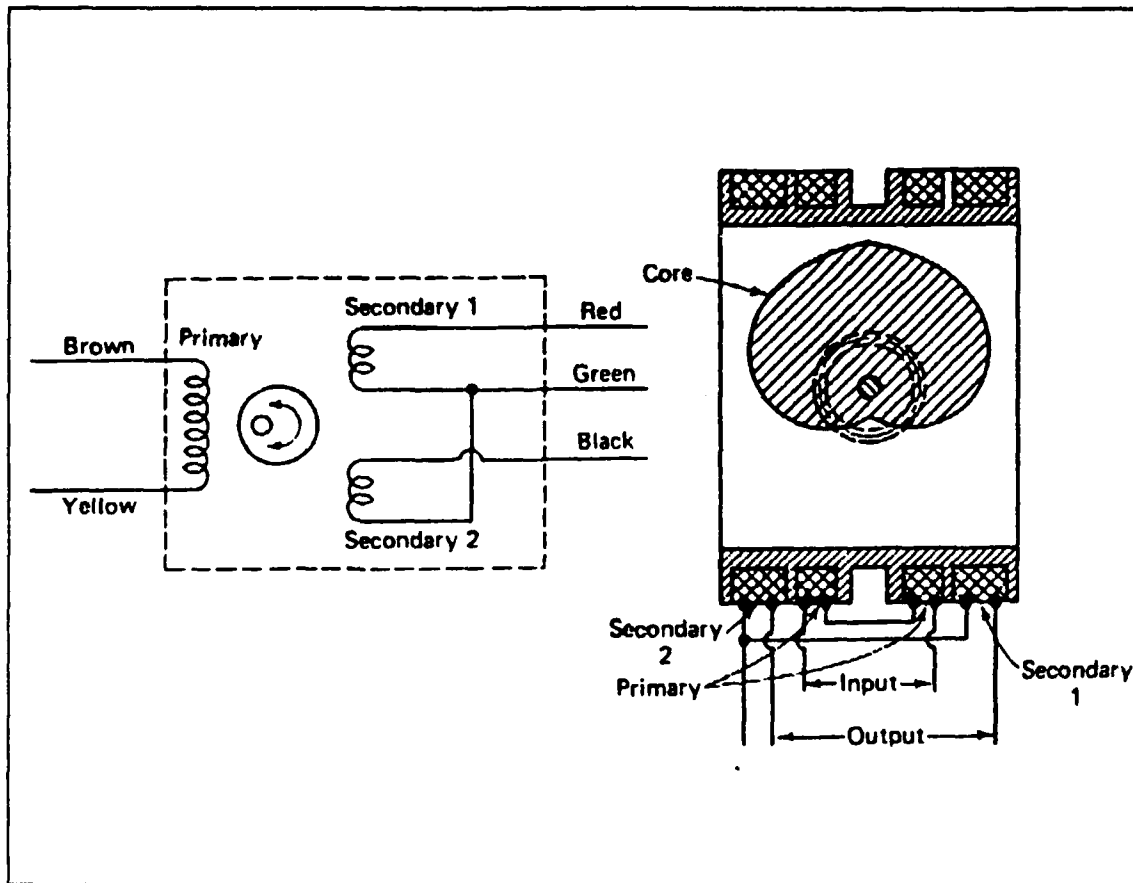


Figure 3. RVDT Schematic: From Ref. 2: p. 98.

b. Capacitive Displacement Transducers

Angular displacement can also be measured by coupling the rotating component to the shaft of a variable capacitor in the manner shown in Figure 5. Lenk describes the operation of the capacitive displacement transducer quite succinctly.

The capacitor ... consists of a metal plate that moves between two fixed metal plates as a shaft is rotated. The three plates, and the air between them, form a capacitor with a capacitance that varies in proportion to the degree to which the plates are meshed. When the plates are completely meshed, the capacitance is at its maximum. When the plates are completely unmeshed, the capacitance is at minimum. [Ref. 4: p. 18]

Capacitive displacement transducers offer many of the advantages of reluctance displacement transducers. They have an effective range of about 300° which, while better than the RVDT's range, is still not adequate for the pan axis [Ref. 4: p. 18]. Additionally they are more sensitive to changes in the ambient temperature. Since the

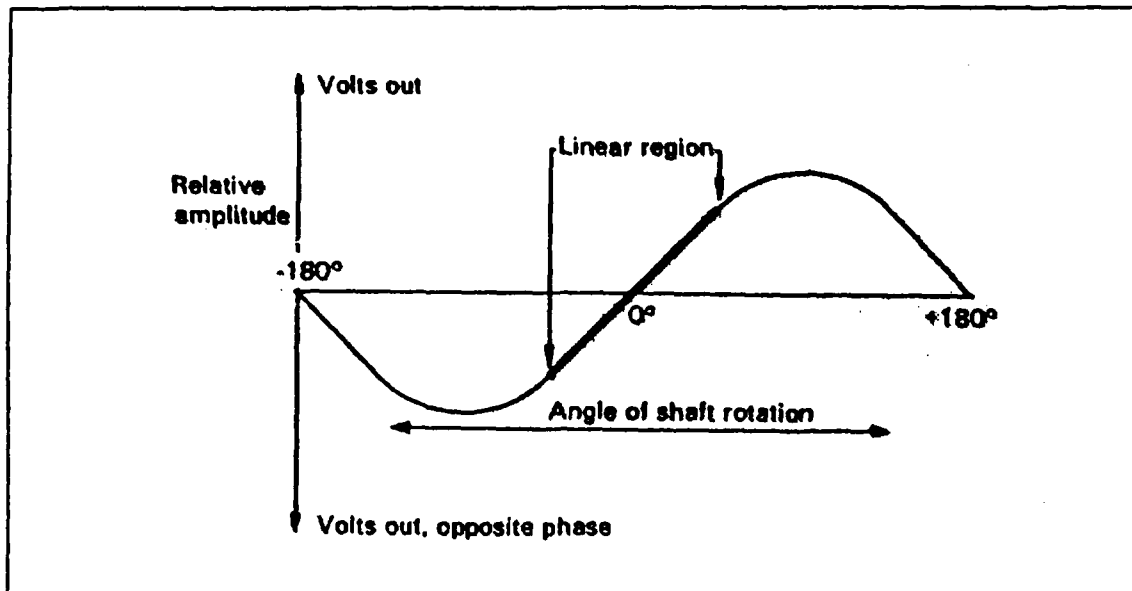


Figure 4. RVDT Output Characteristics: From Ref. 2: p. 95.

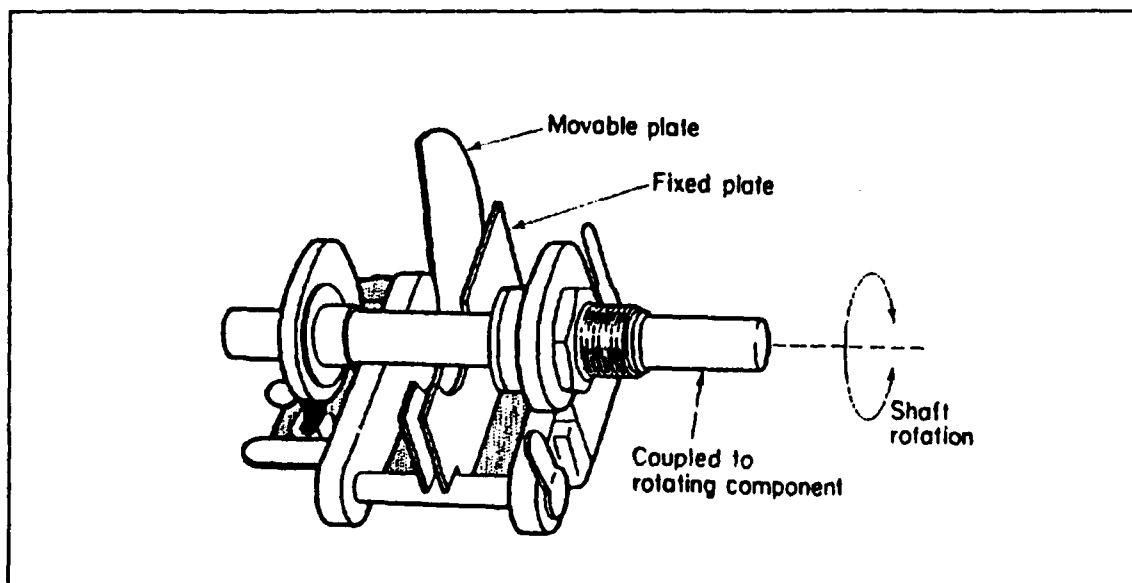


Figure 5. Capacitive Displacement Transducer: Ref. 4: p. 18.

measurement system was being designed to be used outdoors, the use of a capacitive displacement transducer would have required the addition of a temperature compensator in the design. While possible, this would have increased the system complexity considerably. [Ref. 2: pp. 90-91]

c. *Potentiometric Displacement Transducers*

Another very common and relatively simple family of transducers operate by measuring the change in resistance caused by a change in the measurand. There are a wide variety of such devices available. The basic form of potentiometric angular displacement transducers uses a resistance element, formed into an arc, and a movable electrical contact that rotates about the axis of interest. By measuring the change in resistance that results from a change in position, one is able to determine the angular displacement. The resistive element is typically a wirewound element, the resolution of which is determined by the number of turns per unit length of the resistance element. The angular resolution can be increased by increasing the turn density (wires/degree) of the potentiometer.

The practical limit for wire spacing on wirewound elements according to Ref. 6 is between 500 and 1000 turns per inch. From Figure 6 one can see that this limits the angular resolution for a single-turn device to

$$\Delta\theta(\text{rad}) \approx \tan\left(\frac{\Delta x(\text{in})}{R(\text{in})}\right) \quad (1)$$

Therefore,

$$\Delta\theta(\text{rad}) \approx \frac{2\Delta x}{D} = \frac{0.002(\text{in})}{D(\text{in})} \quad (2)$$

To achieve the 10^{-4} rad resolution, specified for the Pan axis, with a single turn potentiometer would therefore require a 20 in diameter potentiometer. Mounting a device this large on the camera servo was simply not feasible. Potentiometers are, however, available with multiple turns. Shaped in a helix fashion similar to that shown in Figure 7, the total length of the potentiometer can be increased, which in turn increases its resolution, without increasing the diameter of the device.

Increasing the resolution of the potentiometer by increasing the turn density in any of the manners described above, however, increases the output impedance of the device, which leads to increasing nonlinearity between the measurand and the transducer

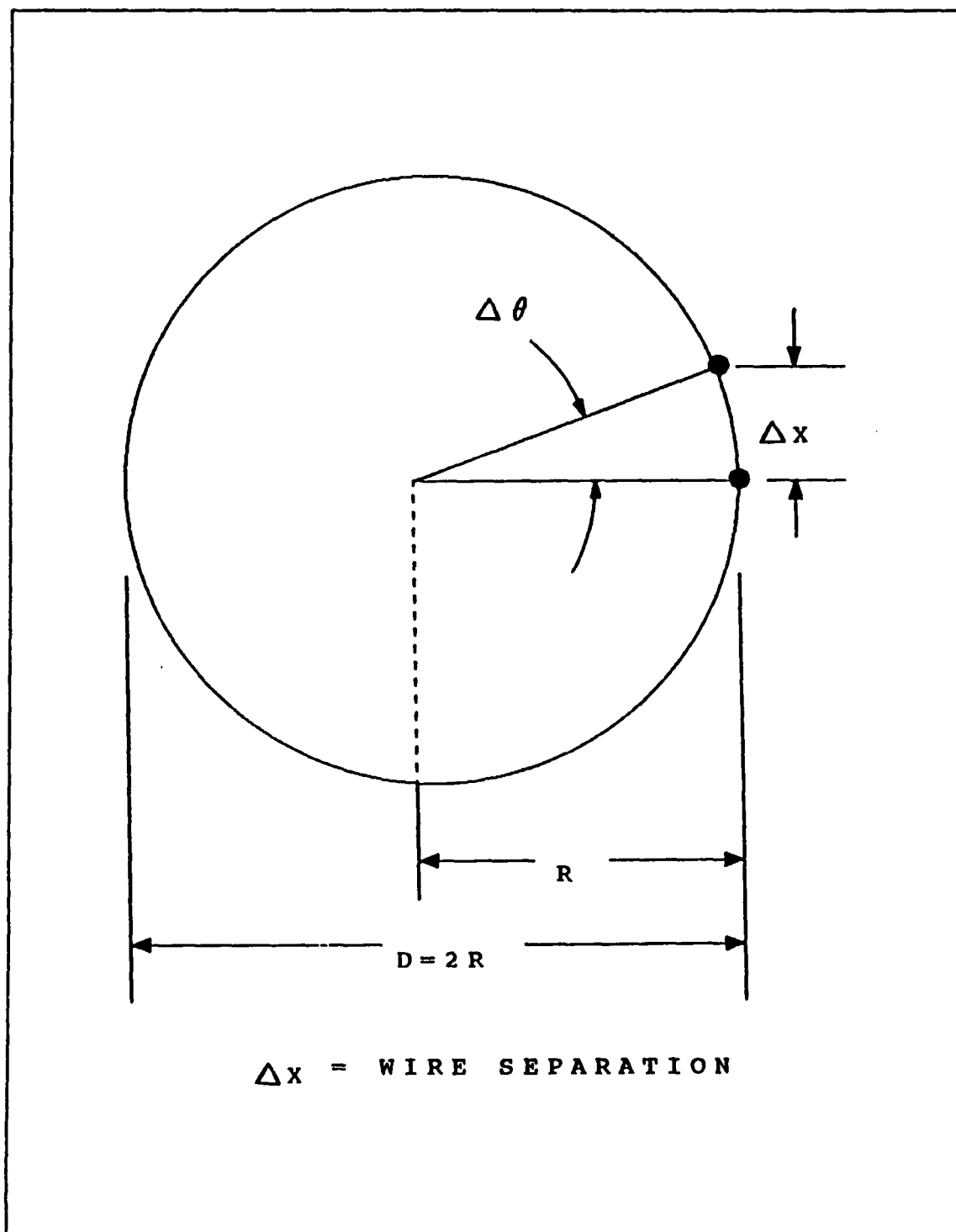


Figure 6. Geometry of an Angular Potentiometric Transducer

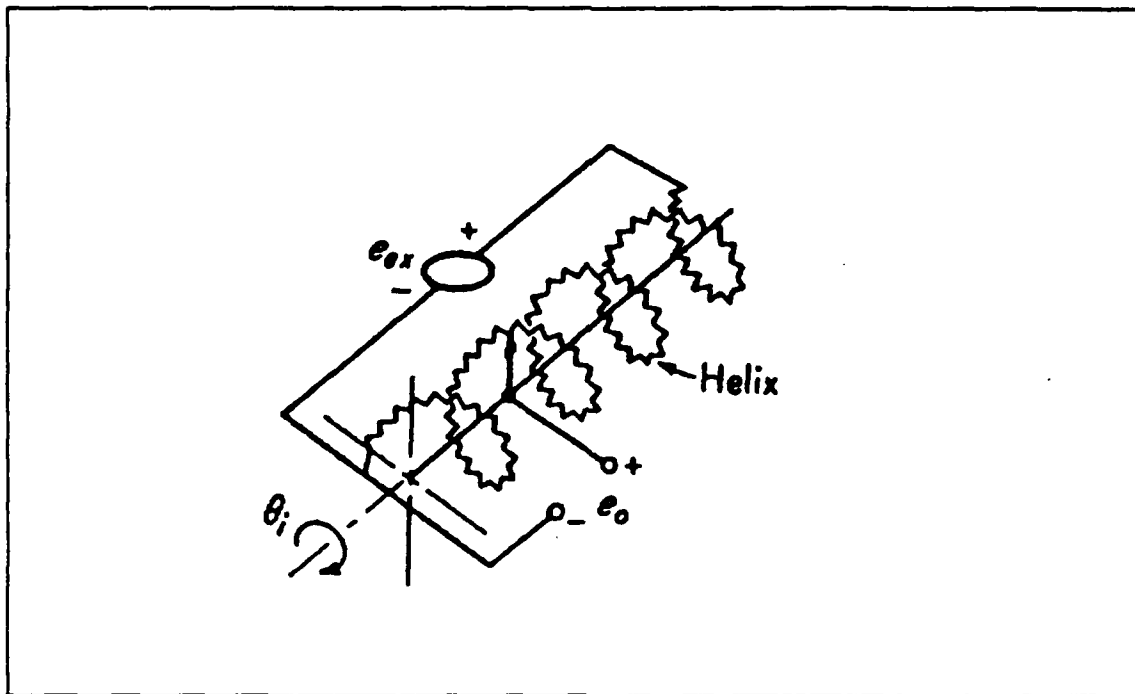


Figure 7. Multiturn Potentiometer: From Ref. 6: p. 218

output. The nonlinear relationship can be seen by analyzing the circuit shown in Figure 8. In the diagram the following variable definitions apply:

- e_x = Input voltage,
- e_o = Output voltage,
- R_p = Total resistance of the potentiometer,
- R_m = Meter resistance,
- x_t = Total range of the potentiometer, and
- x_i = Actual displacement of the potentiometer.

Assuming that R_p is uniformly distributed over x_t , analysis of the voltage divider circuit gives,

$$\frac{e_o}{e_x} = \frac{1}{\frac{x_i}{x_t} + \left(\frac{R_p}{R_m} \right) \left(1 - \frac{x_i}{x_t} \right)} \quad (3)$$

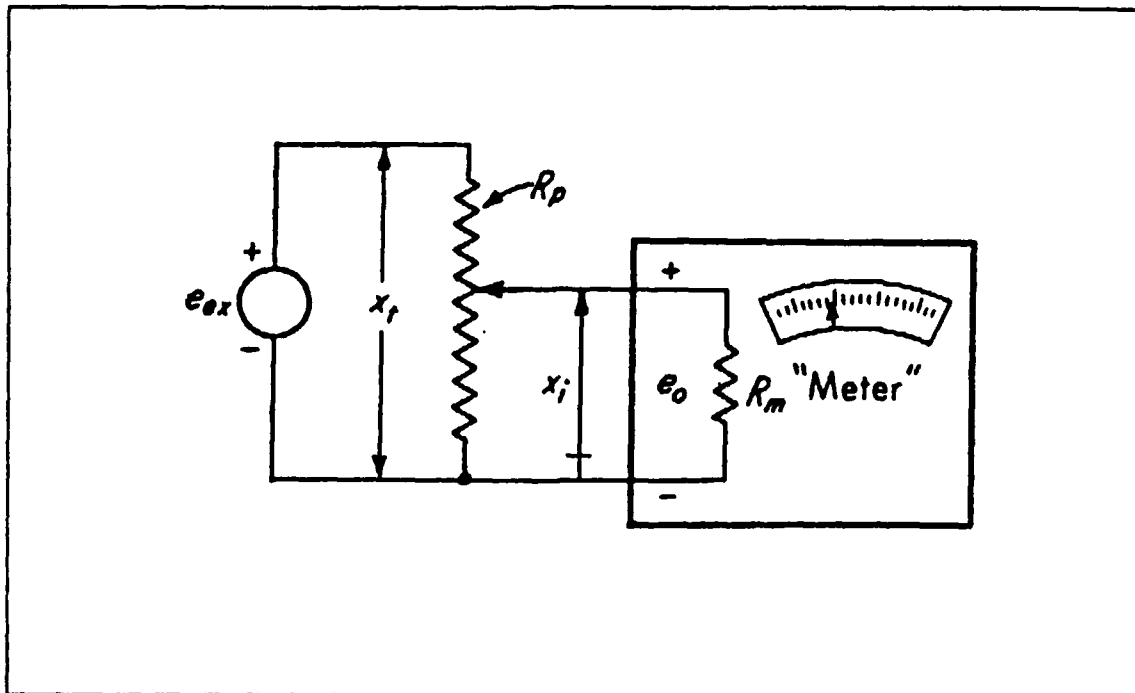


Figure 8. Potentiometric Transducer: From Ref. 6: p. 219

Thus, the ideal (i.e., linear) relationship,

$$\frac{e_o}{e_x} = \frac{x_i}{x_t} , \quad (4)$$

is true only when $R_p R_m = 0$, and since $R_p \neq 0$, and $R_m \neq \infty$, the nonlinear relationship in (3) will always exist. Doebelin states that "for values of $R_p/R_m < 0.1$ the position of maximum error occurs in the neighborhood of $x_i/x_t = 0.67$, and the maximum error is approximately $15(R_p/R_m)$ percent of full scale." [Ref. 6: p. 218] Other potentiometric transducers, which use a resistive element made of carbon film or a conducting plastic, are not subject to the same kind of resolution limitations as wirewound devices; however, they do have high output impedances and the corresponding nonlinearities described above. [Ref. 6: pp. 217-224]

A high quality multiturn potentiometer used in conjunction with a high quality voltmeter offered one possible solution to the design problem. However, the nonlinearity of this arrangement was a significant disadvantage, and the primary reason why potentiometers were not used.

d. Encoders

The angular displacement transducer, referred to in general as an angular encoder or shaft encoder, converts an angular displacement into a digital signal without the use of an analog-to-digital converter. In today's increasingly digital world this can be a distinct advantage.

There are three different transduction methods used in encoders. Magnetic encoders use a pattern made from magnetized and nonmagnetized segments and one or more magnetic sensors that register as either "1's" or "0's" depending on the magnetic characteristics of the section that they are adjacent to. Brush-type encoders are similar, but the sections are made of conducting and nonconducting materials. The conductors are all tied to a common source and the "sensor" is one or more brushes connected to the output. When the brush is in contact with one of the conductors the output is "on" and when the brush is in contact with an insulator the output is "off". Optical encoders (See Figure 9) use a pattern of opaque sections marked on an otherwise transparent disk. A light emitting diode (LED), or other light source, is placed on one side of the disk, and as the disk rotates a light sensor on the other side of the disk "sees" periods of dark and light which it converts into a digital signal. [Ref. 2: p. 106]

Angular encoders are further categorized as either absolute encoders or incremental encoders. Absolute encoders, similar to the optical encoder shown in Figure 9, use a multitrack pattern on a code wheel to produce a unique coded output signal for each incremental change in the measurand. These wheels use a variety of codes, including binary code, binary-coded decimal (BCD) and Gray code, to determine the shaft position. The resolution of an absolute shaft encoder is limited by the number of tracks on the disk and the type of code used. A simple binary or Gray code encoder, which are more efficient than the BCD encoders, with N tracks has an optimum angular resolution of

$$\Delta\theta = \frac{360^\circ}{2^N} \quad (5)$$

Thus, to achieve the desired resolution of 10^{-4} radians on the Pan axis with an absolute encoder would require a code wheel with $N \geq 16$. Since the output from the encoder is unique for each position, these devices are not affected by power outages, and the requirements for a signal processor for such a device would be limited to a simple decoding circuit. These encoders can measure angles of up to 360° without ambiguity.

Incremental encoders use a code wheel which has only one track. As the shaft of the incremental encoder rotates the output from the encoder is a series of equally spaced pulses. These pulses can then be used as an input signal to an up/down (U/D) counter of some sort. The output from the counter is an indication of the displacement of the axis from some predetermined reference. The resolution of an incremental encoder is a function of the number of pulses the code wheel generates per revolution and is given by;

$$\Delta\theta = \frac{360^\circ}{n \times \text{PPR}} \quad (6)$$

where PPR is the number of pulses per revolution of the code wheel, and n is the number of revolutions that the code wheel makes per revolution of the axis of interest. If the incremental shaft encoder was mounted on the shaft of interest ($n=1$) at least 62,832 PPR would be required to ensure a resolution of 10^{-4} radians.

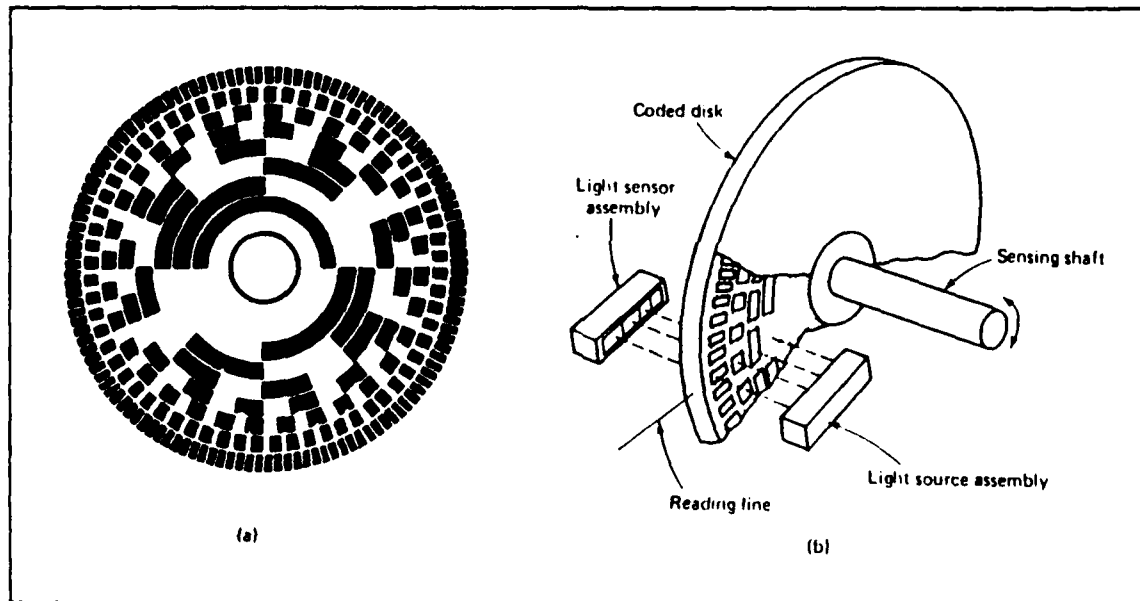


Figure 9. Absolute Photoelectric Angular Encoder: (a) typical code disk; (b) encoder elements. From Ref. 2: p. 107.

Shaft encoders currently range in price from less than \$100.00 to several thousand dollars depending on their capabilities and the method of transduction used. Litton Encoder's Model 60 absolute shaft encoder uses a natural binary code, has 15 tracks (0.1917 mrad resolution) and is available "off the shelf" for approximately \$3000.

Other absolute encoders with comparable resolutions are available at similar prices. No incremental encoders were found which offered the same kind of resolution as Litton's Model 60; however, because they are not limited to one revolution of the axis, the resolution of an incremental encoder can be improved by a factor of n by causing its code wheel to rotate n times for every rotation of the axis of interest. Incremental encoders with 1024 PPR are available from a variety of manufacturers for about \$100 each. Connecting such a device to the axis of interest via a gear train with a 50:1 ratio would theoretically result (from (6)) in a resolution of 0.1227 mrad. Incremental encoders do require more complex signal processing than absolute encoders, and they are affected by power shut-off. Additionally, unlike absolute encoders, any missed or erroneous count that occurs with an incremental encoder will cause a persistent error. [Ref. 7: p. 16]

After considering the measurement system performance criteria and the capabilities and limitations of the various transducers, the use of an incremental, optical shaft encoder appeared to be the best selection for the transducer for each axis. This decision involved balancing the various advantages and disadvantages of the different transducers. The following list gives a summary of the key considerations in this decision.

- Small, lightweight, highly accurate and relatively inexpensive models were readily available. Being small and lightweight suggested that mounting and weatherproofing the transducers in the camera servo should not be too difficult.
- Absolute encoders offer almost all of the advantages of the incremental encoders; they are not affected by power outage, they require less complex signal processing and one time counting errors do not persist. However, these features did not seem to justify the additional price of an absolute encoder.
- Linearity and loading problems associated with the potentiometric displacement transducers were avoided.
- Direct conversion of the measurand into a digital signal precluded the requirement for an A/D converter. (This would have been a disadvantage had the use of an analog signal conditioner been anticipated.)
- Using two identical transducers, each capable of meeting the specifications for the pan axis, would reduce system complexity while still ensuring that the design specifications were met.

C. MOUNTING THE TRANSDUCER

Once the decision to use an incremental optical shaft encoder was made, selection of a specific model remained. Before selection of an actual piece of hardware could be

Table 1. ANGULAR DISPLACEMENT TRANSDUCERS

TRANSDUCER DESIGN	RANGE	RESOLUTION	LINEARITY	OTHER
Reluctive Displacement (RVDT)	0° - 360°	Theoretically infinite; Limited by the signal conditioner.	Poor beyond $\pm 40^\circ$	
Reluctive Displacement (Farrand's INDUCTOSYN)	0° - 360°	$\pm (4 \times 10^{-4})^\circ$	Good	Large size limits usefulness with the camera measuring system.
Capacitive Displacement	0° - 300°	Theoretically infinite; Limited by the signal conditioner.	Good	Temperature sensitive
Potentiometric Displacement	0° - 3500°	Device dependent	Device dependent	The trade-off between range, resolution and linearity due to the loading effect of the noninfinite impedance of the signal conditioning devices used.
Absolute Encoders	0° - 360°	$\frac{360^\circ}{2^n}$	Good	No A/D conversion required. Insensitive to power shut-off.
Incremental Encoders	$\pm \infty$	$\frac{360^\circ}{n \times \text{PPR}}$	Good	Simple. Requires more signal processing than absolute encoder but is less expensive.

done though, one additional practical consideration had to be made; where and how could a transducer be mounted in or on the servo in order to measure the position of the Pan and Tilt axes?

The physical layout of the camera positioning servo made direct connection of any type of transducer to the axes of interest virtually impossible without major modification of the servo itself. Major modification of the servo would have been expensive, time consuming and outside the scope of this thesis. It was not considered an option in this case. Measurement of the Pan and Tilt axes' displacements was most readily accomplished indirectly. Each axis of the servo is positioned by a separate dc motor via a gear train. By mounting the shaft encoder code wheels to the sprockets (items 42 and 43 in

Figure 10) which are each attached to one of the worms, an indirect measurement of the position of each of the wormgears (items 5 and 7 in Figure 10) was possible. This approach, made necessary by the servo design, was a mixed blessing.

The backlash in a worm-wormgear connection will cause the position of the worm to be different for any given wormgear position, depending on whether that position is approached from a clockwise or a counterclockwise direction. In order to correctly determine the displacement of the wormgear by measuring the displacement of the worm, the amount of backlash present must be known (i.e., would have to be determined experimentally) and accounted for by the measurement system. This nonlinear source of error would not have been a concern if the servo was only required to rotate in one direction. This was not the case, however, and hysteresis eventually was determined to be the largest single source of error in the measurement system. A more complete discussion of this topic is included in Chapter IV of this thesis.

Assuming for the moment that the effects of the backlash in the gears could have been completely compensated for, mounting the shaft encoders on the worm provided a measurement advantage analogous to the mechanical advantage afforded by the gear train. Initial measurements indicated that each of the worms turned through $18,000^\circ$ ($50 \times 360^\circ$) for every 360° rotation of the corresponding wormgear. This meant that a shaft encoder with 100 divisions per 360° attached to the worm axis could do the same job as a 5,000 division per 360° encoder attached to the wormgear axis.

D. SELECTING AN OPTICAL SHAFT ENCODER

Once the basic decisions to use incremental optical shaft encoders and to mount the encoders on the worms inside the servo housing had been made, selection of the specific pieces of hardware was relatively straight forward and was primarily a matter of convenience and expediency.

Returning to the design specifications for a moment; the most stringent requirement was to be able to measure the position of the pan axis to within $\pm (5.73 \times 10^{-3})^\circ$. To determine the required resolution for the optical shaft encoder, the following calculations were performed.

First,

$$\frac{360^\circ/\text{Revolution}}{5.73 \times 10^{-3}^\circ/\text{Division}} \approx 62,827 \frac{\text{Divisions}}{\text{Revolution}} \quad (7)$$

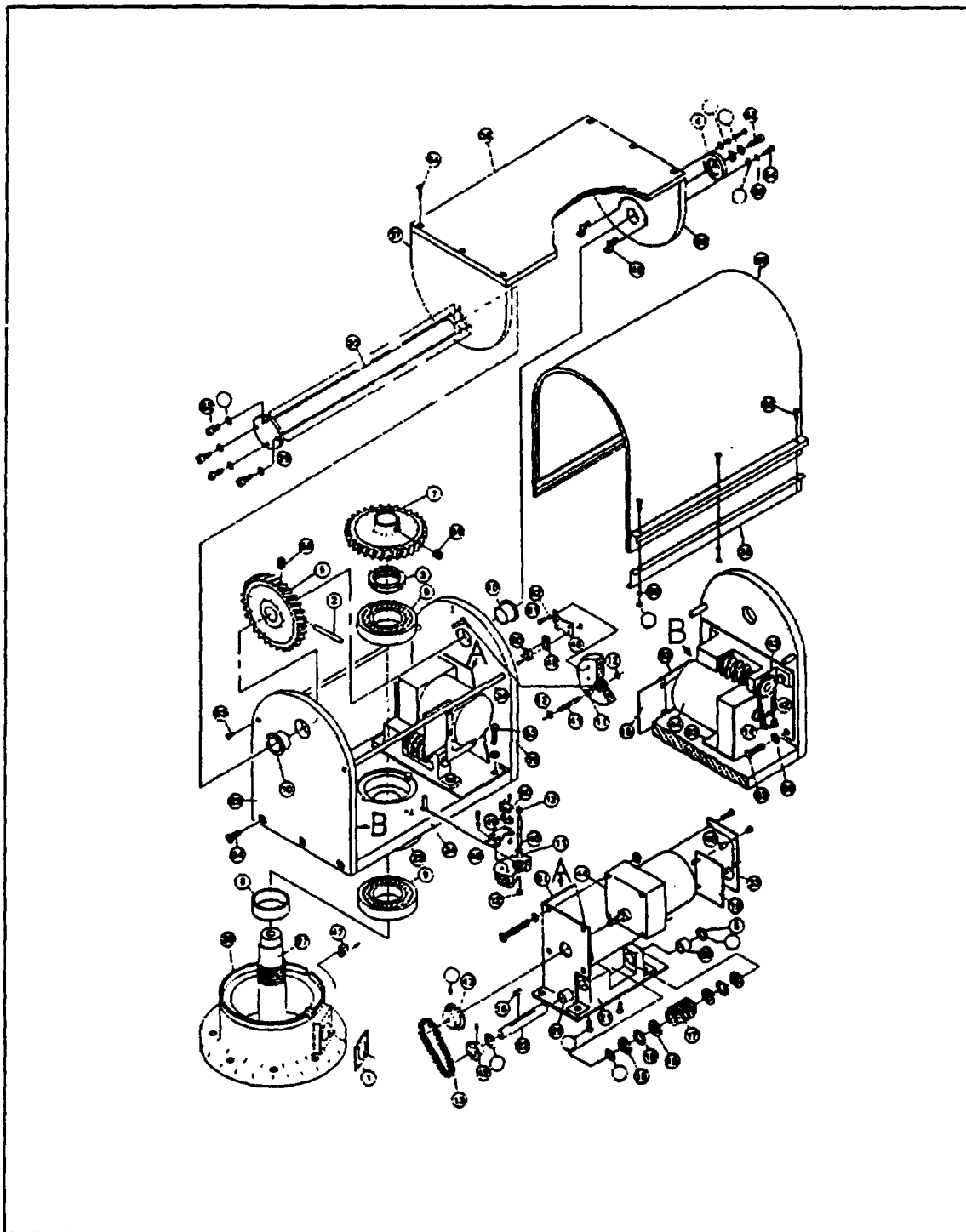


Figure 10. Camera Servo: From Ref. 8: p. 12.

Then, considering the 50:1 gear advantage,

$$\frac{62.827}{50} \approx 1257 \frac{\text{Divisions}}{\text{Revolution}} \quad (8)$$

The task therefore was to find an optical shaft encoder capable of detecting bidirectional rotation with at least 1257 Divisions/Revolution in a package small enough to mount in the servo housing on the worm axis. There was no absolute size limitation; however, due to the construction of the servo it was desirable to find an encoder that was no more than 3 in. in diameter and no more than 1.5 in. in width. The companies that make shaft encoders are capable of custom building devices to meet a customer's specific needs. However, the prices are high, and the lead times are long for these special order parts. The encoder for this system needed to be reasonably priced and readily available to ensure timely completion of the project and to facilitate replacement, if necessary, in the future.

Optical shaft encoders are manufactured by numerous companies including Litton, Honeywell, BEI, IVO and Hewlett Packard. Sales literature from these companies was reviewed prior to making a decision on the specific shaft encoder model to be used. Incremental optical shaft encoders with resolutions that range from one pulse per revolution (PPR) to 2540 PPR are available off the shelf from one or more of these companies. While evaluating sources of supply, incremental optical shaft encoders were also found in use in various laboratories and shops in the Electrical Engineering and Physics Departments at the NPS. Encoders immediately available from stock included two Vernitech 1200 PPR (model VOE-23-1200-AI-LD5-2L1-1603-2) encoders from the Physics Department and two Hewlett Packard (HEDS-6000 J06) encoders from the Electrical Engineering Department. The use of the Vernitech encoders was ruled out because they were unable to detect bidirectional movement without increasing the complexity of the signal conditioning subsystem. Additionally, technical literature requested on two separate occasions from Vernitech was never received.

The HEDS-6000 J06 encoders have a resolution of 1024 PPR. Each encoder provides displacement information in the form of TTL logic level signals via two output channels. When the encoder is properly adjusted the two output signals have a 90° phase difference. This quadrature phase relationship permits these encoders to detect bidirectional displacements. Rotation in one direction will cause Channel A to lead

Channel B (in phase), while rotation in the other direction will cause Channel B to lead Channel A. [Ref. 9: p. 2]

The presence of two output channels in quadrature phase has an additional benefit that is useful in some applications. Since the amount of position information has essentially been doubled, if the signal conditioner is designed to detect both the leading and trailing edges of one of the output channels the resolution of the measurement system can be doubled. The difficulty with using this technique is that multiple oscillations about a single point cannot be detected as such. If the camera were to oscillate less than one half of a pulse width about a transition the signal conditioner would detect and erroneously count the multiple transitions. [Ref. 7: pp. 13-16]

With 1024 PPR, which is less than the 1257 PPR required to meet the 0.1 milliradian accuracy specification on the pan axis, the maximum resolution available, if the HEDS-6000 was attached to the worm, can be calculated as;

$$\frac{360^\circ}{(50 \times 1024)} = (7.03125 \times 10^{-3})^\circ \text{ Pulse}^{-1} . \quad (9)$$

Although this was not sufficient to satisfy the pan axis resolution specification of $(5.73 \times 10^{-3})^\circ \text{ Pulse}^{-1}$ all of the other performance criteria could be satisfied. The trade-off seemed reasonable and was approved prior to proceeding further with the system design.

E. THE DISPLAY

Selecting a method to display the final system output was certainly the least demanding task required in the design of the system. With an expected resolution on the pan axis of approximately 0.007° over a range of 360° (a ratio of about 1:51,500) an analog display seemed out of the question. A five or six digit digital display on the other hand offered a simple, reliable and cost efficient means of presenting the output. Constructing the displays from individual, seven-segment, common anode, LED devices, and the appropriate display drivers was a straight forward task.

F. THE SIGNAL CONDITIONER

Anticipating the use of two incremental shaft encoders as the transducers for the measurement system and the use of digital readouts as the display devices significantly reduced the number of possibilities for the signal conditioning subsystem. In addition to the hardware and software described in each of the subsequent discussions, each

technique listed here would require an edge detector to detect the transitions in the TTL signals from the shaft encoders.

- Up/down counter with table look-up.
- Up/down counter and multiplication.
- Add/subtract.
- Microcomputer.
- Microprocessor.

1. Up/down (U/D) counter with table look-up

This technique would involve the use of a shift register, some associated logic, an U/D counter and a table look-up device such as an erasable programmable read only memory (EPROM). The shift register would serve as a hardware buffer that could be used to account for the hysteresis introduced by the worm-wormgear assembly. The length of the buffer would have to be determined experimentally. The logic associated with the shift register would determine the "validity" of each transition (count) signal from the edge detector by checking the contents of the shift register and comparing the current direction of rotation with the previous direction of rotation. Whenever the logic detected a change in rotation direction, or a partially full, or a partially empty buffer (depending on the direction of rotation), the transition would not represent a "valid" count since any of these conditions would indicate that the transition was due to a change in the position of the worm without a corresponding change in the position of the wormgear. Thus, the present transition would be the result of hysteresis due to the backlash in the gear train and the transition would be "invalid". Such a transition would cause the contents of the hysteresis buffer to be modified appropriately. A more complete discussion of this topic is contained in Chapter IV. The shift register and associated logic could be built from common TTL devices readily available at the NPS.

Once a count had been determined to be valid, an U/D counter would be used to keep a running total of the number of counts. Again, such a device could be built using readily available TTL devices such as the 74LS168A, Synchronous 4-Bit Up/Down Decade Counter, or the 74LS169A, Synchronous 4-Bit Up/Down Binary Counter. The output from the U/D counter would then be used as an address to "look up" a predetermined number stored in an EPROM.

This design approach was considered relatively straightforward, and at least initially seemed like a viable option. Its major advantage was that it was conceptually quite simple. This simplicity had a price though; it would have been very hardware in-

tensive and consequently would have been a very inflexible design. For example, if at a later date the use of an arbitrary reference was desired, additional hardware would have to be added to the signal conditioner so that the counter could be initialized to the arbitrary starting point. Since all of the processing would have to be done in hardware, even a minor modification in the system could necessitate a major design revision. Another consideration was that saving in excess of 51,000 unique positions in the EPROM presented a nontrivial problem that would need to be solved if this technique was used.

2. Up/down counter and multiplication

This is very similar to the previous case, differing only in that instead of looking up a predetermined position, in a memory device, a multiplier would be used to multiply the output of the U/D counter by a predetermined constant. As an example, if experimental results indicated that the shaft encoders generated one pulse for every 0.00703125° that the camera was displaced, then each time a valid count was received, the updated count would need to be multiplied by 0.00703125 in the final stage of the signal processor. The result would be the new position. Again, while conceptually simple this idea had some significant disadvantages. Even more hardware intensive than the first approach, this design would also have extremely limited flexibility.

Accomplishing the multiplication would have posed a formidable task. The scale factor would have to be written as some integer (e.g., 0.00703125 would become 703125, or 70323, or 7031, etc.) depending on the desired accuracy. The count, already an integer, would be multiplied by the constant and the correct position of the decimal point would have to be determined. Locating the decimal point would be a relatively simple task, but multiplication of two numbers such as 51,000 and 70,313 would not be as easy. At least one 16 bit by 16 bit binary multiplier (i.e., TRW's MPY016H) is currently available, but since the number 70313 cannot be represented in binary by less than 17 bits, the multiplication could have been accomplished in either of two ways. One solution would have been to perform the multiplication in two or more stages. Alternatively, 70313 could be "rounded" to 7031. The second option would create a cumulative round-off of about $(1.28 \times 10^{-3})^\circ$ per 360° rotation (assuming 51,200 pulses per 360°). This round-off error would probably have been acceptable, but the complexity and limited flexibility of either multiplication scheme made the U/D counter and multiplication an unacceptable candidate for the signal processing subsystem.

3. Add/subtract

A third design concept considered the elimination of the U/D counter altogether. The same logic proposed for use in the previous two designs could have been

used to check the validity of a count and to determine the direction of rotation. However, instead of valid counts being sent to an U/D counter as before, these counts would now signal an adder to add or subtract a predetermined constant from the running total. Just as before, this simple idea could probably have been made to work at least once, but its usefulness as a part of a larger system would certainly have been limited. The large number of components required to realize this design would have increased the probability of failure, complicated troubleshooting and reduced overall flexibility.

4. Microcomputer

If the signal processing subsystem was built around a microcomputer (PC), virtually all of the disadvantages associated with the previously discussed approaches would be eliminated. Since all of the logic could be implemented in software, modifications to the system would be relatively simple to make, and the system's flexibility would be enhanced. However, dedicating a microcomputer, even an inexpensive model, to the signal processing tasks for this measurement system was considered overkill, and timesharing with one of the PC's already in service was possible, but not considered practical or convenient since these microcomputers had already been dedicated to a variety of tasks.

5. Microprocessor

One final option for the signal processor remained. Microprocessors are relatively inexpensive and powerful and are available in a wide variety of makes and models. If a microprocessor was used instead of a microcomputer or a straight hardware processor, the "nice to have" requirements such as flexibility, ease of modification and capacity for expansion, as well as the required signal processing functions could all be satisfied. On the other hand, microprocessors have one distinct disadvantage; they are not user friendly. The use of a microprocessor implied countless hours spent tracking individual bits, debugging assembly language code, studying timing diagrams, etc.. No matter how distasteful the thought, however, a microprocessor was clearly the best way to perform the signal processing functions of the measurement system.

As with the selection of the transducer, once the basic design approach had been determined, selection of a specific device was a relatively straight forward task. The choice of one microprocessor over another was a function of the processor's ability to perform the required tasks, cost effectiveness and availability. Motorola's MC68705U3 seemed to satisfy all of these requirements. The MC68705U3 is a four kilobyte EPROM microprocessor, built using HMOS (high-density NMOS) technology with an eight bit architecture. The "68705" operates on a 5.0 volt dc supply, has 112 bytes of on chip RAM, four vectored interrupts, 24 TTL/CMOS compatible bidirectional I/O lines (eight

lines are LED compatible), eight dedicated input lines and an internal eight bit timer with a seven bit programmable prescaler. [Ref. 10: p. 1]

In Ref. 10 Motorola advertises the following software features:

- Programming language similar to the 6800 family.
- Byte efficient instruction set.
- Easy to program.
- True bit manipulation.
- Bit test and branch instructions.
- Versatile interrupt handling.
- Powerful indexed addressing for tables.
- Versatile index register.
- A full set of conditional branches.
- Memory usable as registers/flags.
- Single instruction memory examine/change capability.
- Ten powerful addressing modes.
- All addressing modes apply to EPROM, RAM and I/O.

One key advantage to using the MC68705U3 was that one of the microprocessors, and a Motorola M68705EVM (the evaluation/programming module for the M6805 family of devices) were both available for immediate use at the NPS. The fact that the 68705 utilized HMOS technology suggested that it should be a relatively low cost microprocessor. In fact, except for the price of a phone call, a second microprocessor was obtained free of charge from a local electronics wholesaler. Additional microprocessors, to be used as replacements and as backup devices were ordered for about \$20.00 each.

One potential problem with using a microprocessor begged checking prior to proceeding. Initial measurements of the camera's maximum rotation velocity produced the following results.

$$\omega_{PAN(max)} \approx 1.0 \text{ rpm} \quad (10)$$

$$\omega_{TILT(max)} \approx 0.5 \text{ rpm} \quad (11)$$

Again the requirements for the pan axis presented the most stringent design limitations. Since the optical shaft encoders were anticipated to deliver 51,200 PPR (1024×50) the

microprocessor on the pan axis had to be capable of processing 51,200 pulses/minute (1.172 ms / pulse). The MC68705U3 is designed to operate with an oscillator frequency (f_{osc}) of between 0.4 MHz and 4.4 MHz and has an instruction cycle time ($4/f_{osc}$) of between 0.950 μ s and 10 μ s. Assuming that a 4.0 MHz clock was used, the instruction cycle time would be 1.0 μ s. This would mean that the processing of each pulse would have to be accomplished in no more than 1172 instruction cycles to ensure that no pulses would be missed.

III. DESIGN

A. GENERAL

The schematic diagrams for the measurement system are shown in Appendix A; Appendix B contains copies of the printed circuit board plans. Before describing the detailed operation of each of the individual components of the measurement system, a brief overview of its basic theory of operation is in order. The measurement system is actually two separate systems operating independently. The system designed to measure the azimuth or pan angle will subsequently be referred to as the "Pan System", and the other system, designed to measure the elevation or tilt angle, will be referred to as the "Tilt System". However, because the two systems are quite similar the discussion which follows will only specifically describe the operation of both systems where their operation differs.

In the most general terms, the measurement system shown in Figure 2 on page 6 uses two microprocessors to count the pulses generated by the incremental shaft encoders, and to provide output signals to the display devices. The counting function performed by each microprocessor involves determining the direction of rotation and determining whether each count is "valid". Valid counts are encoder pulses which result from the displacement of the camera servo, while invalid counts are a result of the hysteresis in the gear train. The number of valid counts is directly proportional to the angular displacement of the camera axis.

Both of the displays are capable of presenting the position information in two basic forms. In the Count Mode they display the number of pulses that have been detected, and in the Position Mode they display the angle in degrees that the number of pulses represents. A third display mode, which is a combination of the first two, is also available. In the third mode, referred to as the "Blinking Mode", the display will alternately display the count and the angle.

B. SHAFT ENCODER AND LINE DRIVER

Figure 11 shows the basic components of the HEDS-6000 incremental optical shaft encoder. The encoder is approximately 56 mm in diameter and 20 mm deep. The code wheel assemblies for the HEDS-6000 J06 encoders are designed to mount on 0.25 in. shafts. Since the mounting surface shown in Figure 11 is not part of the encoder kit, and did not exist on either of the worm axes, two such surfaces were machined in the

Physics Department Shop and attached to one end of each of the worms. Each surface has a 0.25 in. diameter shaft to which one of the code wheel assemblies is attached. Two sheet metal brackets, also made in the Physics Department Shop, are bolted to the servo frame. The encoder bodies are mounted to these brackets. Figure 12 shows the shaft encoders mounted in the camera servo. [Ref. 9: p.1]

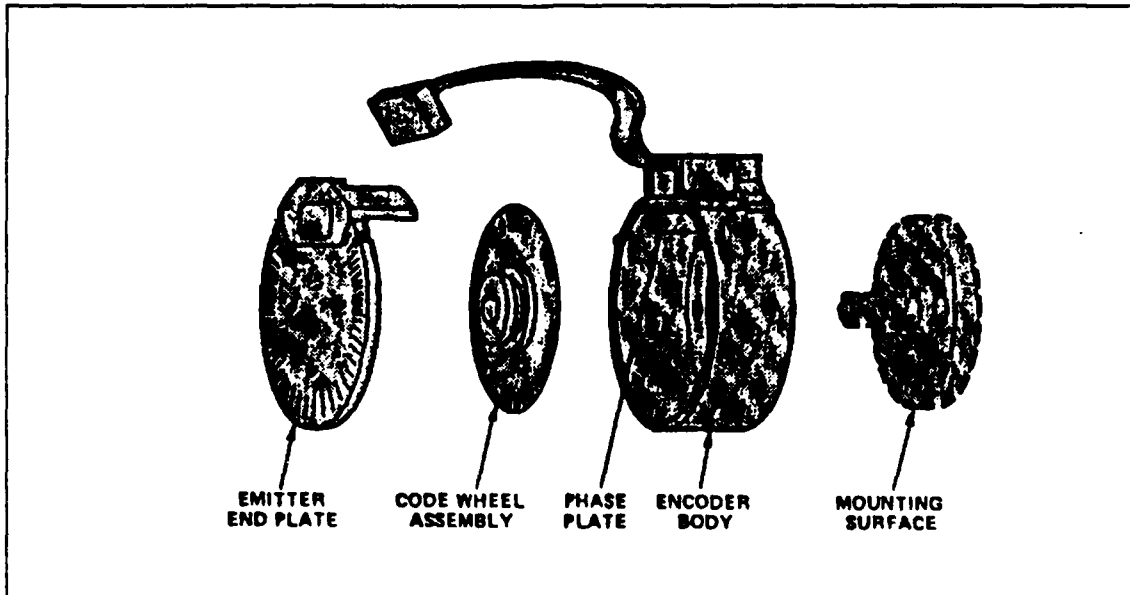


Figure 11. HEDS-6000 Series Encoder Kit: From Ref 9: p.6.

Also seen in Figure 12 is a printed circuit board mounted between the two optical shaft encoders. Each of the encoders is electrically connected to the board via a separate ten wire ribbon cable. The power and the output signals from the shaft encoders are transmitted through these cables. A sketch of the ribbon cable connector and the pinout for the connector are shown in Figure 13. Each connector is attached to a ten pin header on the printed circuit board. Pins 2, 7 and 9 are connected to a +5.0 Vdc power supply external to the camera servo. A description of the power supply is given later in this chapter. Pins 3, 4, 5 and 6 are connected to the power supply ground. The HEDS-6000 does not have an index pulse, therefore pin 10 is not connected.

The remaining two pins on each header connect the output channels of the shaft encoders to two 74S140 line drivers. Each 74S140 is a dual four-input NAND gate 50-Ohm line driver. The line drivers are powered by the same supply as the encoders. They serve as buffers between the encoders and the transmission lines which are used to transmit the encoder signals to the signal conditioner. The line drivers' typical high

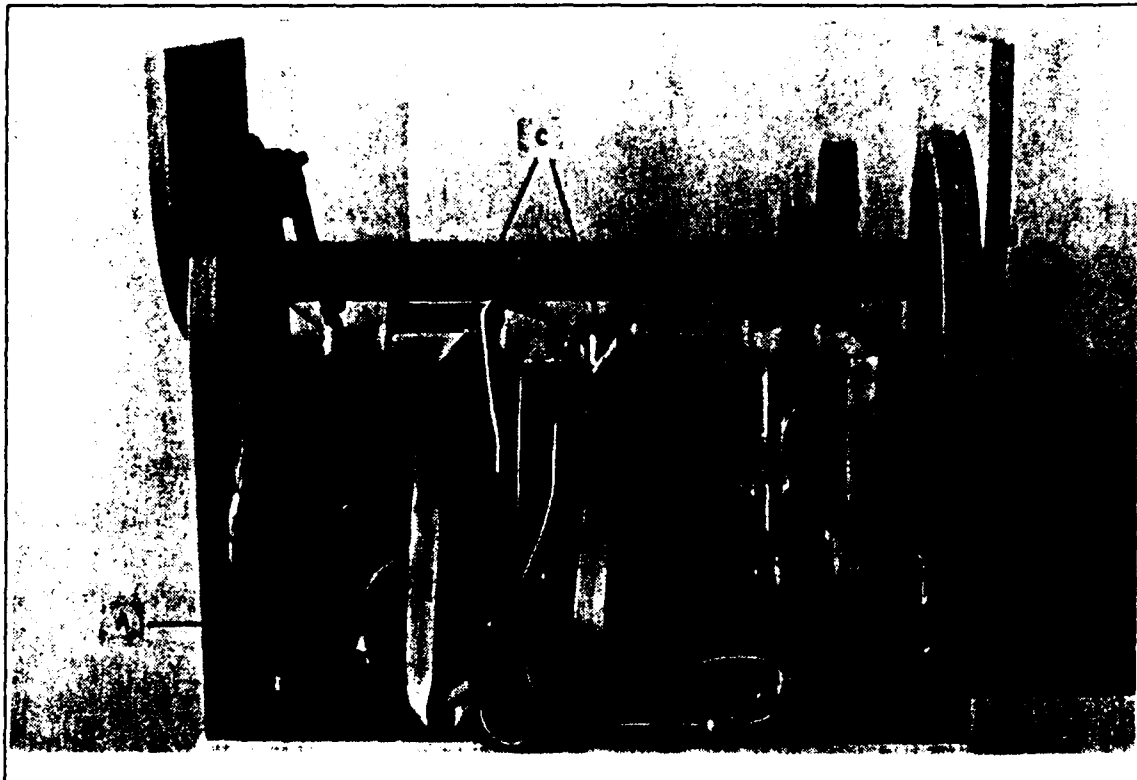


Figure 12. Modified Camera Servo: (a) Optical shaft encoder used to measure Pan axis displacement, (b) Optical shaft encoder used to measure Tilt axis displacement, (c) Ribbon cable, (d) Printed circuit board.

output current is 10 mA and the maximum is 18 mA. Resistance in the transmission line was measured to be approximately 35 Ω , and to be on the safe side a 10 Ω connector loss was assumed. The voltage drop due to an 18 mA current through a 45 Ω resistance is 0.81 V. A "voltage high" signal received at the signal conditioner should therefore be about 4.19 V. This is well above the maximum, positive-going threshold voltage specification of 2.0 V for the 7414 Schmitt triggers, which are used to receive the signals at the signal processor. [Ref. 11: pp. 5-73, 5-74, 6-44]

C. ENCODER-MICROPROCESSOR INTERFACE

The signals transmitted by the two line drivers are Channels A and B of each of the shaft encoders. These signals contain the raw data which the signal processor converts into position information. Three pairs of multiple pin connectors are used in the encoder-microprocessor interface. The pinouts for these connectors are shown in

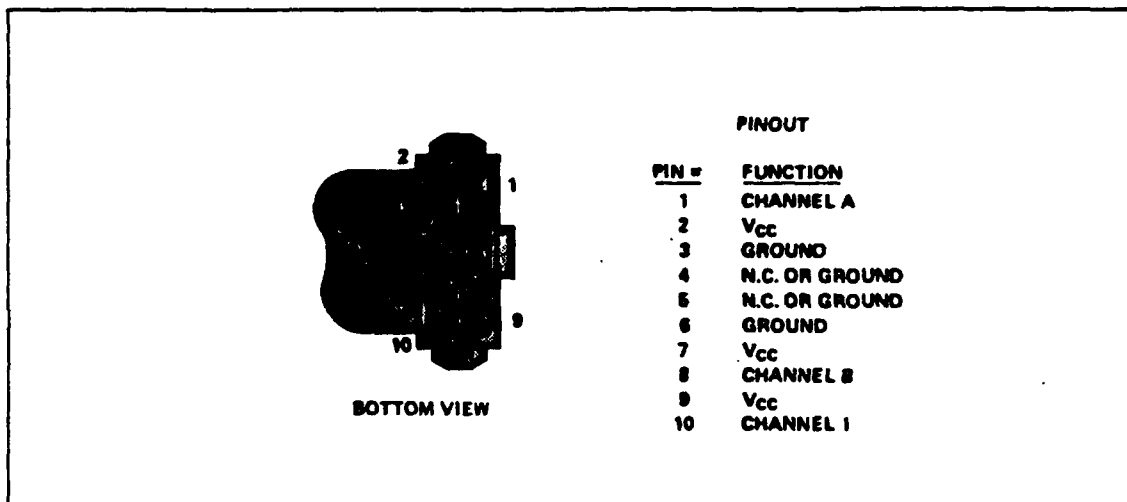


Figure 13. Encoder Connector Specifications: From Ref. 9: p. 6.

Figure 14. Each of the four signals is received at the signal processor by a 7414 Schmitt trigger which is used to "clean up" the signal. The Schmitt triggers lower the system's susceptibility to errors caused by slow state transitions and increase the signals' fan out capabilities [Ref. 7: p. 13].

The output of each Schmitt trigger is routed to an input port of the appropriate microprocessor. Each Channel A signal is also the input to an edge detector. The edge detectors each consist of three 7414 inverters, a 74LS86 EXOR gate and a 47 nF capacitor, configured in the manner shown in Figure 15. This configuration causes the interrupt line to go low for approximately 2 μ s each time Channel A transitions from low to high or from high to low. Since an oscillator frequency, f_{osc} , of 4.0 MHz is being used, the interrupt pulse width, t_{WL} , must be greater than or equal to 1.25 μ s [Ref. 10: p. 3]. The value of the capacitor required to achieve the 2 μ s delay was determined experimentally.

D. SWITCHES

The measurement system has 10 switches that allow the operator to control specific functions of the signal processors and the displays. Figure 16 shows the physical location of these switches on the control panel. Switches SW1(P) and SW1(T) control the reset lines to the microprocessors. Switches SW2(P), SW2(T) and SW5 control the display mode. The Function and Set switches; (SW3(P), SW3(T), SW4(P) and SW4(T)) allow the user to change the length of the hysteresis buffer in the microprocessor. The

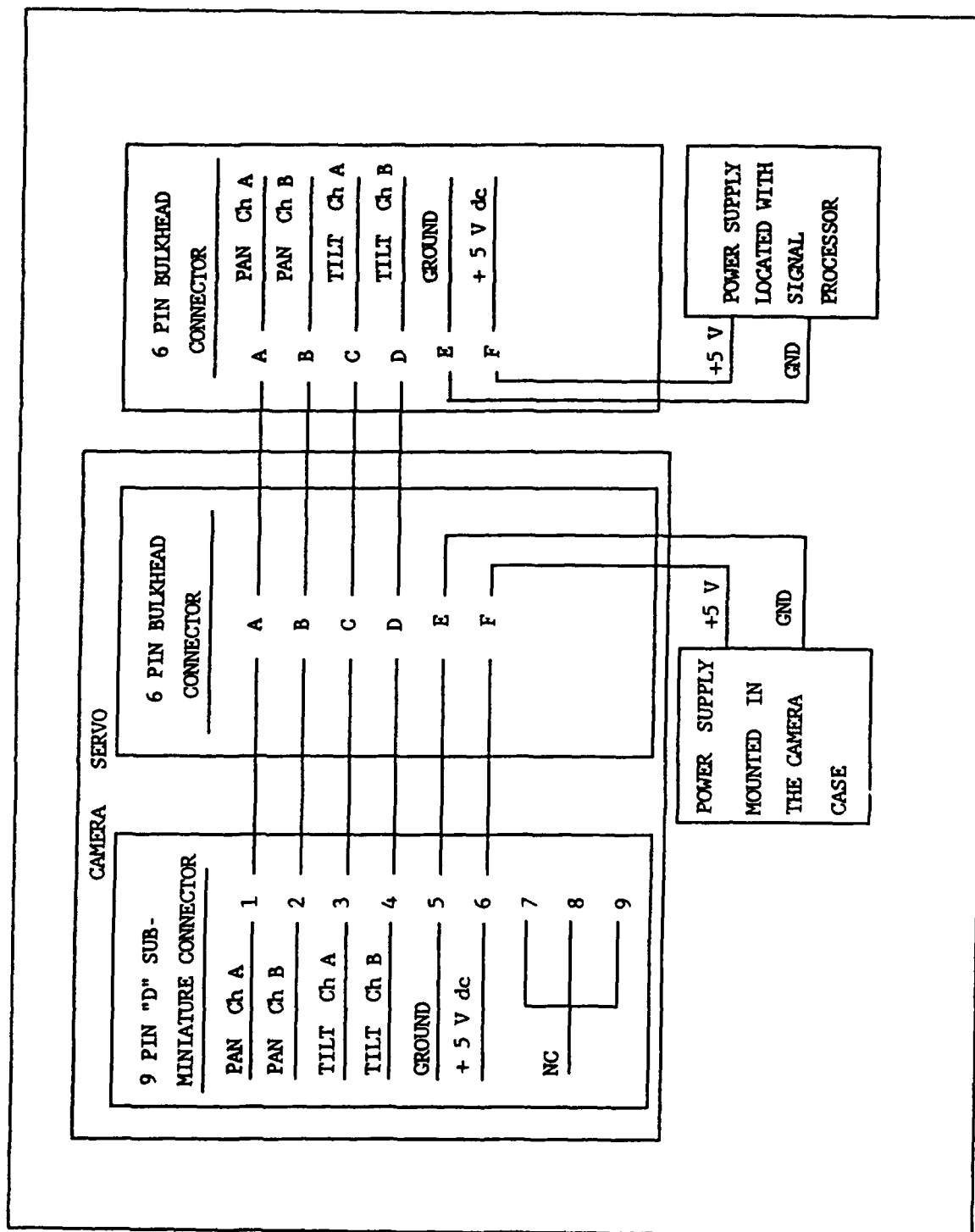


Figure 14. Encoder-Microprocessor Connector Specifications

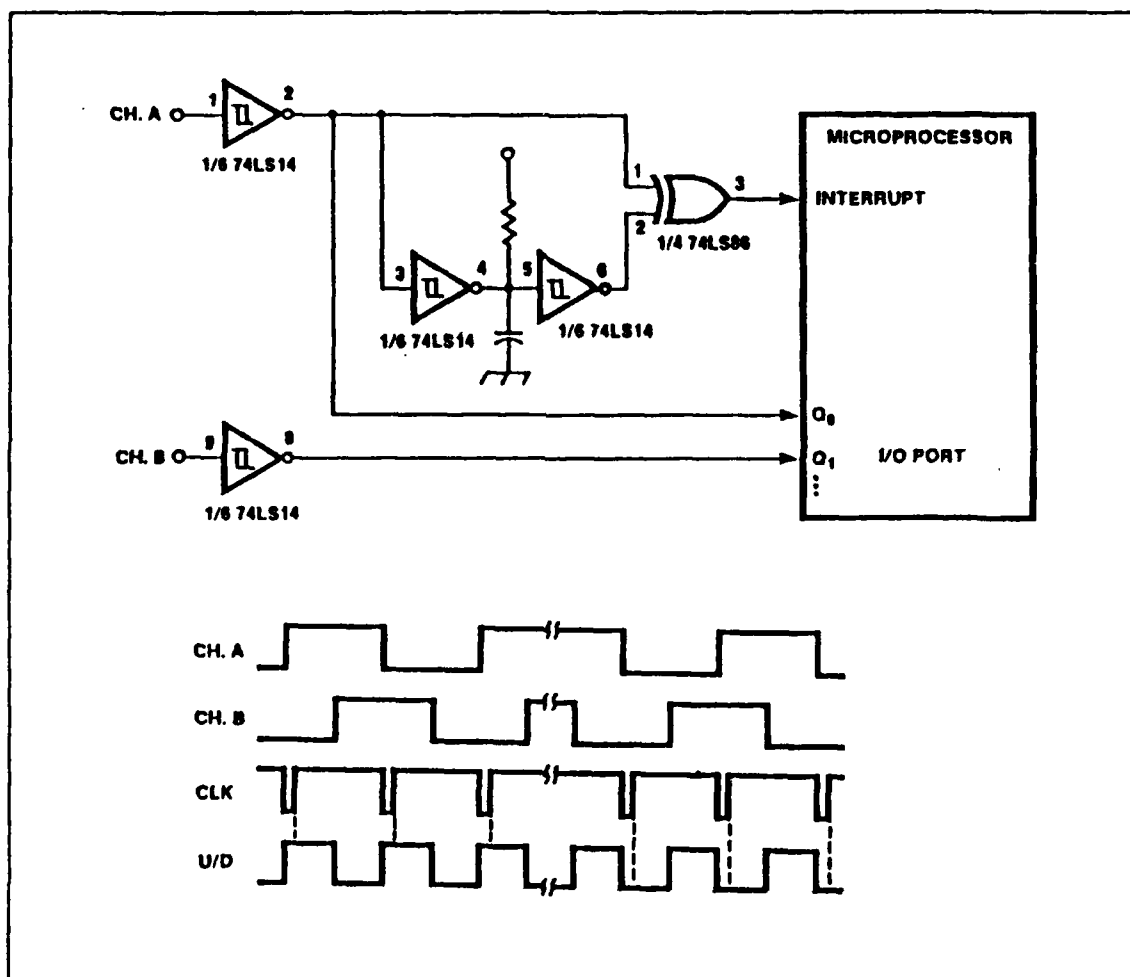


Figure 15. Interrupt Interface: After Ref 7: p. 14.

master power switch is SW6. Table 2 identifies the switches by name, description and function.

Any mechanical switch will "bounce" or "chatter" when it is thrown, and since the operation of the signal processor depends on the number of times that the Display Mode and Set switches change position, these switches had to be "debounced". A very simple but effective way to do this is with an $\overline{RS}$ latch. Switches SW2(P), SW2(T), SW4(P) and SW4(T) are each debounced in this manner. Each latch is made from two 74S00 NAND gates connected in the manner shown in Figure 17. [Refs. 13: pp. 132-135, 12 : pp. 3,4]

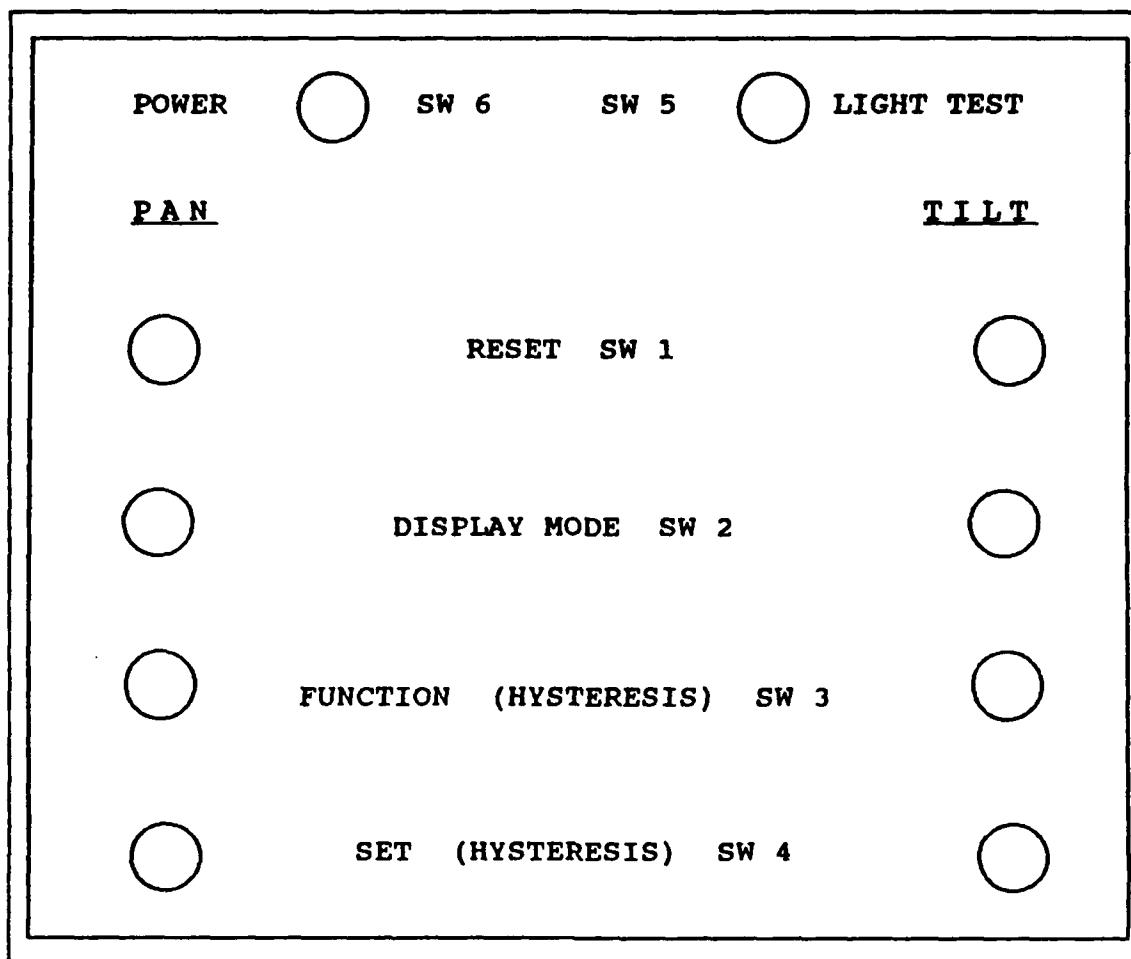


Figure 16. Control Panel

E. MC68705U3

1. General

The two 40 pin MC68705U3 microprocessors (MPU's) are the heart of the measurement system. With the exception of the light test signal, every signal in the system is either part of the input to one of the MPU's or part of their output. The MPU's were programmed using the assembly language syntax, assembler directives and instruction set for the M6805 family of microprocessors which are described in Ref. 14. The Pan and Tilt programs are listed and their operation is described in Appendix D. The pin assignments for the MC68705U3 are shown in Figure 18. Table 3 briefly describes the purpose of each pin and the actual connections for the two MPU's.

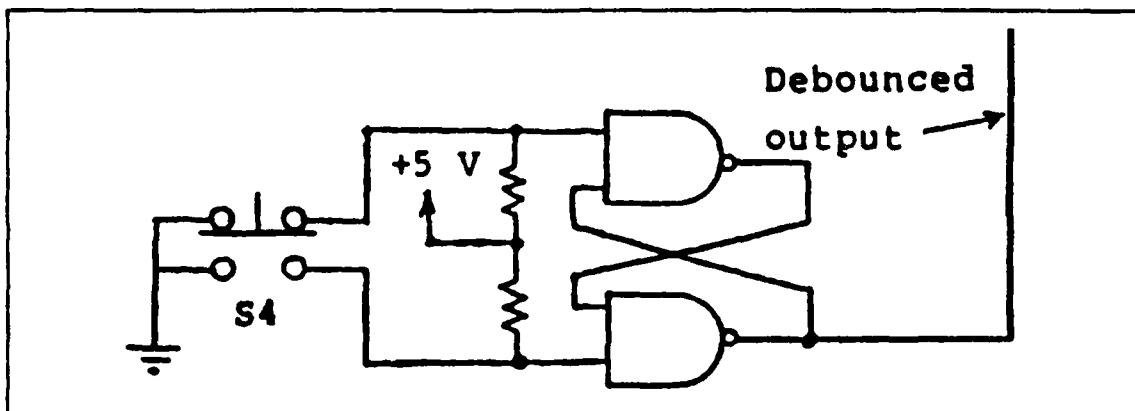


Figure 17. Debouncing circuit: After Ref 12: p. 4.

2. Memory Map

a. Input/Output (I/O)

The memory map for the MC68705U3 is shown in Figure 19. The digits following a "S" are the hexadecimal representation of the address for a specific memory location. The data registers occupy the first four memory locations of each MPU. Thus the information written into the registers at S000, S001 and S002 is written to the output ports A, B and C respectively. Port D, at address S003, is an input only port as indicated in Table 3. In order to determine the state of the input lines, the contents of the register at S003 must be read by the MPU. Registers S004, S005 and S006 are the data direction registers (DDR's) for Ports A, B and C respectively. Because all three ports are used as "output only" ports, in this application, the DDR's are all established as such by an initialization routine performed by the MPU's during their initial power-up and after each external reset. [Ref. 10: pp. 5, 12, 14]

Pin 18 of the MPU can be used as either a general purpose input line or as an interrupt line. The primary interrupt line on each MPU is used to signal the occurrence of a state transition on Channel A. Pin 18 is used as a second interrupt line to signal a display mode change request from the operator. The Miscellaneous Register (MR) at address S0A is used to control the operation of the second interrupt line ($\overline{\text{INT2}}$). In order to establish pin 18 as an interrupt line, bit 6 of the MR is cleared by the Initialization Routine. The $\overline{\text{INT2}}$ Interrupt Request Bit, bit 7 of the MR, is cleared by default upon reset. It is set when a falling edge is detected on the Display Mode line which is connected to pin 18. When this occurs and bit 6 of the MR is cleared, an interrupt request is generated. This interrupt request causes the display mode to change.

Table 2. SIGNAL PROCESSOR AND DISPLAY SWITCHES

NAME	DESCRIPTION AND FUNCTION
PAN RESET (SW1(P))	Momentary action push button switch: Resets the Pan Microprocessor. Causes the Pan Display to be reset to zero.
TILT RESET (SW1(T))	Same as SW1(P) except it affects the Tilt System only.
PAN DISPLAY MODE (SW2(P))	Single pole double throw toggle switch: Each time the switch position is changed the Pan Display toggles from Count mode, to Position Mode, to Blinking Mode, to Count Mode, etc..
TILT DISPLAY MODE (SW2(T))	Same as SW2(P) except it affects the Tilt Display only.
FUNCTION (HYSTERESIS) (SW3(P))	Single pole double throw switch: When closed, causes the "Function" line of the Pan Microprocessor to go low and causes the size of the hysteresis buffer to be displayed on the Pan Display. Enables SW4(P).
FUNCTION (HYSTERESIS) (SW3(T))	Same as SW3(P) except it affects the Tilt System only.
SET HYSTERESIS (SW4(P))	Single pole double throw switch: Inoperable unless SW3(P) is closed. If SW3(P) is closed, each time the position of SW4(P) is changed the length of the hysteresis buffer is incremented by one. Maximum buffer length is 25. Toggling SW4(P) when the buffer length is 25 will cause the buffer length to be reset to zero.
SET HYSTERESIS (SW4(T))	Same as SW4(P) except it affects the Tilt Hysteresis buffer.
LIGHT TEST (SW5)	Single pole single throw switch: When closed, lines 1, 2, 7, 8, 10, 11 and 13 on each of the LED displays will go low. Unless an element is burned out, every digit in both displays should be an eight.
POWER (SW6)	Single pole single throw switch: When closed, applies + 5.0 V dc power to the signal processors and the displays.

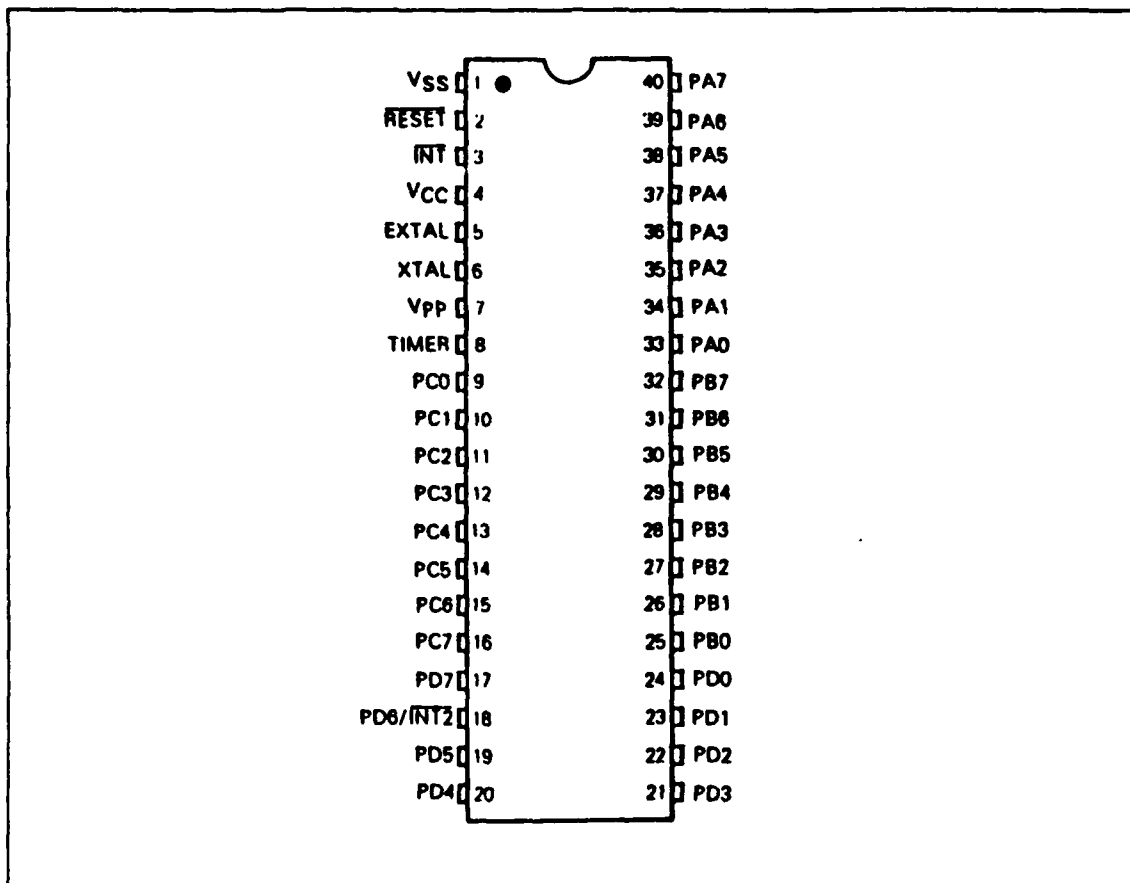


Figure 18. MC68705U3 Pin assignments: From Ref. 10: p. 1.

Once bit 7 has been set by an interrupt, it must be cleared by software to avoid repeated and unwanted interrupts from occurring. This task is performed by the Mode Change Routine in each EPROM. [Ref. 10: pp. 1, 10, 13, 15]

b. Timer

The operator can cause either or both of the displays to "blink" by using the Display Mode Switches, SW2(P) and SW2(T). When one of the systems has its display in the Blinking Mode, the associated MPU uses its timer to generate a timer interrupt request every second. The interrupt request causes the MPU to execute the Mode Change Routine. A block diagram of the timer is shown in Figure 20. The timer consists of an eight-bit counter which is decremented toward zero by the f_{CIN} input. When the counter reaches zero, it sets the Timer Interrupt Request Bit (TIR) of the Timer Control Register (TCR), and a timer interrupt request is generated unless the

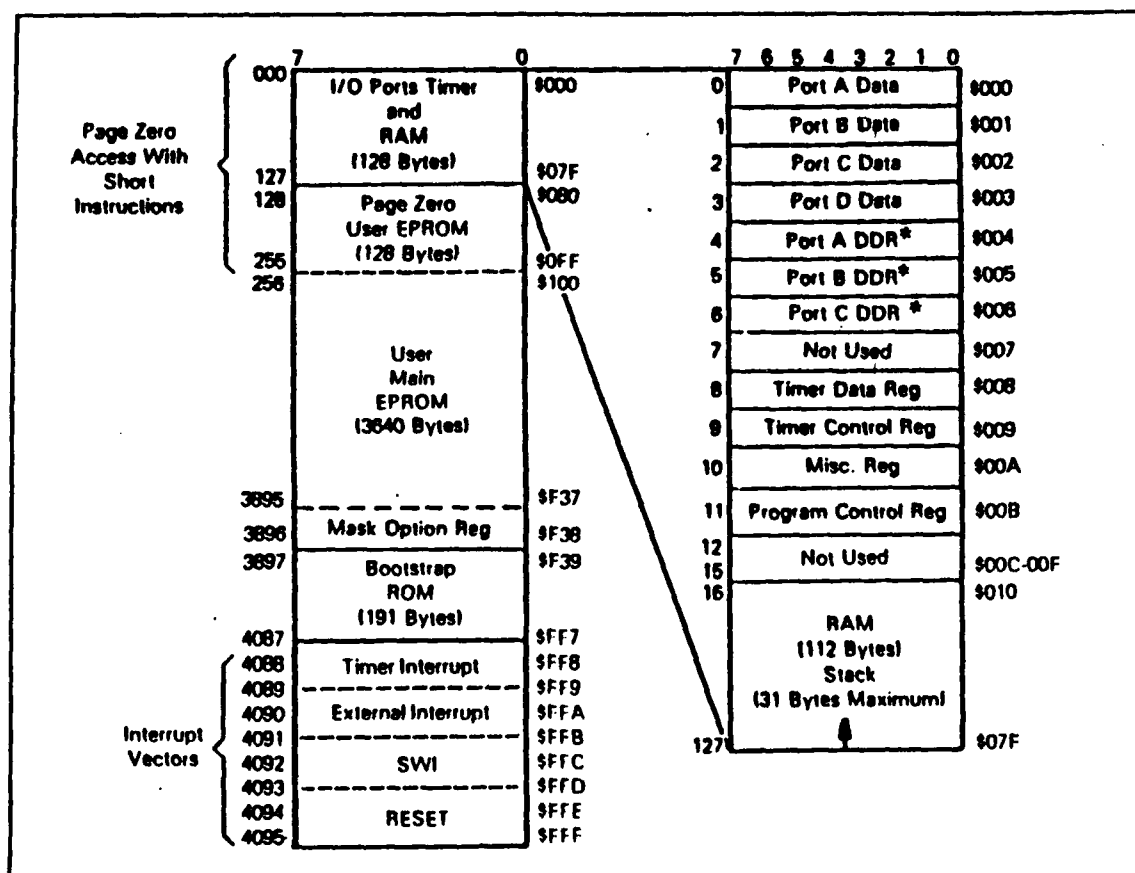


Figure 19. MC68705U3 Memory Configuration: From Ref. 10: p. 5.

Timer Interrupt Mask Bit (TIM) of the TCR is set. A brief description of each of the timer registers and their configuration follows.

(1) *Timer Data Register (TDR)*. The TDR is the eight-bit counter which sets the TIR bit of the TCR when it decrements to zero.

(2) *Timer Control Register*. The contents of the TCR determine the general operation of the timer.

- Bit 7, Timer Interrupt Request (TIR), signals a TDR underflow when it is set and will cause a timer interrupt request if the TIM bit of the TCR is clear. The TIR is cleared by the MPU reset or by program control.
- Bit 6, Timer Interrupt Mask (TIM), inhibits a timer interrupt request when it is set. It is set by external reset or program control to inhibit the Blinking Mode, and is cleared by software when the Blinking Mode is requested by the operator.
- Bit 5, External or Internal Clock Select (TIN), is used to select the timer clock source. Since the internal clock is used in this application, the TIN bits of both

Table 3. MPU CONNECTIONS

Pin	Name	Description
1	V _{SS}	Ground
2	$\overline{\text{RESET}}$	When $\overline{\text{RESET}}$ is pulled low program execution halts, all variables are reinitialized and the Pan display is set to zero. SW1(P) controls the RESET line on the Pan MPU.
3	$\overline{\text{INT}}$	Allows asynchronous interruption of the processor. When $\overline{\text{INT}}$ is pulled low by the Count Edge Detector the MPU executes the "Count Routine".
4	V _{CC}	+ 5 V dc power connection.
5	EXTAL	External clock input. Connected to a 4.0 MHz external clock which provides the MPU system clock.
6	XTAL	Crystal clock input. Connected to ground since an external clock is used.
7	V _{PP}	Programming voltage pin. Connected to V _{CC} for normal operation.
8	Timer	External timer control input. Connected to V _{CC} since the internal timer is used.
	Port C	General Purpose I/O lines.
9	PC0	The two least significant digits in the display are represented in binary coded decimal (BCD) by these eight lines.
10	PC1	
11	PC2	
12	PC3	
13	PC4	
14	PC5	
15	PC6	
16	PC7	
	Port D	General Purpose input lines.
17	PD7	PD7 is the Channel A input to the MPU.
18	$\overline{\text{PD6}}$ INT2	PD6 is used as a second interrupt line. When PD6 goes low the MPU changes display modes.
19	PD5	PD5 is the Channel B input into the MPU.
20	PD4	PD4 is the Function input into the MPU.
21	PD3	PD3 is the Set input into the MPU.
22	PD2	PD2-PD0 are not used and are tied to ground.
23	PD1	
24	PD0	

Table 4. MPU CONNECTIONS (CONTD.)

Pin	Name	Description
	Port B	General Purpose I/O lines (LED compatible).
25	PB0	The most significant digit is represented in BCD by PB0-PB3 except on the Tilt MPU where these lines are connected to ground. PB4 determines which digits in the display are blanked. PB5 is not used. Connected to ground. PB6 determines the presence or absence of the display minus sign. PB7 determines the presence or absence of the display decimal point.
26	PB1	
27	PB2	
28	PB3	
29	PB4	
30	PB5	
31	PB6	
32	PB7	
	Port A	General Purpose I/O lines.
33	PA0	The third and fourth least significant digits are represented in BCD by these eight lines.
34	PA1	
35	PA2	
36	PA3	
37	PA4	
38	PA5	
39	PA6	
40	PA7	

MPU's are always cleared. For the same reason the Timer pins are connected to V_{CC} (see Table 3).

- Bit 4, External Enable (TEE), is not used by the measurement system. By keeping the TEE clear at all times, the 68705's internal timer is used exclusively.
- Bit 3, Prescaler Clear (PSC), is not used in this application; always cleared.
- Bits 2-0, Prescaler Select (PS2, PS1 and PS0), are always set during program execution. This causes the internal timer signal frequency to be divided by 128.

(3) *Mask Option Register (MOR)*. Unlike the TDR and TCR the MOR is not software programmable; instead, it is implemented in EPROM.

- Bit 7, the Clock bit, is cleared to allow operation of the external 4.0 MHz clock.
- The Timer Option bit (TOPT), bit 6, is also cleared in this application. This permits the TCR to be software programmable.
- Bit 5 is cleared to permit the use of the internal clock with the timer.
- Bits 4 and 3 are not used.

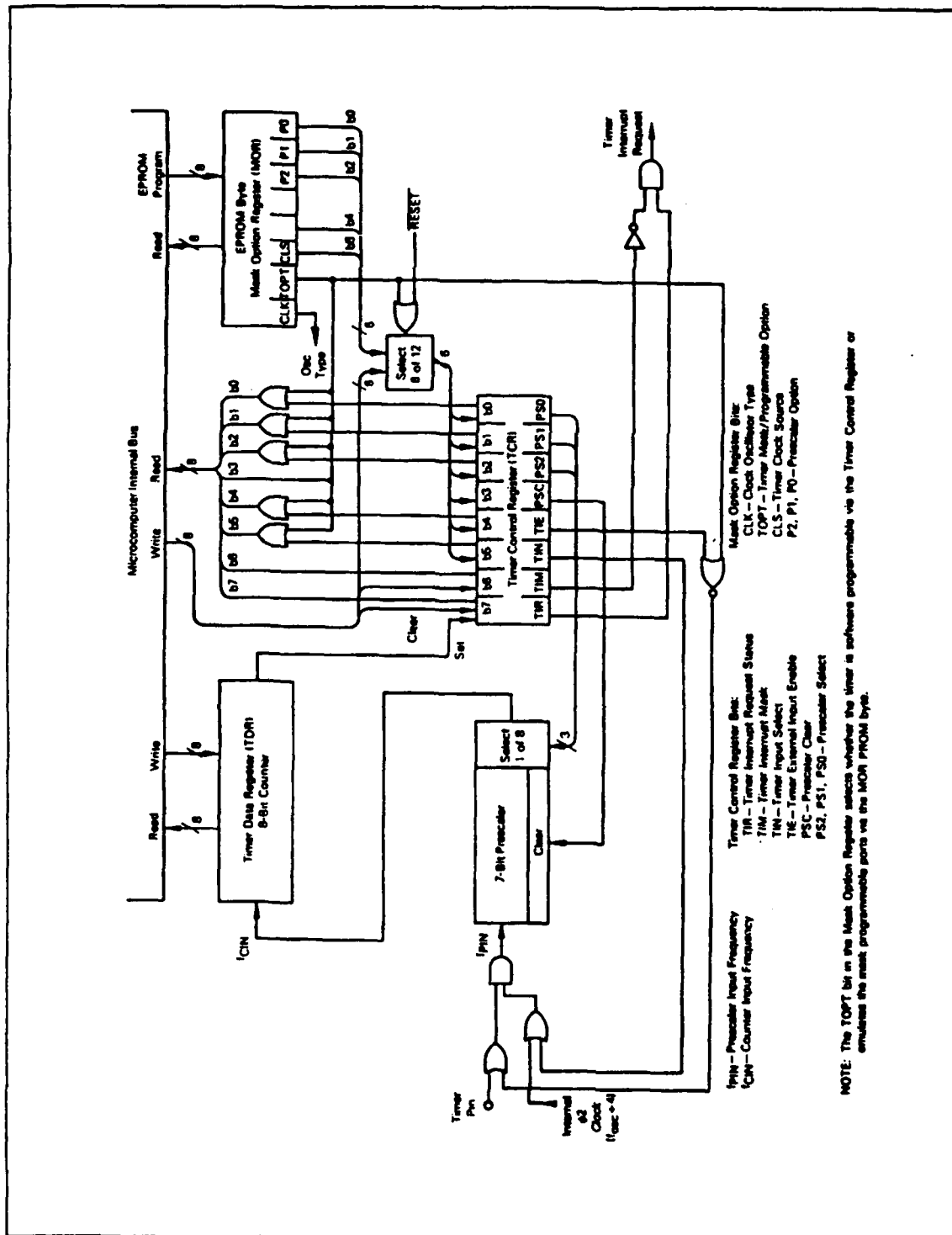


Figure 20. MC68705U3 Timer Functional Block Diagram.: From Ref. 10: p. 8.

- Bits 2-0 are all set and serve the same function as PS2, PS1 and PS0 bits of the TCR. [Ref. 10: pp. 6-8, 13-15]

3. RAM

The MC68705U3 has 112 bytes of RAM. The 112 bytes includes 31 bytes that can be used for the stack. Use of the stack is quite limited. During interrupts it is used to save the contents of the CPU registers and the program counter. During subroutine calls only the program counter is saved. The user's program has no other access to the stack. The programs written for each of the MPU's require less than 25% of the available RAM. The Pan MPU uses 27 of the 112 available bytes and the Tilt MPU uses only 22 bytes. The programs listed in Appendix D explain the function and give the location in memory for each of the variables. [Ref 10: p. 5]

4. ROM

The 3776 bytes of user EPROM in the MC68705U3 are divided into three separate blocks in the memory. Page Zero User EPROM is the ROM located between address S080 and S0FF. Because these addresses are only one byte long, instructions located in Page Zero ROM can be referenced with addressing modes not permitted with instructions located in other parts of the memory. Between address S100 and SF37 is the User Main EPROM. This portion of the memory in each MPU contains the vast majority of the signal conditioning programs. Located in another portion of the EPROM are the Interrupt Vectors. In each of these locations is the address of the first instruction the MPU is to execute when a particular interrupt occurs.

As with the RAM only a fraction of the available EPROM has been used in this application. The Pan MPU uses 899 bytes of the 3776 available and the Tilt MPU uses only 767 bytes. Since both programs are so small, one could reasonably ask why the two programs were not both put in one MPU. The primary problem with this idea is that each microprocessor can perform only one operation at a time. As indicated at the end of Chapter II, if the camera servo is rotating about its vertical axis at its maximum velocity of 1 rpm, the Pan signal conditioner must be capable of counting and displaying 51,200 counts per minute. Using a 4.0 MHz clock this allows the MPU 1172 μ s to count each pulse. Similarly the Tilt MPU has 1758 μ s to count each pulse when the camera is rotating at its maximum velocity about the horizontal axis. Assuming that the camera is rotating at its maximum velocity on both axes at the same time, and one MPU is being used to count the pulses from both encoders, the MPU needs to count 76,800 pulses per minute, which only allows 781.3 μ s per pulse. The Pan MPU currently requires a max-

imum of 1032 instruction cycles or $1032\mu\text{s}$ to count a single pulse, and the maximum execution time for a single pulse on the Tilt axis is $825\mu\text{s}$. Thus, a single 68705 lacks the computational speed required to ensure that no counts would be missed if it was used to process the data from both encoders.

5. Central Processing Unit (CPU)

The CPU of the M6805 Family is implemented independently from the I/O or memory configuration. Consequently it can be treated as an independent central processor communicating with I/O and memory via internal address, data and control buses. [Ref 10: p. 6]

The CPU has five registers that are available for use by the operator. The function of each of these is described below.

- The Accumulator (A) is a general purpose data register used for arithmetic calculation and data manipulation.
- The Index Register (X) can be used as a second accumulator but is generally used for the indexed addressing mode. In the indexed addressing mode an effective address is created by adding the contents of X to a number provided by the instruction.
- The Program Counter (PC) contains the memory address of the next instruction to be executed by the MPU.
- The five bits of the Condition Code Register (CCR) keep information concerning the results of the last instruction executed by the MPU. Reference 14 gives a detailed description of each of the instructions in the M6805 Family Instruction Set and explains the effect of each instruction on the CCR. A brief description of each bit in the CCR follows.
 - The Carry (C) bit is set if a carry or a borrow was generated by the last arithmetic instruction. The state of the C bit can be software controlled.
 - The Zero (Z) bit is set if the result of the last arithmetic, logic or data manipulation instruction was zero.
 - The Negative (N) bit is set if bit seven of the result of the last arithmetic, logic, or data manipulation instruction is set.
 - The Half Carry (H) bit is set if an ADD or an ADC instruction causes a carry to occur between bits 3 and 4 of the result.
 - The Interrupt Mask (I) bit is set when an external interrupt ($\overline{\text{INT}}$) occurs. If another interrupt occurs (e.g. Timer Interrupt or $\overline{\text{INT2}}$) when the I bit is set, the second interrupt is latched so that it can be processed as soon as the I bit is cleared. The I bit can be set or cleared by software.
- The contents of the Stack Pointer (SP) are the address of the next available location on the stack. As previously discussed, the stack is only used to keep track of the PC during subroutine branches, and all of the CPU registers during an interrupt. [Refs. 10: p. 6, 14 : pp. 14-15]

6. Input

Each MPU uses six input lines. Two of these lines, $\overline{\text{INT}}$ and $\overline{\text{INT2}}$, are interrupt lines that detect a negative-going edge on their respective lines. The other four lines are general purpose input lines on Port D. All of the pins on Port D are TTL compatible which made the hardware design relatively straightforward. The electrical characteristics for the input pins are listed on p. 2 of Ref. 10.

The general operation of the two interrupt lines is described in Table 3 on page 39. Once they are understood, interrupts are a simple yet powerful tool. Only three of the four interrupts available on the MC68705U3 are used by the Pan and Tilt programs. The software interrupt is not used. When the MPU is interrupted, current program execution is halted, the contents of the CPU registers are placed on the stack, and the MPU fetches the contents of the appropriate interrupt vector from memory. After the interrupt vector has been fetched, the PC is moved to that address and execution of the interrupt routine begins. There is no ambiguity when an external interrupt occurs since there is a dedicated interrupt vector in memory. The timer interrupt and $\overline{\text{INT}}$ however share the Timer Interrupt Vector. When one of these interrupts occurs, the interrupt routine must determine the source of the interrupt by checking the TIR bit of the TCR and bit 7 of the MR to determine the source of the interrupt [Ref. 10: p. 11]. Normal program execution resumes at the point at which the interrupt occurred when the interrupt routine executes a return from interrupt (RTI) instruction.

The Function and Set lines on pins 20 and 21 are connected to the Function and Set switches. The operation of these switches is described in Table 2 on page 36. The remaining two input lines to each MPU are Channels A and B from the respective shaft encoders. The MPU programs use the information from these two inputs to determine the direction of rotation and to identify repeated oscillations about a single transition.

7. Output

Each MPU is designed to provide position information at its output in two basic forms. On the Pan axis, in the Count Mode a number between -51,200 and +51,200 constitutes the output while in the Position Mode the output is an angle between 0° and 360°. A five digit display with a minus sign is sufficient for the count display. Using a five digit display with a decimal point in the Position Mode permits the angle to be displayed to the nearest hundredth of a degree. This resolution is not quite as good as the resolution of the shaft encoders ($\pm 0.007^\circ$); however, final testing of the measurement system revealed that resolution is actually limited to about $\pm 0.02^\circ$ on the Pan axis and

about $\pm 0.14^\circ$ on the Tilt axis. The five digit display is therefore completely adequate for this system.

The Pan MPU uses 23 of its 24 output pins to represent the five digits, a minus sign and a decimal point. Each of the five digits is available in BCD form on four output pins of the MPU. The five digits are referred to as Digit 1, Digit 2, etc., with Digit 1 being the least significant digit and Digit 5 being the most significant digit. Port A has as its output the BCD representation of Digit 3 and Digit 4. Digit 1 and Digit 2 are represented by the output of Port C. The low four bits of Port B contain the BCD representation of Digit 5. These 20 output lines are the input to five 74LS47, BCD/7-Segment Decoder/Drivers, which decode the BCD signals and drive the common anode LED indicators. The output from Pin 29, PB4, is one input to a 74LS32 OR gate, the output of which is used to blank leading zeros out of the display. Pin 30 is not used and is tied to ground. The remaining two output pins drive two LED segments in the display. The signal on pin 31 turns the minus sign off and on, and the signal on pin 32 determines whether the decimal point is displayed.

The electrical characteristics of the I/O Ports are given on p. 4 of Ref. 10. The output characteristics of Ports A, B and C are compatible with the input characteristics of the 74LS47 and the 74LS32 given on pp. 4-59 and 4-48 of Ref. 11. The pins on Port B are capable of sinking 10 mA when Port B is configured as an output port. A 220 Ω resistor placed in series with each of the display segments limits the current to approximately 9 mA and permits the MPU to drive the decimal point and minus sign directly.

One consideration in the design of this system was to provide a system capable of being readily expanded to meet changing needs. To this end, in addition to being connected to the LED display devices via the 74LS47's, the BCD data lines are also connected to a header on each of the MPU circuit boards. If, at a later date, the position information needs to be used in another system, a jumper connected to each of the headers could provide the information with little or no modification.

The Pan and Tilt signal processing subsystems are virtually identical in the hardware used to implement them. The only difference is that the Pan system has a five digit display, and the Tilt system needs only four digits to display its position information. Consequently, the Tilt system does not use Digit 5, and pins 25-29 are tied to ground.

F. DISPLAY

Each digit represented in BCD at the output of the MPU is decoded by a 74LS47 BCD/7-Segment Decoder/Driver. The decoding devices each convert a four bit BCD representation of a number into seven signals that each drive a separate segment of a common anode, seven segment, LED display. The 74LS47 is capable of sinking 24 mA from each of the LED segments. Without a current limiting resistor between each of the output pins on the 7447 and the corresponding pin on the display element however, this maximum current is exceeded. When this happens the LED's have a very short life, the 7447 overheats and the system fails to function properly. The addition of a 220 Ω resistor in each branch limits the current to about 9 mA per segment, and permits trouble-free operation.

Three of the output pins on each MPU are not used as inputs to the 7447's. As discussed in the previous section, the Decimal and Minus lines each drive individual LED segments directly. The third line, also mentioned briefly in the preceding section, is used with the Blanking In/Ribbon Blanking Out (BI/RBO) signal from Digit 4's 7447 to determine the Ribbon Blanking In (RBI) signal into the 7447 which drives the display for Digit 3.

The term "blanking" simply means removing the leading zeros from the display. The two display modes available from the MPU's have different blanking requirements. In the Position Mode the three least significant digits are not blanked, while in the Count Mode, all but the least significant digit are blanked. The RBI and BI/RBO pins on the 7447's, the Blank line out of each MPU and the OR gates, connected as shown in the schematics in Appendix A, provide this capability.

The Light Test (LT) pin on each 7447 is connected to SW5. When the switch is closed, the Light Test line goes low and each of the output lines on each of the 7447's also goes low, thus sinking current from all of the LED segments simultaneously. This feature allows the operator to check for inoperable display segments.

G. POWER SUPPLIES

The two power supplies shown in Figure 2 on page 6 are each +5.0 Vdc supplies. The power supply which provides power to the shaft encoders and the line drivers is physically mounted in the camera housing. It was built by modifying the +12 Vdc auto iris power supply. This was accomplished using an LM7805 Voltage Regulator in the manner shown in Figure 8 of Appendix A. The auto iris requires only 100 mA at +12 Vdc for correct operation, and the LM7812 Voltage Regulator has an available

output current of 1.0 A [Refs. 15, 16]. The remaining 900 mA is available to the LM7805 to power the encoders and the line drivers. Reference 9 lists the maximum power requirement for the HEDS-600 as 40 mA at +5 Vdc, and Ref. 11 specifies the maximum power requirement for a 74S140 is 1 mA at +5 Vdc. Thus, the 84 mA requirement for the two encoders and four line drivers is well within the capabilities of the modified power supply.

The second power supply is capable of providing 6.0 A at +5 Vdc which is more than adequate to provide the 1.4 A needed by the signal processors and the display devices. The power supply also has 12 Vdc and -5 Vdc ports. To preclude the potentially disastrous results which might occur if the power supply were incorrectly connected to the signal processor/display devices, the circuitry shown in Figure 21 was included on each MPU and display printed circuit board.

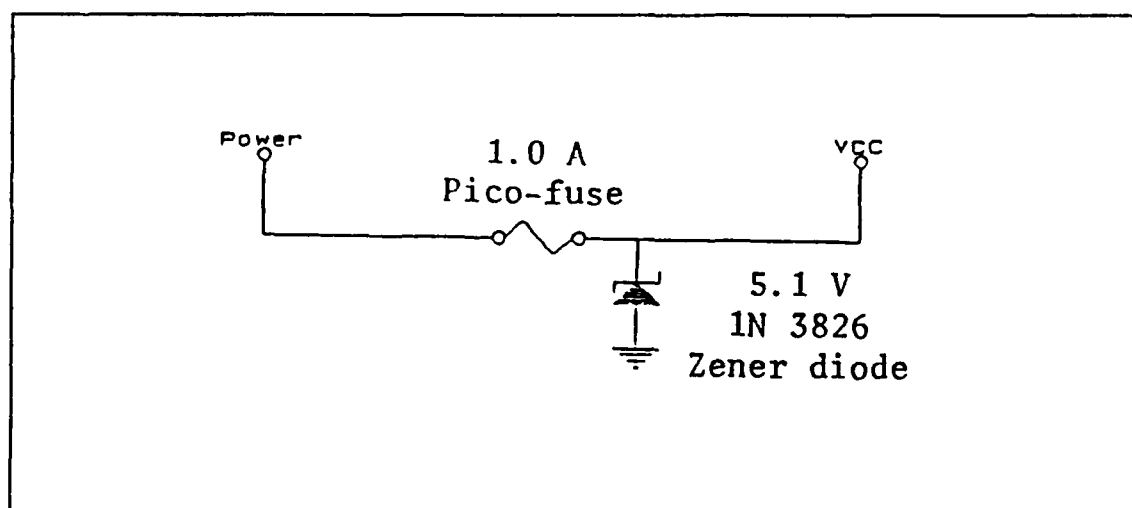


Figure 21. Reverse/Over-voltage Protection Circuit

IV. CALIBRATION , TESTING AND IMPLEMENTATION

A. GENERAL

Once the basic system design had been completed, and the MPU programs had been written, a prototype system was constructed. The prototype system might also be called the development model, since it was not only used to test the design , but was also used to calibrate the MPU programs. A block diagram of the prototype system is shown in Figure 22. The M68705EVM Evaluation Module (subsequently referred to as the EVM) provided the capability to debug and evaluate the MC68705U3-based signal processing subsystem. Operation of the signal processing MPU was performed by an MC68705U3 resident on the EVM.

The prototype system provided considerable flexibility in the testing and calibration of the system. The assembly language programs for the MPU's were written and edited on the PC. They were then assembled and linked using the 2500 A.D. 6805 Cross Assembler and 2500 A.D. Linker [Ref. 17: pp. (1-1)-(2-38)]. The result, a Motorola S19 output file (see [Ref. 17: pp. (A-1)-(A-4)]), was then down-loaded to the EVM using the file transfer program, Kermit. Downloading procedures are detailed in [Ref. 18: pp. (3-10)-(3-25),(3-37)]. The PC-EVM interface is shown in Figure 23.

After the program had been down-loaded into the MC68705U3 resident on the EVM, data entry and program debugging were controlled via the CRT monitor keyboard. The CRT-EVM interconnection is shown in Figure 24 and the monitor commands are described in [Ref. 18: pp. (3-8)-(3-25)].

The remainder of the signal processing functions were realized using hardware external to the EVM. These functions included edge detection of the output signals from the shaft encoders, decoding the output of the MPU, and generating the signals to drive the display devices. This portion of the prototype, referred to by [Ref. 18] as the "target system", was built on breadboards and is represented by the block in the center of Figure 22. The target system was connected to the MCU via a 40-pin jumper header, J1, on the EVM. The pinout for J1 is shown in Figure 25. The labels in Figure 25 refer to the labels used in the schematic diagrams which are shown in Appendix A.

B. CALIBRATION

Once the MPU programs were capable of counting the pulses generated by the shaft encoders, the programs needed to be "calibrated". This calibration procedure required

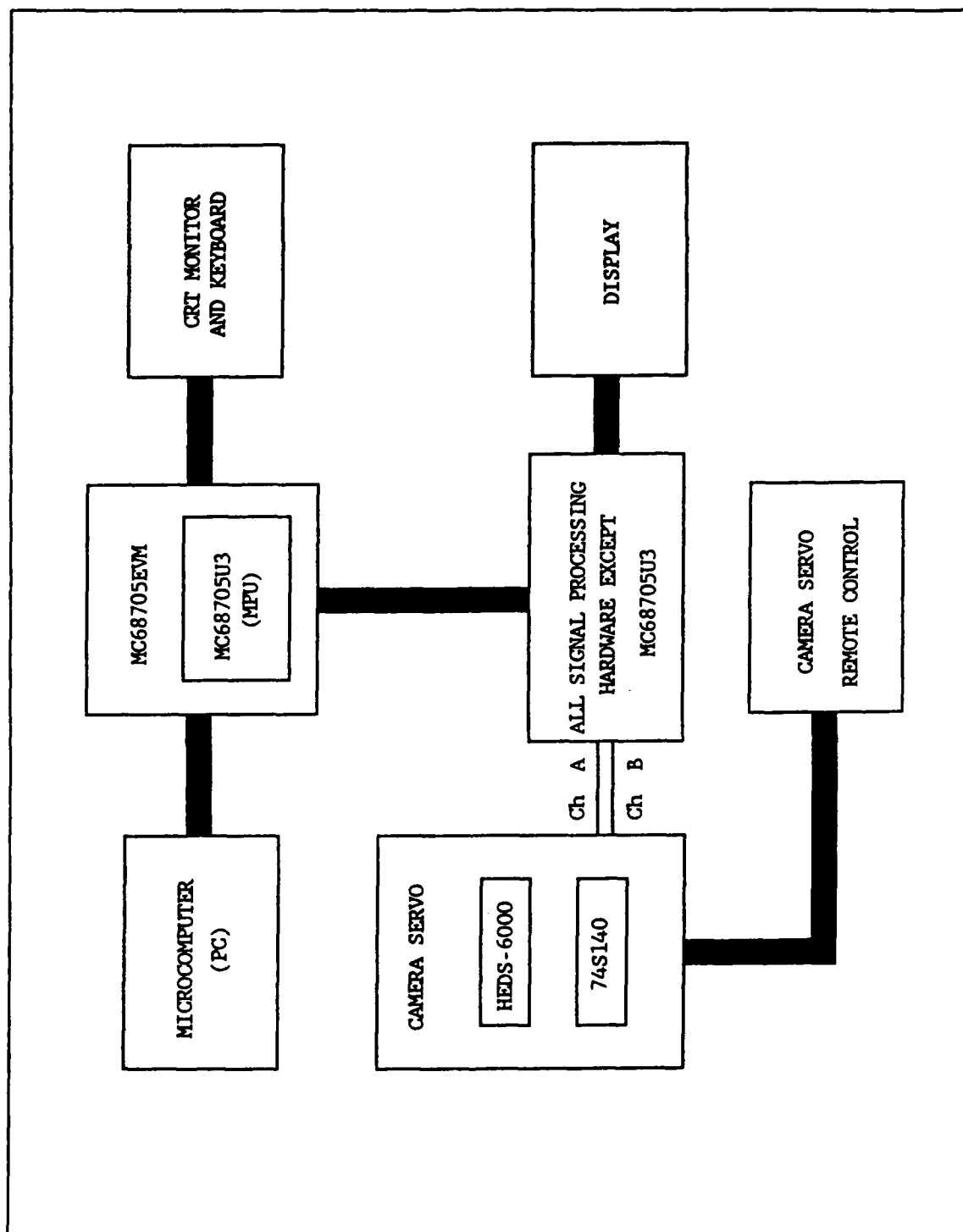


Figure 22. Prototype/Development Model

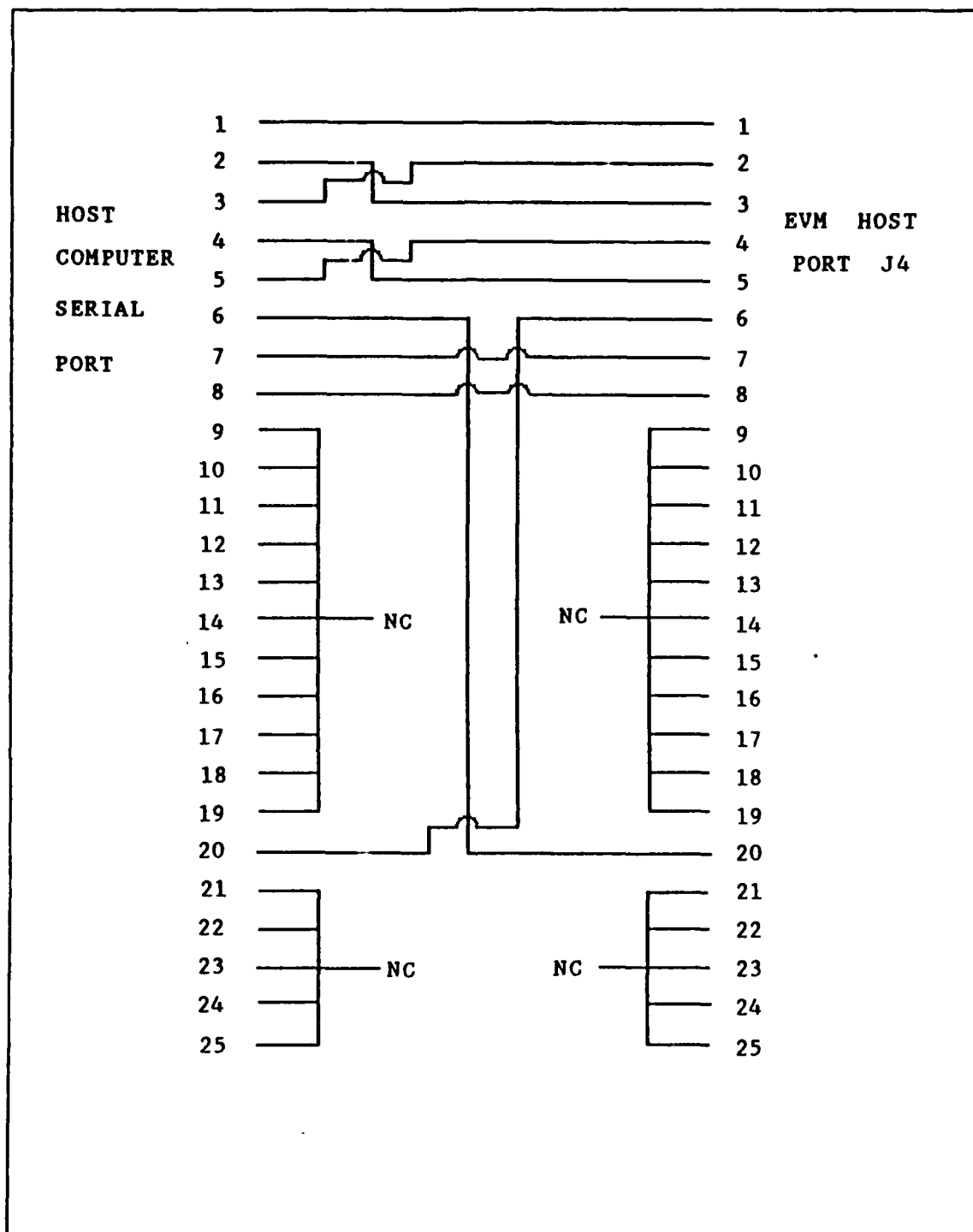


Figure 23. Host Computer - Evaluation Module Connections

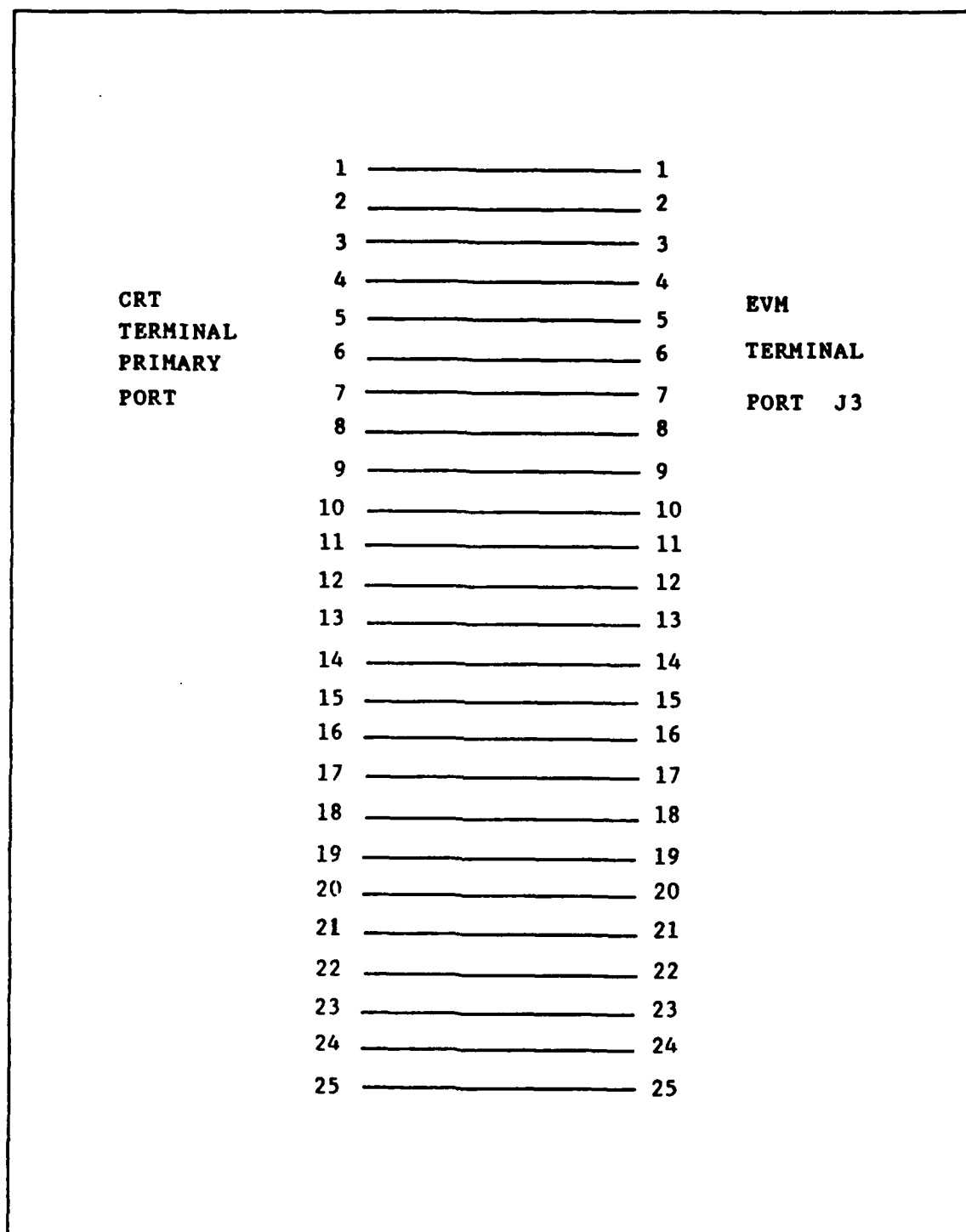


Figure 24. Monitor - Evaluation Module Connections

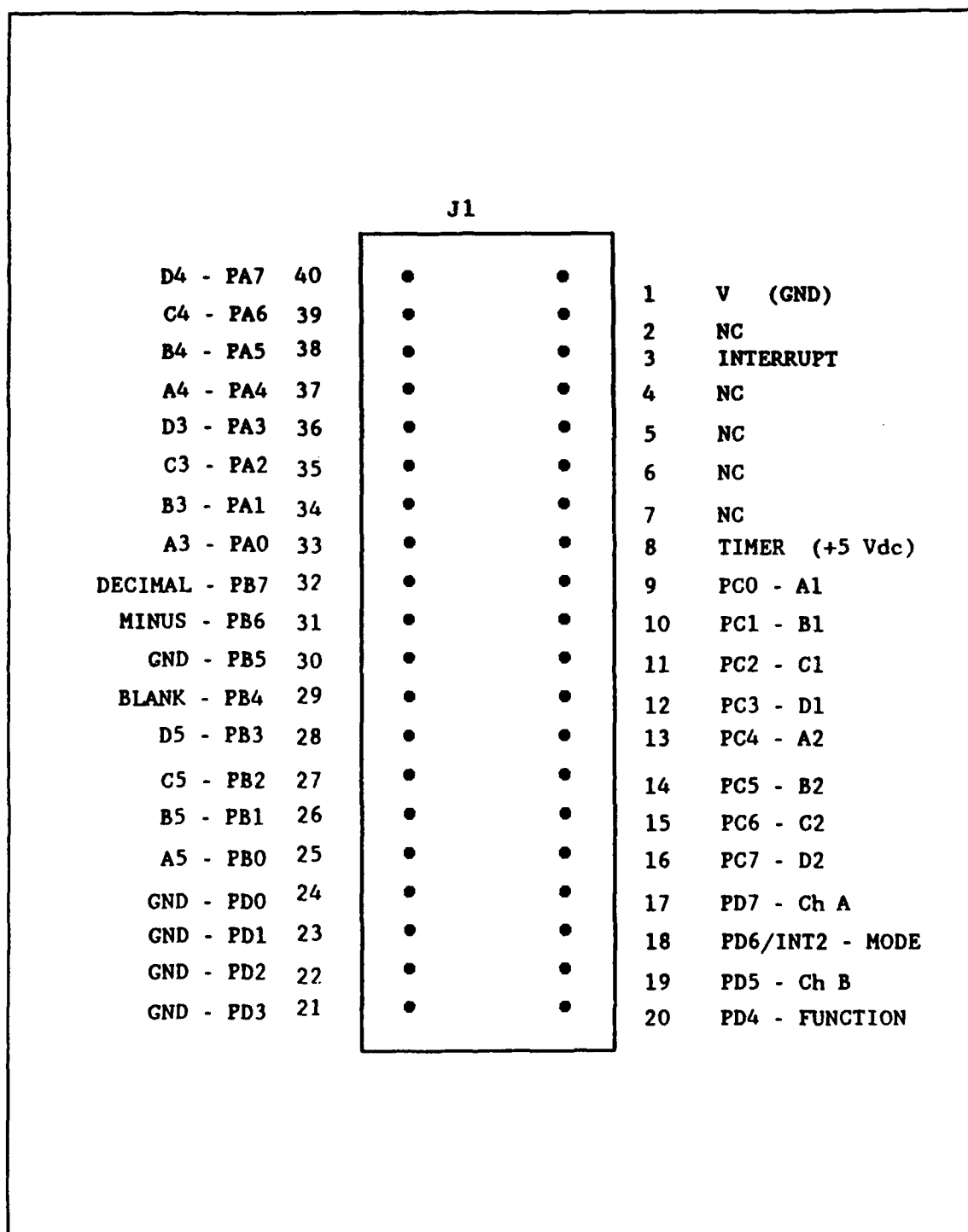


Figure 25. Evaluation Module - Signal Processor Connections

determining the angular distance through which the camera rotated between successive pulses from the shaft encoder. This number is a scale factor, which, when multiplied by the total number of pulses from the shaft encoder, yields a number equal to the angular displacement of the camera. The calibration procedure also involved determining the amount of hysteresis present in each of the gear trains.

1. Scale Factor

To determine the scale factor (SF) the simple geometric relationship

$$\theta = \tan^{-1}\left(\frac{\text{opposite}}{\text{adjacent}}\right) \quad (12)$$

was used. Using a small laser attached to the camera servo, and the geometry shown in Figure 26, the SF could be experimentally determined. As the camera servo was rotated through an angle, θ , the MPU was used to count the output pulses from the shaft encoder. The laser beam was projected on a vertical surface at a distance, a , away from the axis of rotation. The beam of the laser spread to a diameter of approximately 0.4 in. over a distance of 30 ft. A template with a 0.4 in. diameter aperture was used to mark the location of the "spots" on the distant wall. The distance between the spots, l , was measured by selecting one edge of one of the marks and measuring the distance to the corresponding edge of the distant mark. Then, having determined l and a and reading the count, C , from the display, the SF could then be determined from

$$\begin{aligned} \text{SF}(\text{degrees/Pulse}) &= \frac{\theta}{C} \\ &= \frac{\tan^{-1}\left(\frac{l(\text{in})}{a(\text{in})}\right)}{C} \end{aligned} \quad (13)$$

Using Equation (13) to simplify the expression,

$$d(\text{SF}) = \frac{\delta(\text{SF})}{\delta l} dl + \frac{\delta(\text{SF})}{\delta a} da \quad (14)$$

yields

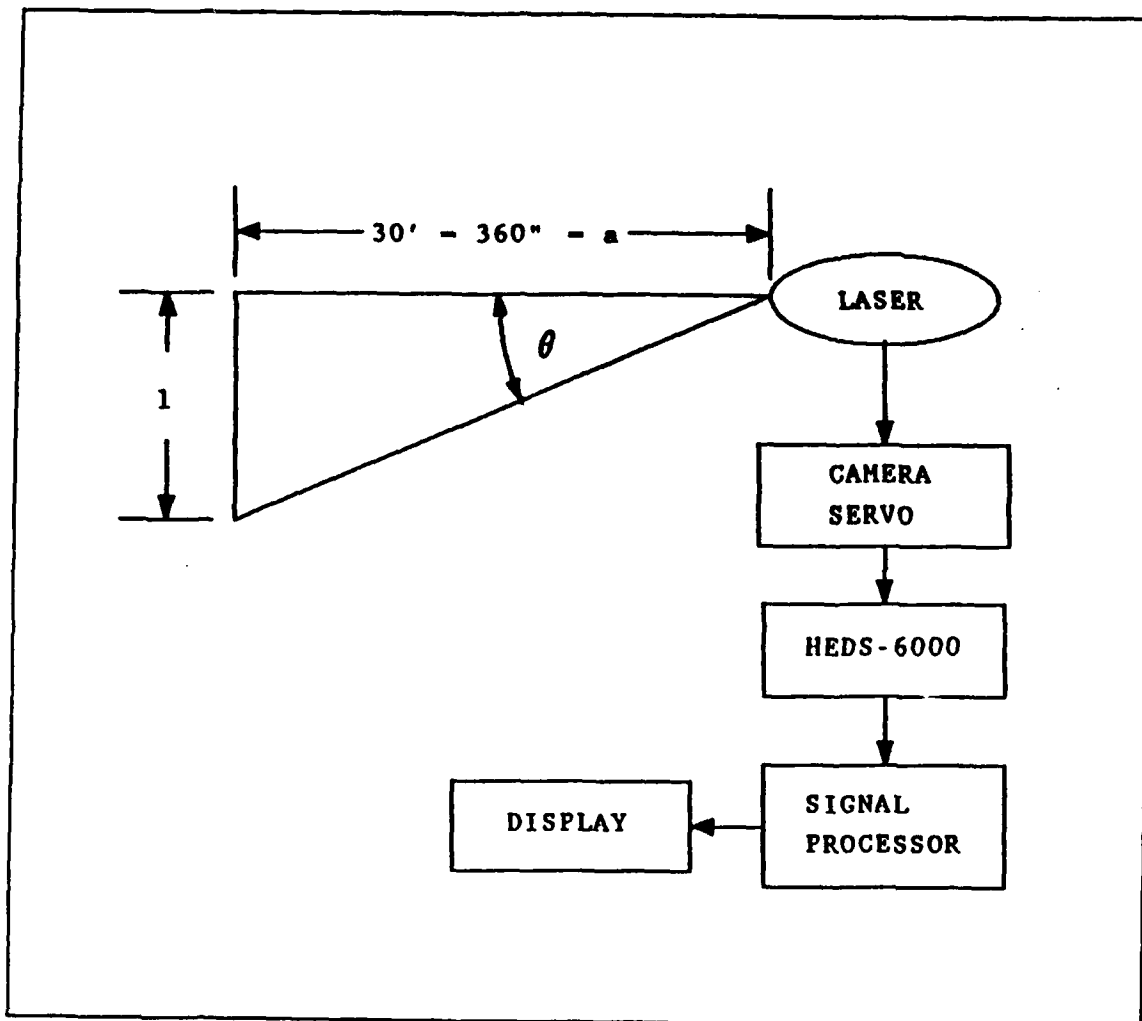


Figure 26. Geometry Used to Determine the Scale Factor

$$\begin{aligned}
 d(SF) &= \frac{1}{C} \frac{\delta \theta}{\delta l} + \frac{1}{C} \frac{\delta \theta}{\delta a} da \\
 &= \frac{1}{C} \left(\frac{a}{a^2 + l^2} \right) dl + \frac{1}{C} \left(-\frac{l}{a^2 + l^2} \right) da \\
 d(SF) &= \frac{(adl - lda)}{C(a^2 + l^2)}, \quad (15)
 \end{aligned}$$

which indicates that C , a and l should all be as large as possible to minimize the error in SF due to a measurement error in a or l . The physical size of the laboratory limited the distance, a , to 30 ft. When $a = 30$ ft, l was limited to about 3.5 ft in the horizontal

plane and about 4.0 ft in the vertical plane. By modifying the geometry as shown in Figure 27, the count, which from Equation (13) is directly proportional to θ , could also be maximized. The configuration shown in Figure 27 was used to obtain the scale factor calibration data for the Pan axis. However, since the servo is incapable of rotating 360° about the Tilt axis, the test configuration shown in Figure 26 had to be used to collect the data for that axis.

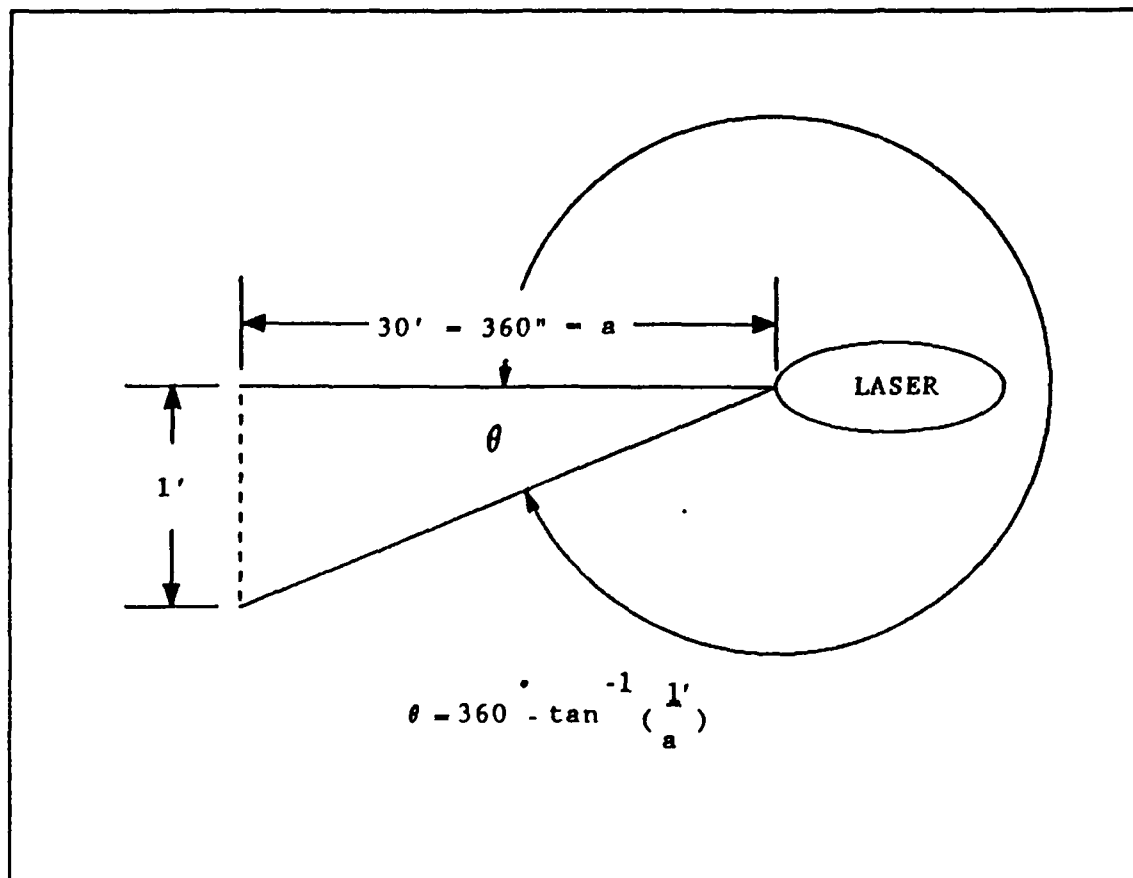


Figure 27. Alternate Geometry Used to Determine the Scale Factor

Adopting the notation, $\bar{X}$, to represent the mean value of a random variable, X ; if X is discrete with N measured values,

$$\bar{X} \approx \frac{1}{N} \sum_{i=1}^N X_i \quad (16)$$

where X_i is the i th measured value of X , and the approximation becomes better as N approaches infinity.

Using the expression in Equation (16) and the measured data for the scale factors, from 31 measurements on the Pan axis,

$$\overline{SF}_{\text{Pan}} = (7.0312 \times 10^{-3})^\circ \text{Pulse}^{-1} , \quad (17)$$

and after 32 measurements on the Tilt axis,

$$\overline{SF}_{\text{Tilt}} = (7.0452 \times 10^{-3})^\circ \text{Pulse}^{-1} , \quad (18)$$

where the subscripts indicate the axis. The actual implementation of these scale factors is described later in this chapter and in the documentation for each of the MPU programs.

If the error in the i th measurement is described by

$$e_i = X_i - \bar{X} , \quad (19)$$

then the root mean square (RMS) error in N measurements of X is given by;

$$\sigma_x = \sqrt{\frac{1}{N} \sum_{i=1}^N (X_i - \bar{X})^2} . \quad (20)$$

Note that this is also the definition of the standard deviation of X .

The RMS errors in the Pan and Tilt scale factor measurements were determined from Equation (20) and the measured data to be;

$$\sigma_{SF_{\text{Pan}}} = (4.62 \times 10^{-6})^\circ \text{Pulse}^{-1} \quad (21)$$

$$\sigma_{SF_{\text{Tilt}}} = (6.89 \times 10^{-6})^\circ \text{Pulse}^{-1} . \quad (22)$$

As before, the subscripts are used to identify the axis and the source of the error. The fact that the errors are small compared to the mean values suggests that the means should closely approximate the actual values for the scale factors.

2. Hysteresis

Houghton defines backlash in wormgearing as "...the total play between the surfaces of the worm and worm wheel teeth measured normal to the faces." [Ref. 19: pp. 1.4, 1.5] Backlash only poses a problem in the measurement system when the servo's

direction of rotation changes. Figure 28 is a typical hysteresis curve. As long as the direction of rotation of the worm is increasing the $\theta_{\text{WORM}}/\theta_{\text{WORMGEAR}}$ relationship is linear. However, when the direction of rotation reverses there is a region, depicted by the left pointing arrows, where the position of the worm changes without a corresponding change in the position of the wormgear. Note that once all of the backlash has been taken up the $\theta_{\text{WORM}}/\theta_{\text{WORMGEAR}}$ relationship is again linear until the direction of rotation changes.

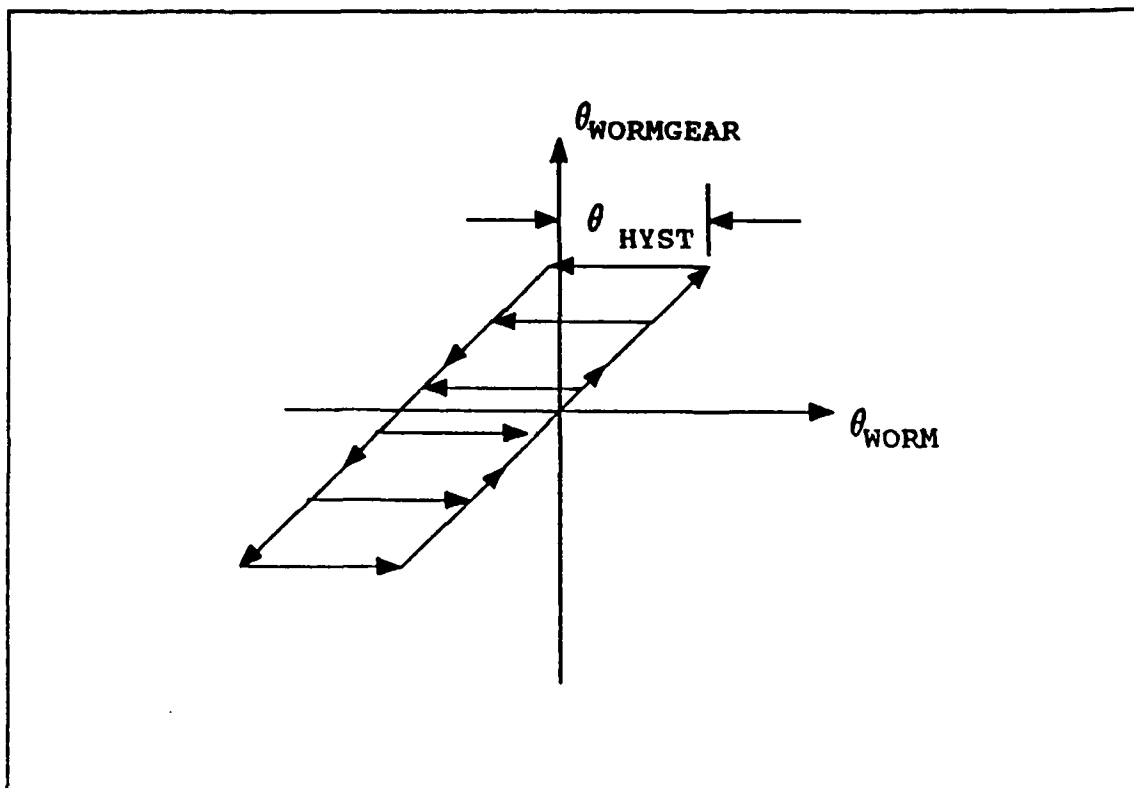


Figure 28. Typical Hysteresis Curve

The purpose of the hysteresis buffer in the MPU is to permit the signal processor to account for the backlash error introduced into the measurement by the worm-wormgear connection. The theory of operation for the buffer is relatively straight forward and is best described by the flow diagram in Figure 29. The buffer is a data byte in the MPU RAM. As long as the buffer is full, i.e., the contents are equal to the predetermined buffer length, a clockwise (CW) signal from the shaft encoder (increasing elevation and increasing azimuth are defined as CW rotation for the purposes of this system) causes the position counter to be incremented. Similarly, counter-clockwise

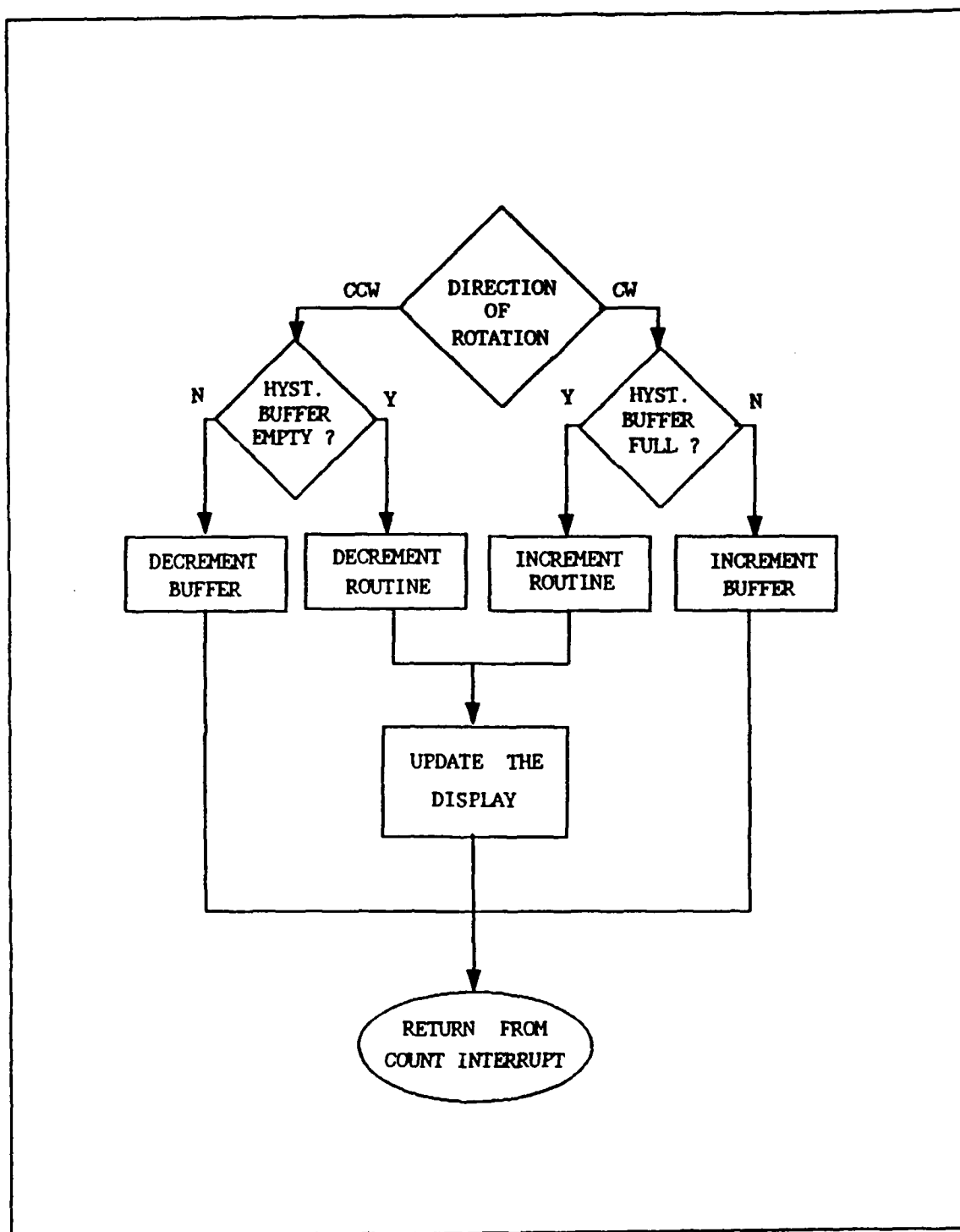


Figure 29. Operation of the Hysteresis Buffer

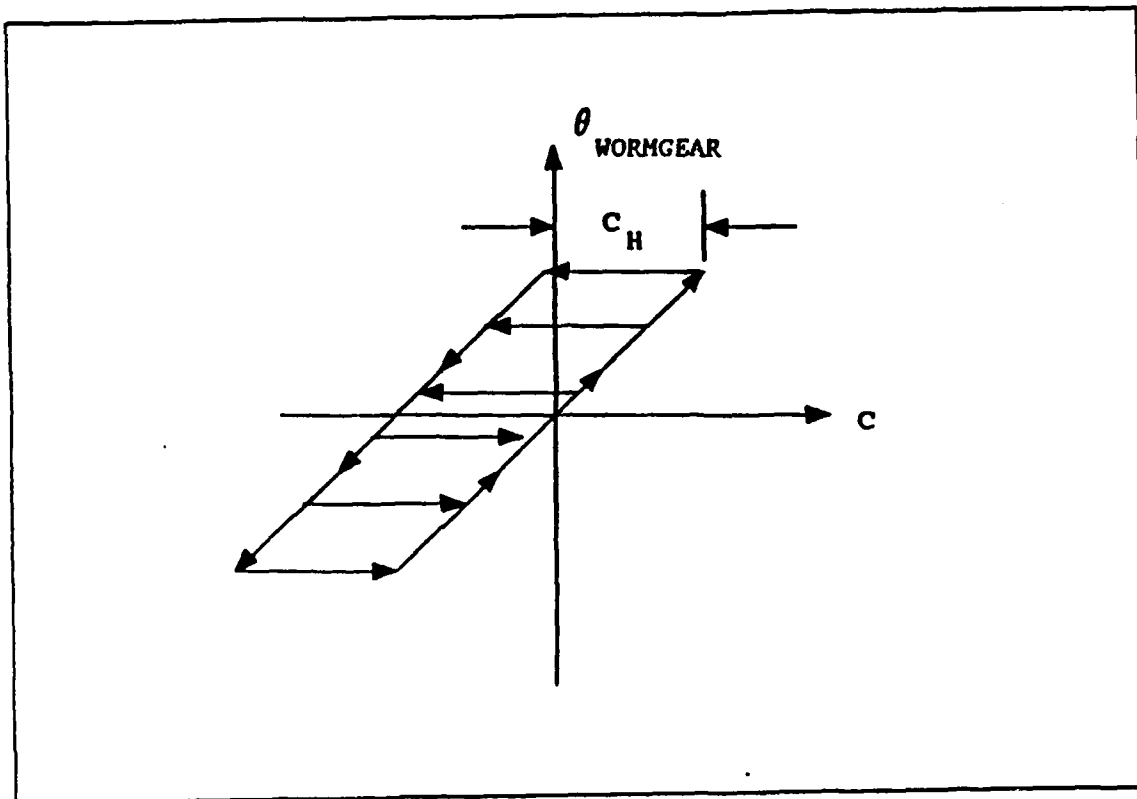


Figure 30. Hysteresis Curve

(CCW) signals cause the position counter to be decremented if the hysteresis buffer is empty, i.e., the contents are equal to zero. These two situations correspond to the two linear sections in Figure 28. From Equation (13), the horizontal separation of these two lines is related to the length of the hysteresis buffer, C_H by the expression

$$C_H = \frac{\Delta\theta_H}{SF} \quad (23)$$

Similarly, using the $\overline{SF}$ to map θ_{WORM} into C , and the fact that the displacement of the wormgear equals the displacement of the axis of interest, the curve shown in Figure 30 can be obtained from Figure 28. From Figure 30 it is apparent that two different pulse counts can be obtained for any given position, θ , depending on whether that position is approached from a CW or a CCW direction. The difference in the two counts is a measure of the hysteresis present in the gear train and is also the required length for the hysteresis buffer. By using this difference as the length of the hysteresis buffer, counts received by the MPU which occur while the gears are operating on one of the horizontal

sections of the curve in Figure 30 are not considered "valid" and therefore do not cause the MPU to modify the position. Using Equation (23) and data collected in the laboratory the average hysteresis present in each of the gear trains was determined (from 45 measurements on the Pan axis and 30 measurements on the Tilt axis) to be

$$\bar{C}_{H(\text{Pan})} = 7.39 \text{ Pulses} \quad (24)$$

$$\bar{C}_{H(\text{Tilt})} = 6.06 \text{ Pulses} \quad (25)$$

and the RMS errors were calculated to be,

$$\sigma_{C_{H(\text{Pan})}} = 1.0 \text{ Pulses} \quad (26)$$

$$\sigma_{C_{H(\text{Tilt})}} = 0.91 \text{ Pulses} . \quad (27)$$

C. IMPLEMENTATION OF THE CALIBRATION DATA

1. Background

Figure 31 outlines the basic operation of each of the MPU's. Although each of the routines is described in detail by the comments included in the programs, the operation of the Count Routine is the heart of the program and should be explained prior to discussing the actual implementation of the experimental results.

When the system operator causes the camera servo to rotate, each optical shaft encoder translates the displacement of one of the axes into two series of digital pulses. The two pulse trains, referred to as Channels A and B, are TTL logic level signals. When the logic level of Channel A transitions from low to high (rising edge transition) or from high to low (falling edge transition), the edge detector (See Figure 15 on page 33) pulls pin 3 of the associated MPU low for approximately 2 μsec . When this occurs an external interrupt (EXT INT or $\overline{\text{INT}}$) request is generated and the MPU begins execution of the Count Routine.

As mentioned in Chapter III, since both rising and falling edge transitions are detected by the edge detector, the signal processor must be capable of detecting multiple oscillations of the shaft about a single logic level transition point. Accordingly, the first tasks performed by the Count Routine are to determine the direction of rotation and to simultaneously determine whether the interrupt is the result of a stationary shaft oscillation. To do this the Count Routine checks the state of pin 17 (Channel A) and pin 19 (Channel B). Operation of this portion of the routine is summarized in Table 5.

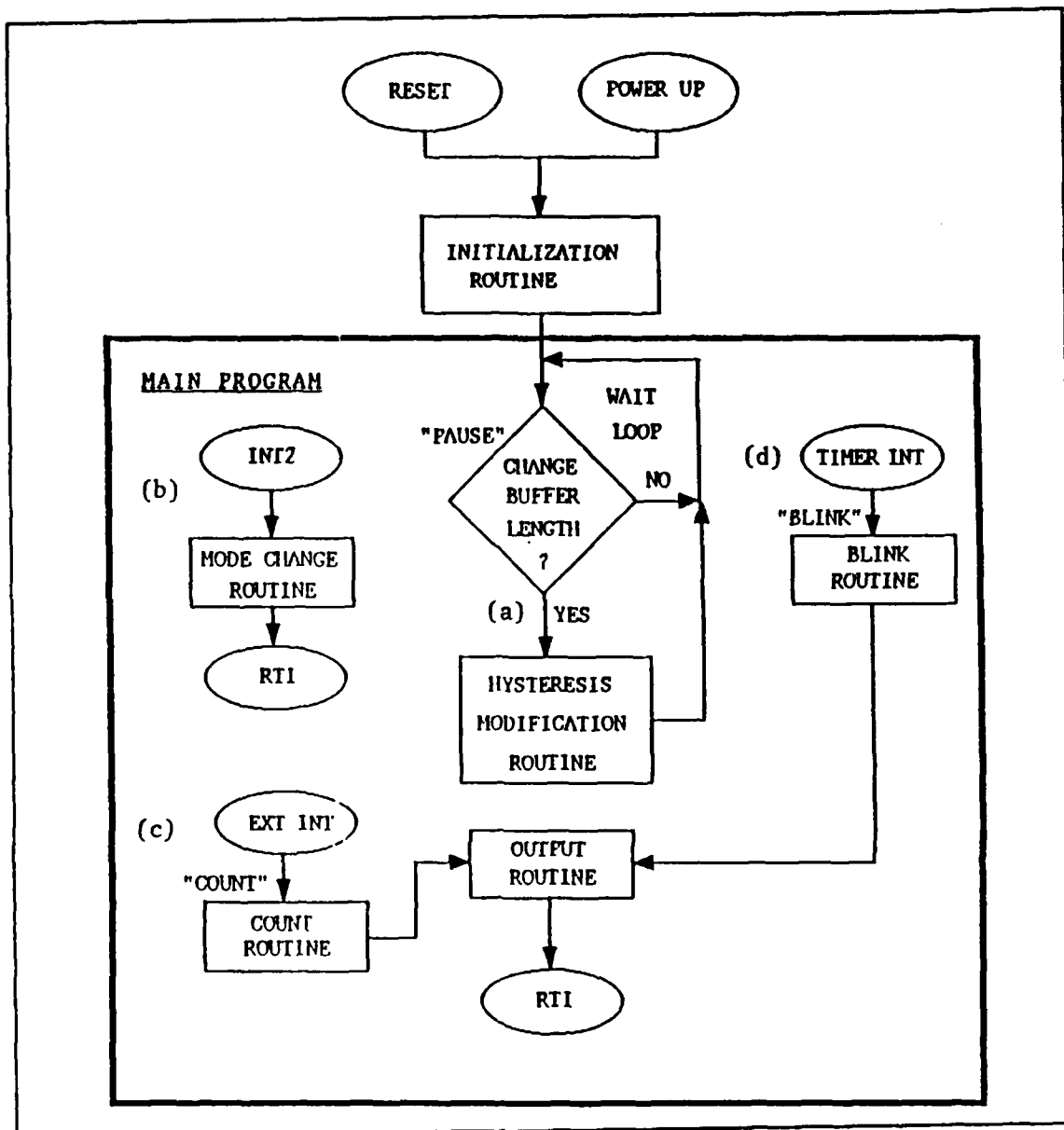


Figure 31. Program Flow Diagram: Program executes in the Wait Loop until; (a) the operator requests to modify the hysteresis buffer, (b) the operator requests to change the display mode, (c) an external interrupt is generated by the Channel A edge detector or, (d) a timer interrupt causes the display mode to "blink". All interrupt routines are terminated with a return from interrupt (RTI) command.

Note that CW rotation is indicated when Channel B leads Channel A in phase and CCW rotation is indicated if Channel A is leading Channel B. The possibility of erroneously counting multiple oscillations about a single point is eliminated by "counting" only the leading edge transitions when the shaft is rotating CW and only the trailing edge transitions when the rotation is CCW. All other transitions cause the program to execute a "return from interrupt" (RTI) instruction.

2. Implementing the Hysteresis Buffer

The transitions that are to be counted cause the program to compare the contents of the hysteresis buffer, HYSTCT, and the direction of rotation to the experimentally determined buffer length, $HYST \approx \bar{C}_H$. If the rotation is CW and the buffer is full (i.e., HYSTCT = HYST), or if the rotation is CCW and the buffer is empty (i.e., HYSTCT = 0), then the "slack" due to the gear backlash should have been taken up, the transitions are considered "valid" and the MPU modifies the position appropriately. "Invalid" counts cause the contents of the hysteresis buffer to be incremented or decremented depending on whether the present direction of rotation is CW or CCW (Figure 29 refers).

Table 5. COUNT ROUTINE LOGIC

Channel A	Channel B	Direction of Rotation	Count the Pulse?	Action
Low	Low	CW	No	Increment the hysteresis buffer.
Low	High	CCW	Yes	Decrement the position.
High	Low	CCW	No	Decrement the hysteresis buffer.
High	High	CW	Yes	Increment the position.

From the calibration data for the Pan axis, $\bar{C}_{H(Pan)} \approx 7.4$ and $\sigma_{C_{H(Pan)}} \approx 1.0$. Because the length of the hysteresis buffer must be an integer value, $\bar{C}_{H(Pan)}$ needed to be rounded off. Rounding to the nearest whole number initially seemed the most logical approach. Upon further consideration, however, it was decided to round 7.4 up to 8. Considering the relatively small data base (45 measurements) upon which the average was based, the fact that the standard deviation was 1.0 and that the gear backlash will only increase

with time, this seemed like the most reasonable approach. The buffer length for the Tilt axis was set equal to 6 ($\overline{C}_{H/Tilt} = 6.06$).

3. Implementing the Scale Factor

There are three counters in each MPU that keep track of the position information for the axis of interest. The first, BINCT, is simply a binary counter that is incremented by one for each valid CW count and decremented by one for each valid CCW count. The other two counters consist of two sets of pointers, two sets of data registers and a shared data table. Each byte in a pointer points to an address in the table that contains two BCD digits which make up a portion of the position information.

In order to increment (decrement) the pulse count, BCDCT, by one, the count pointer, CTPTR, is incremented (decremented) by one causing it to point to a new table address. The contents of the table at the new addresses are then moved into BCDCT. Modification of the position counter, DEGRES, is performed in much the same manner. DEGRES contains a BCD number that, when multiplied by 0.001, represents the angular position (in degrees) of the shaft of interest. Thus, each time the camera is displaced in a CW direction through one degree, the contents of DEGRES should be incremented by 1000. To do this, the position pointer, PTR, must be incremented (decremented) by seven or eight each time CTPTR is incremented (decremented) by one. Incrementing PTR by seven corresponds to an angular displacement of 0.007° and since $\overline{SF}_{Pan}$ and $\overline{SF}_{Tilt}$ are each slightly larger than 0.007° , periodically PTR must be incremented by eight to reduce the cumulative round off error. Specifically, if PTR is incremented by seven each time a valid CW pulse is detected (except when BINCT is an even multiple of 32) and is incremented by eight when BINCT is a modulo 32 number, the effective scale factor is given by;

$$\begin{aligned} SF_{eff} &= \frac{1}{32} (31(0.007) + 0.008) \\ &= 0.00703125^\circ \text{Pulse}^{-1} , \end{aligned} \quad (28)$$

which is slightly larger than the desired $0.0070312^\circ \text{Pulse}^{-1}$, for the Pan axis and slightly smaller than the desired $0.0070452^\circ \text{Pulse}^{-1}$ for the Tilt axis. To further reduce the cumulative round off on the Pan axis, every 16,384 ($2^{14} = 32 \times 512$) counts PTR is incremented by seven instead of eight. This results in an effective scale factor of,

$$SF_{eff_2} = \frac{1}{512} \left\{ 511 \left[\frac{1}{32} (31(7) + 8) \times 10^{-3} \right] + 0.007 \right\} \quad (29)$$

$$= (7.03119 \times 10^{-3})^\circ \text{Pulse}^{-1} ,$$

which is within two parts in one million.

The maximum error introduced into the measurement should occur when the camera is rotated through the largest possible angle. To predict this error on the Pan axis, when the camera has been displaced by 360° ,

$$BCDCT = \frac{360^\circ}{SF_{Pan}} \quad (30)$$

$$= 51,200 \text{ Pulses}$$

so the position error using SF_{eff_1} and SF_{eff_2} should be;

$$e_{Pan} = 360^\circ - [3(SF_{eff_2}) + (51,200 - 3(16,384))(SF_{eff_1})] \quad (31)$$

$$= 0.00295^\circ .$$

Thus, the error due to the scale factor on the Pan axis should be well within the desired resolution of $\pm 0.006^\circ$.

Using SF_{eff_1} alone as the scale factor for the Tilt axis, the maximum theoretical error over $\pm 12^\circ$ due to the scale factor round off is determined in the same manner.

$$BCDCT = \frac{12^\circ}{SF_{Tilt}} \quad (32)$$

$$= 17,033 \text{ Pulses}$$

So that,

$$e_{Tilt} = 12^\circ - 17,033(SF_{eff_1}) \quad (33)$$

$$= 0.0234^\circ ,$$

which again is significantly less than the required resolution of $\pm 0.23^\circ$ for the Tilt axis.

The final step in the Count Routine is a branch to the Display Routine. Depending on whether the MPU is in the Count or Position Mode, the Display Routine copies the contents of BCDCT or DEGRES to the output ports and then executes an RTI instruction.

D. FINAL TESTING

1. General

Final laboratory testing and evaluation of the measurement system was performed after the calibration results had been implemented in each of the MPU Count Routines. The purpose of the testing was to verify that the calibration results had been properly coded into the MPU's and to determine the resolution capabilities of the measurement system experimentally.

This verification process included determining the combined error due to the hysteresis and scale factor errors. The use of some simple multiple random variable theory was therefore required. From [Ref. 20: pp. 121,122] the variance of a weighted sum of M random variables is the weighted sum of their covariances, $C_{X_i X_j}$, and is given by,

$$\sigma^2 = \sum_{i=1}^M \sum_{j=1}^M \alpha_i \alpha_j C_{X_i X_j} , \quad (34)$$

where α_i is the weight associated with X_i . Additionally, the covariance can be expressed as

$$C_{XY} = \rho \sigma_X \sigma_Y , \quad (35)$$

where ρ is the normalized second-order moment and is known as the correlation coefficient of X and Y . The correlation coefficient is bounded by

$$-1 \leq \rho \leq 1 . \quad (36)$$

In the case where there are two equally weighted random variables, $M=2$ and $\alpha_i = \alpha_j = 1.0$. Substituting into Equation (34) and expanding

$$\sigma^2 = C_{XX} + C_{XY} + C_{YX} + C_{YY} . \quad (37)$$

Using Equation (35),

$$\sigma^2 = \sigma_X^2 + 2\rho\sigma_X\sigma_Y + \sigma_Y^2 . \quad (38)$$

Combining (36) and (38) yields

$$\sigma_X^2 - 2\sigma_X\sigma_Y + \sigma_Y^2 \leq \sigma^2 \leq \sigma_X^2 + 2\sigma_X\sigma_Y + \sigma_Y^2 . \quad (39)$$

The bounds of the combined scale factor and hysteresis errors can therefore be determined from

$$\sqrt{\sigma_{e_{SF}}^2 - 2\sigma_{e_{SF}}\sigma_{e_H} + \sigma_{e_H}^2} \leq \sigma_e \leq \sqrt{\sigma_{e_{SF}}^2 + 2\sigma_{e_{SF}}\sigma_{e_H} + \sigma_{e_H}^2} \quad (40)$$

where:

- σ_e = standard deviation of the combined error,
- $\sigma_{e_{SF}}$ = standard deviation of the scale factor error, and
- σ_{e_H} = standard deviation of the hysteresis error.

Note that the bounds are determined by the two cases where the hysteresis error, e_H , and the scale factor error, e_{SF} , are "completely correlated". The upper bound corresponds to the case where an increase in e_{SF} implies an increase in e_H , and the lower bound corresponds to the case where an increase in e_{SF} directly implies a decrease in e_H .

A third case is also of particular interest. If e_H and e_{SF} are completely uncorrelated, i.e., $\rho = 0$, then from Equation (38),

$$\sigma_e = \sqrt{\sigma_{e_{SF}}^2 + \sigma_{e_H}^2} \quad (41)$$

which can also be written as

$$e = \pm \sqrt{e_{SF}^2 + e_H^2} \quad (42)$$

where $e = \pm \sigma_e$ is the 1.0 σ error due to the scale factor and hysteresis errors, e_{SF} and e_H respectively. Based on the physical nature of the two errors it is reasonable to assume that e_{SF} and e_H are statistically uncorrelated; however, no experimental data was collected to support this hypothesis. Due to this lack of a priori information, the maximum RMS error, $e_{max} = \pm \sigma_{e_{max}}$, given by

$$e_{max} = \pm \sqrt{e_{SF}^2 + 2e_{SF}e_H + e_H^2} \quad (43)$$

will be used to describe the resolution capabilities of the measurement system.

2. Pan Axis

a. Hysteresis

To test the operation of the Pan axis hysteresis buffer, the Initialization Routine was programmed to set the buffer length to 8. Then, as described in the first section of this chapter, the servo was used to position the beam of a small laser on a fixed target. By approaching the target alternately from a CW and a CCW direction and

comparing the difference in the output counts from the shaft encoders, the hysteresis error was determined. The average error after 31 measurements was

$$\bar{e}_{H(\text{Pan})} = -0.1880 \text{ Pulses} , \quad (44)$$

and the RMS error was

$$\sigma_{e_{H(\text{Pan})}} = 1.7699 \text{ Pulses} . \quad (45)$$

Since the mean error is "near zero" compared to the standard deviation, the 1.0σ error e_H , due to the hysteresis can be determined from

$$e_H = \pm (\sigma_{e_H}) \overline{SF} \quad (46)$$

so that

$$e_{H(\text{Pan})} = \pm 0.0124^\circ . \quad (47)$$

b. Scale Factor

Verification of the scale factor was performed in the same manner as the scale factor calibration, except that the MPU was calibrated in the Count Mode and tested in the Position Mode. Since these tests sought to find the maximum error due to the scale factor, and the error is directly proportional to the angle that is being measured, these tests were conducted by displacing the camera servo through the maximum angles permitted by the camera and the laboratory. Specifically, on the Pan axis the servo was rotated through approximately 360° . The mean error due to the scale factor on the Pan axis was determined from 15 samples to be

$$\bar{e}_{SF(\text{Pan})} = -0.0018^\circ \quad (48)$$

and the RMS error was

$$\sigma_{e_{SF(\text{Pan})}} = 0.00890^\circ . \quad (49)$$

As with the hysteresis error, if we neglect the small bias due to the $\bar{e}_{SF(\text{Pan})}$, we can describe the 1.0σ RMS error due to the scale factor as

$$\begin{aligned} e_{SF(\text{Pan})} &= \pm \sigma_{SF(\text{Pan})} \\ &= \pm 0.00890^\circ . \end{aligned} \quad (50)$$

c. Combined Error

From Equation (42) the combined error on the Pan axis if e_H and e_{SF} are uncorrelated can be estimated as

$$\begin{aligned} e_{Pan} &= \pm \sqrt{(0.0124)^2 + (0.0089)^2} \\ &= \pm 0.01526^\circ \end{aligned} \quad (51)$$

And from Equation (43) the maximum combined error on the Pan axis is

$$e_{Pan_{max}} = \pm \sqrt{(0.0124)^2 + 2(0.0124)(0.0089) + (0.0089)^2} \quad (52)$$

$$e_{Pan_{max}} = \pm 0.0213^\circ \quad (53)$$

The combined error is approximately three times larger than the design specification limit and is due primarily to the hysteresis error.

3. Tilt Axis

a. Hysteresis

The procedure used to verify the operation of the calibrated Tilt MPU was identical to that described in the previous section. Using a hysteresis buffer length of 6 resulted in

$$\bar{e}_{H(Tilt)} = -0.0965 \text{ Pulses} \quad (54)$$

and,

$$\sigma_{e_{H(Tilt)}} = 1.3156 \text{ Pulses} \quad (55)$$

after 13 samples. As before we can define the 1.0σ error from $e = \sigma \sqrt{SF}$ to be

$$e_{HTilt} = \pm 0.00529^\circ \quad (56)$$

b. Scale Factor

Testing the scale factor on the Tilt axis was limited by the physical construction of the servo and the size of the laboratory. The angle over which testing could be performed was limited to $\pm 6^\circ$ from the horizontal plane. Consequently, the RMS error for the scale factor on the Tilt axis was determined in exactly the same manner as

the RMS error for the Pan axis scale factor, but since the error due to rounding of the scale factor is directly proportional to the angle being measured the results were multiplied by 2.0 to account for the limited range of the test. The modified results should therefore be representative of the maximum error one should expect if the measurement system is used to measure elevation angles over a range of $\pm 12^\circ$.

The error due to the scale factor is described from 16 samples by

$$\bar{e}_{SF(Tilt)} = 0.0070^\circ \quad (57)$$

and,

$$\sigma_{e_{SF(Tilt)}} = 0.0665^\circ \quad (58)$$

Including the factor of two in the calculation we have

$$\begin{aligned} e_{SF(Tilt)} &= \pm 2(0.0665^\circ) \\ &= \pm 0.1330^\circ \end{aligned} \quad (59)$$

c. Combined Error

The combined RMS error is determined in the same manner as before. If e_H and e_{SF} are uncorrelated,

$$\begin{aligned} e_{Tilt} &= \pm \sqrt{(0.1330)^2 + (0.00529)^2} \\ &= 0.1331^\circ \end{aligned} \quad (60)$$

and the maximum combined RMS error is

$$e_{Tilt_{max}} = \pm \sqrt{(0.1330)^2 + 2(0.1330)(0.00529) + (0.00529)^2} \quad (61)$$

$$e_{Tilt_{max}} = \pm 0.1383^\circ \quad (62)$$

The Tilt axis measurement system appears to perform well within the required resolution specifications.

E. FINAL IMPLEMENTATION

Once the program debugging, calibration and testing were completed, final implementation of the system remained. Taking the design from the prototype/development model to a fully functional system was a straightforward but time-consuming evolution.

The plans for the printed circuit boards (PCB's) were made directly from the schematics shown in Appendix A; the boards were then etched and assembled from the plans which are shown in Appendix B. All of this work was performed by sailors attached to the Academic Division of the NPS.

As previously discussed, the M68705EVM Evaluation Module provided a powerful and flexible means of debugging and evaluating the performance of the microprocessor based signal conditioner. Additionally, once program testing was completed the EVM's EPROM microprocessor programmer provided the means to program the EPROM MCU's. A detailed, but simple to follow, programming procedure for programming the MC68705U3 is given in [Ref. 18: pp. (3-26)-(3-27)].

V. CONCLUSIONS AND RECOMMENDATIONS

A. SYSTEM PERFORMANCE

The prototype system was calibrated and successfully tested in a laboratory environment. Experimental results indicate that the system is capable of measuring the video camera's elevation over a range of $\pm 12^\circ$ with a resolution of $\pm 0.138^\circ$ and its azimuth over 360° with a resolution of $\pm 0.021^\circ$. The system was designed to be low cost, reliable, and easy to operate. Only time will tell whether these objectives were truly achieved.

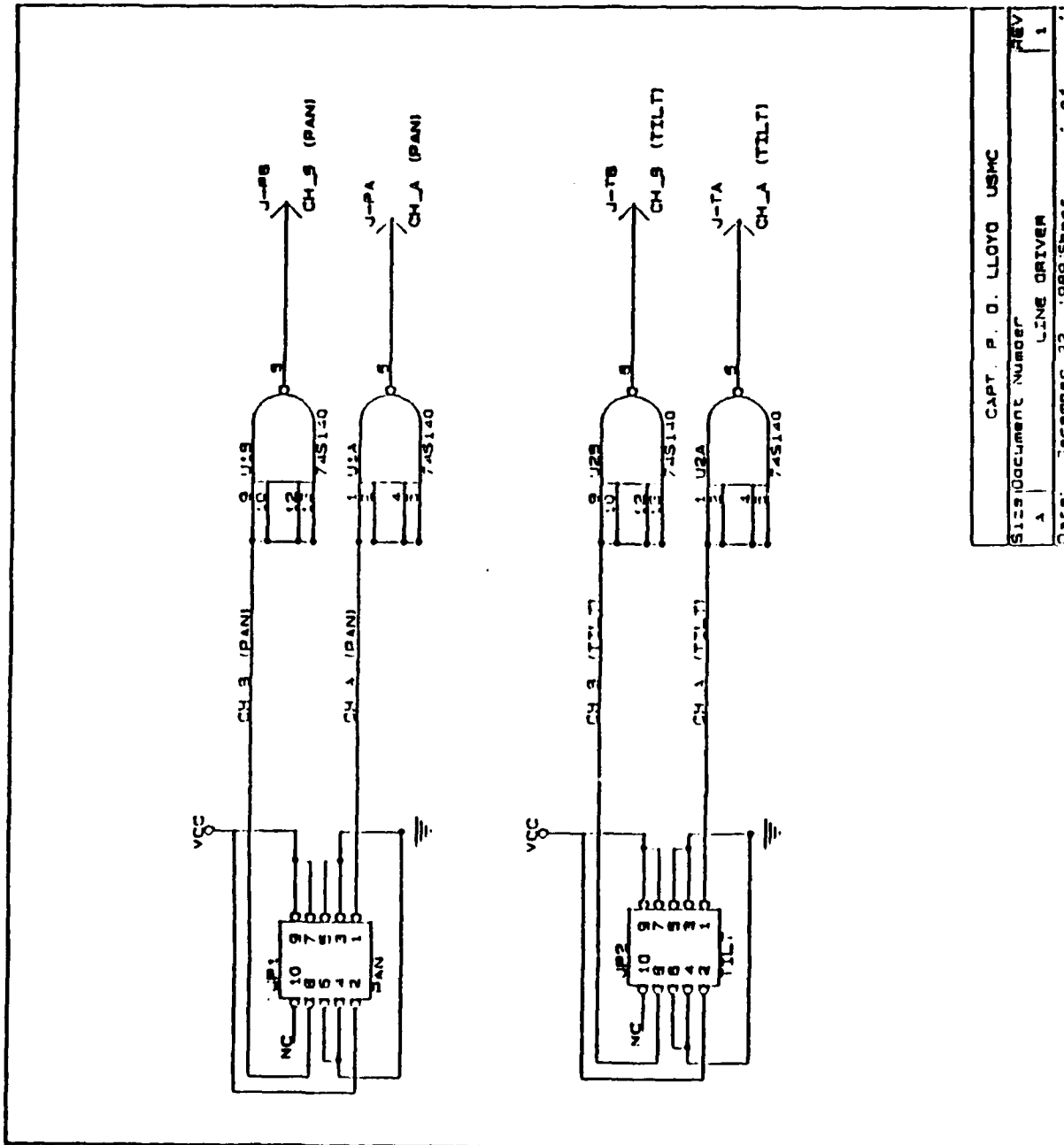
The portion of the system that will be located outdoors has been weatherproofed and is ready to be placed in service. Printed circuit board plans for the remainder of the system have been developed, but final implementation of the system is still ongoing. Once the system is fully operation additional testing should be performed in order to verify the completed system's performance. Although the laboratory results indicate that the system is capable of meeting all of the design criteria except for the required resolution on the Pan axis, the system must be further tested in a non-laboratory environment. "...The proof of a good design rests in the ability of the system to function in the outside world." [Ref 21]

B. RECOMMENDATIONS FOR FURTHER WORK

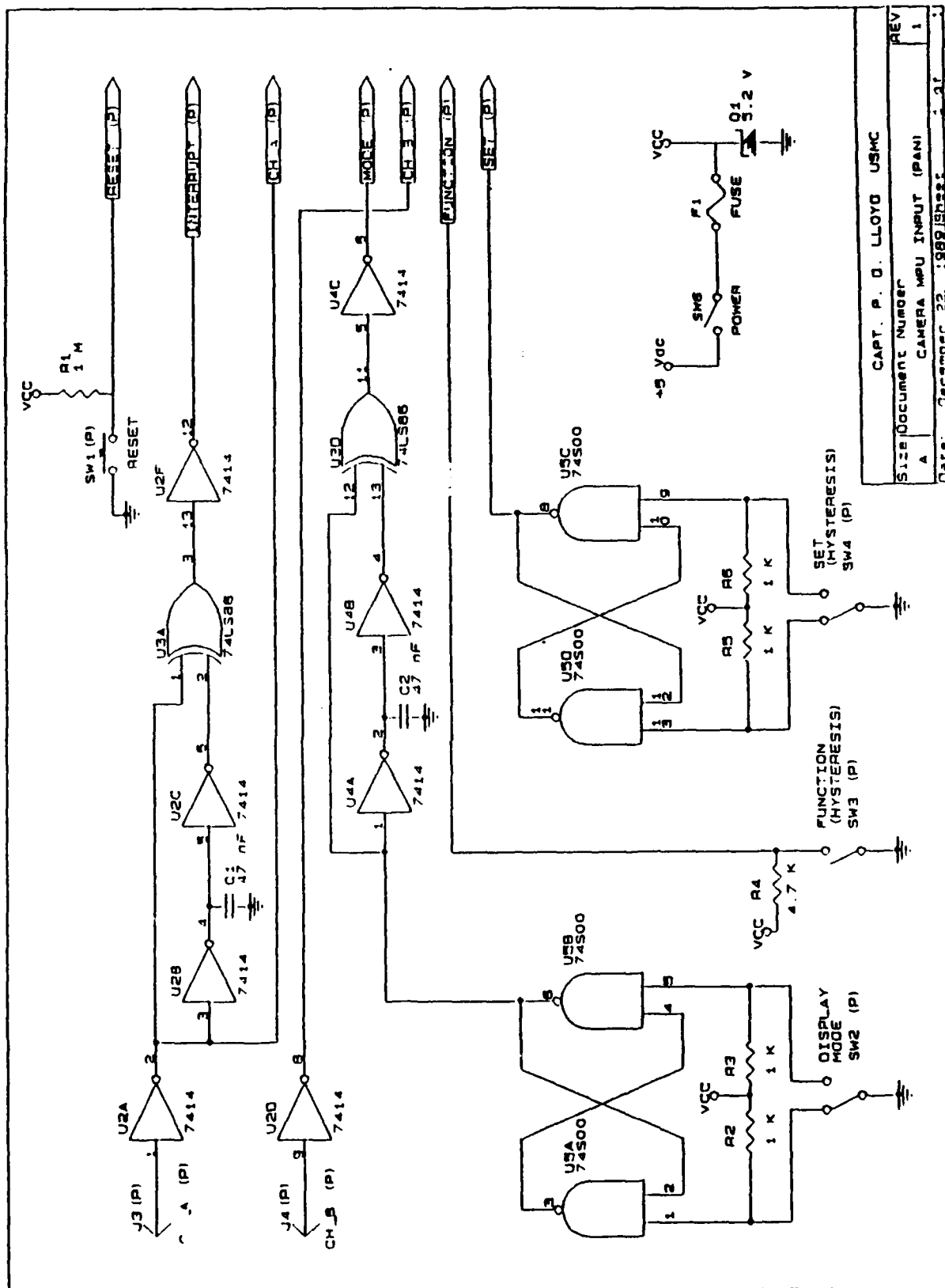
There are several areas for follow-on work with this project. Some possibilities are:

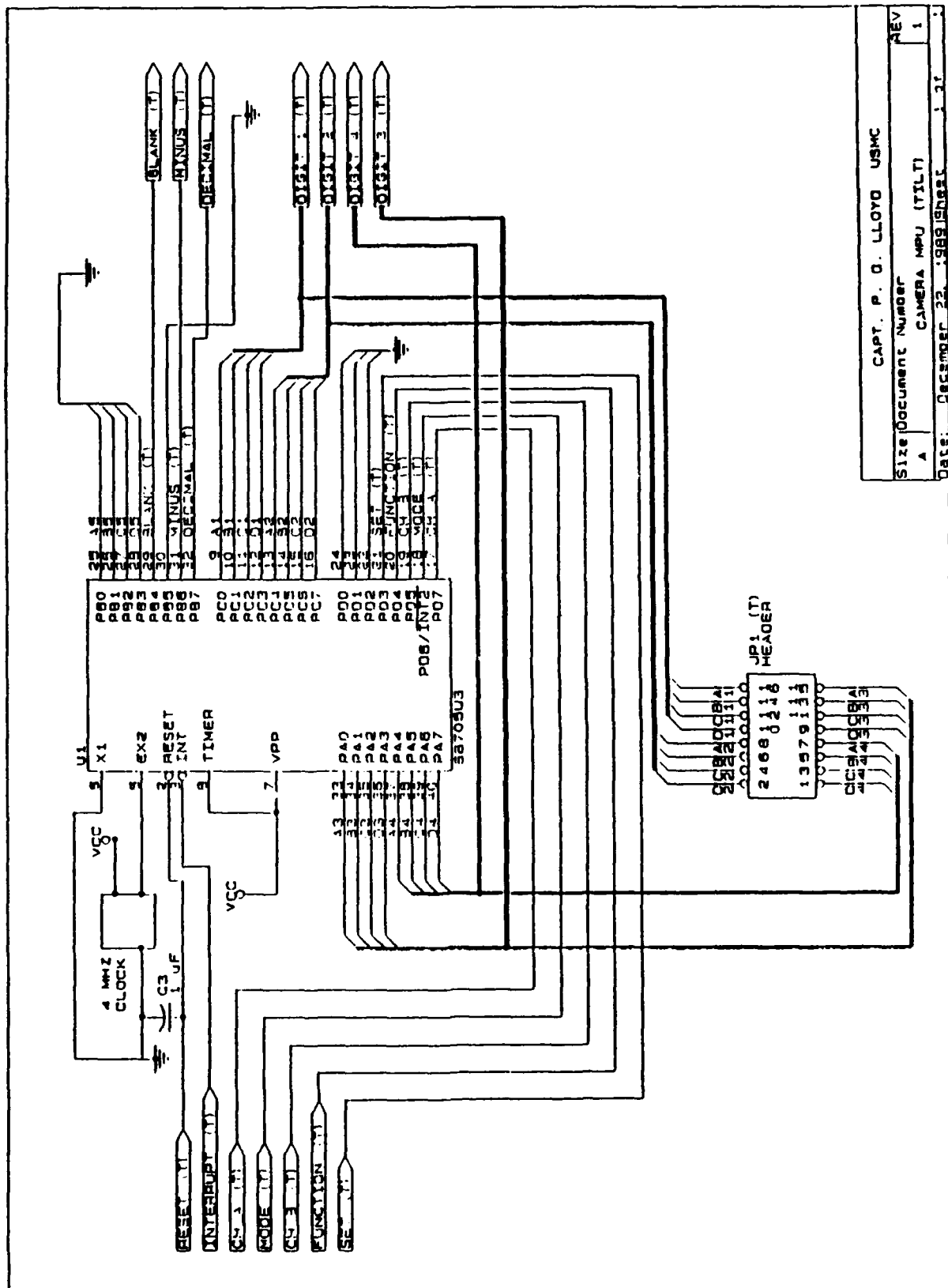
- Incorporate the measurement system's output into the video image being created by the video camera. This would permit a permanent record of the position information to be stored with the video image and would facilitate identification of the image at a later date.
- Design and build an automatic feedback control system for the camera.
- Implementation of a second video camera at the NPS, together with the NPS modified IRSTD, would permit triangulation of a target and would consequently provide range information which is not currently available. This information could provide valuable additional information to those who are developing the signal processing algorithms.

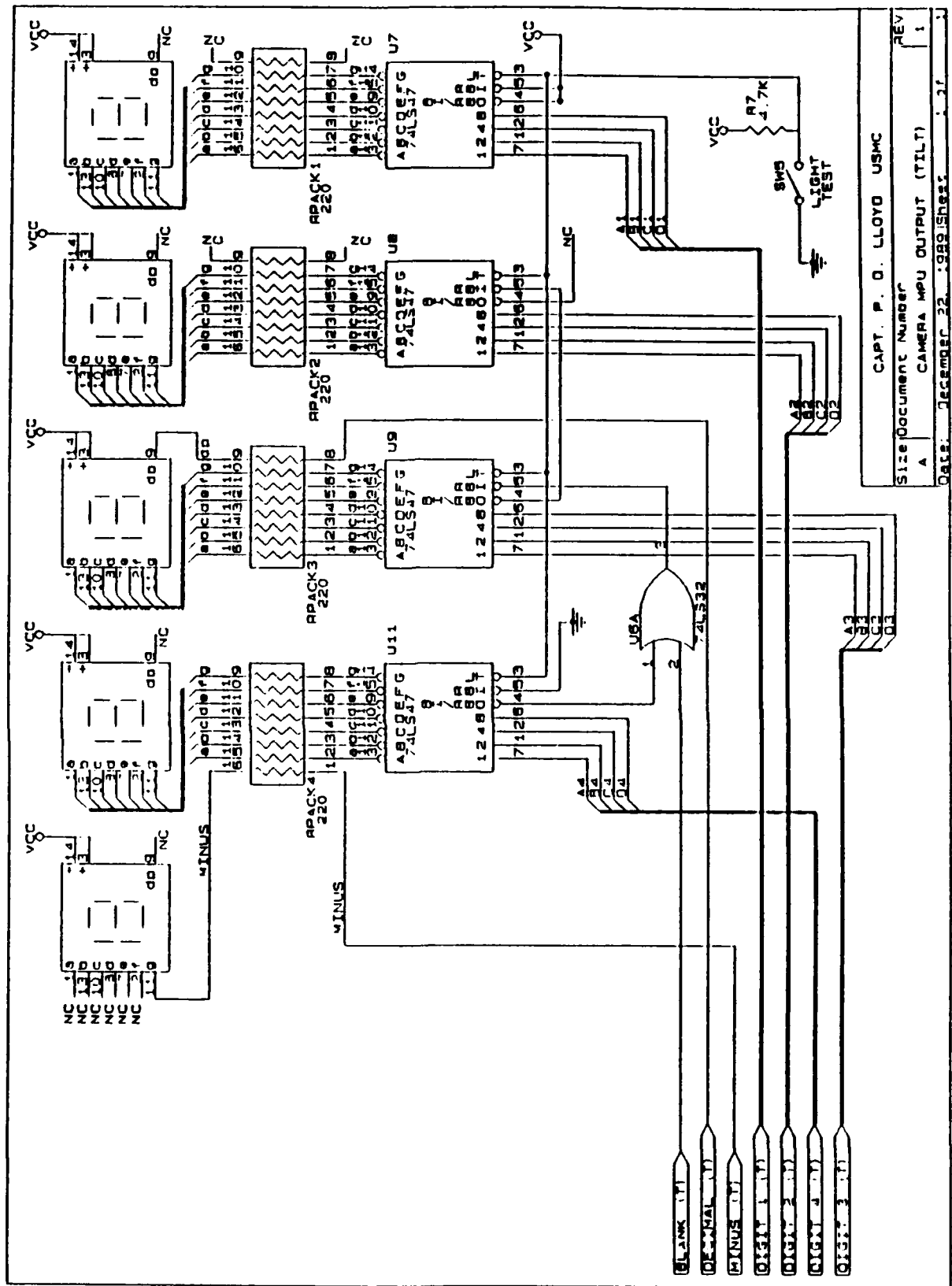
APPENDIX A. SCHEMATIC DIAGRAMS



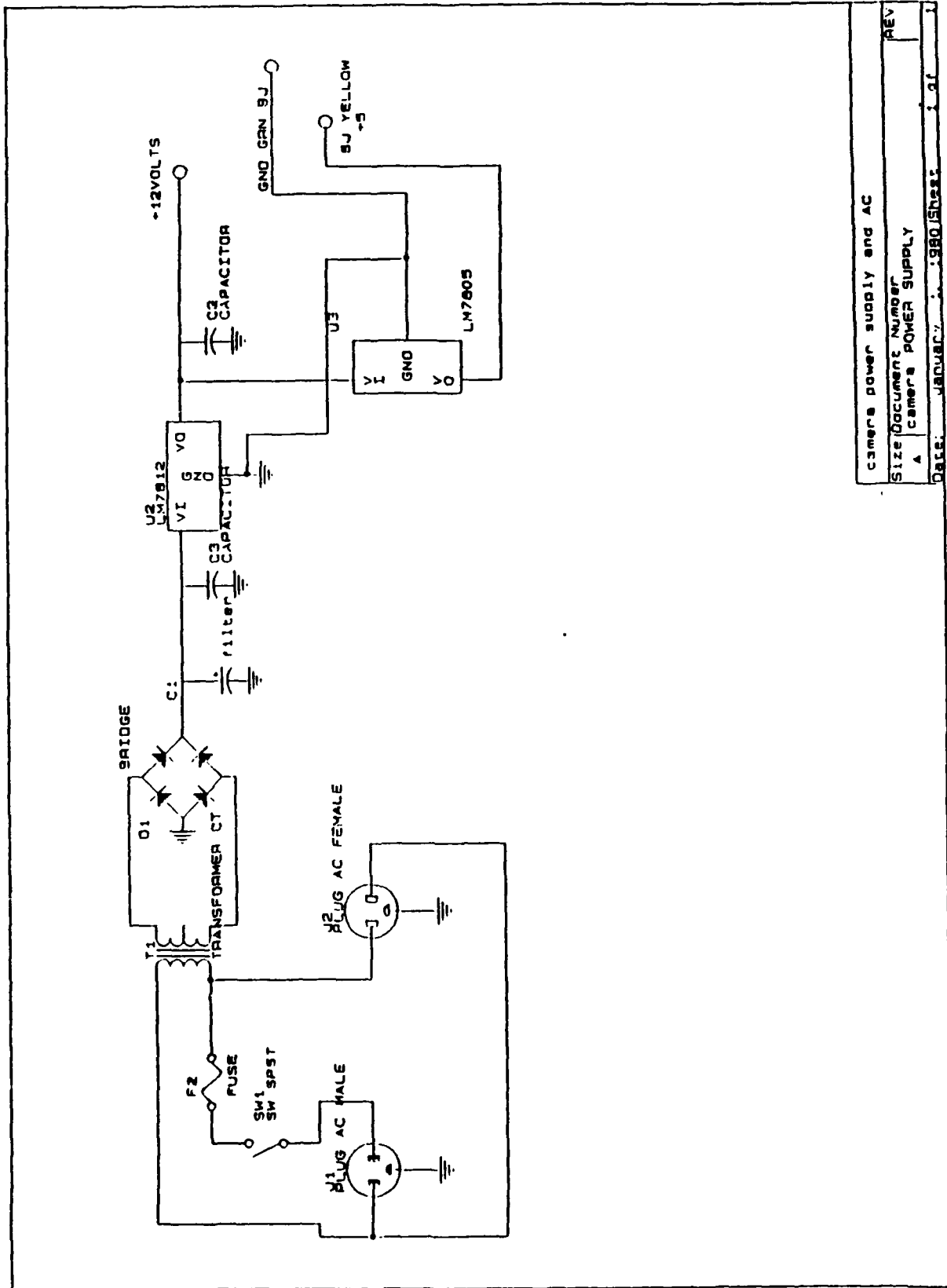
CAPT. P. O. LLOYD USMC	
Size	Document Number
A	LINE DRIVER
REV	1
DATE:	December 22, 1980







CAPT. P. O. LLOYD USMC
Size/Document Number
A CAMERA MPU OUTPUT (TILT)
Date: December 22, 1989/Sheet 1 of 1



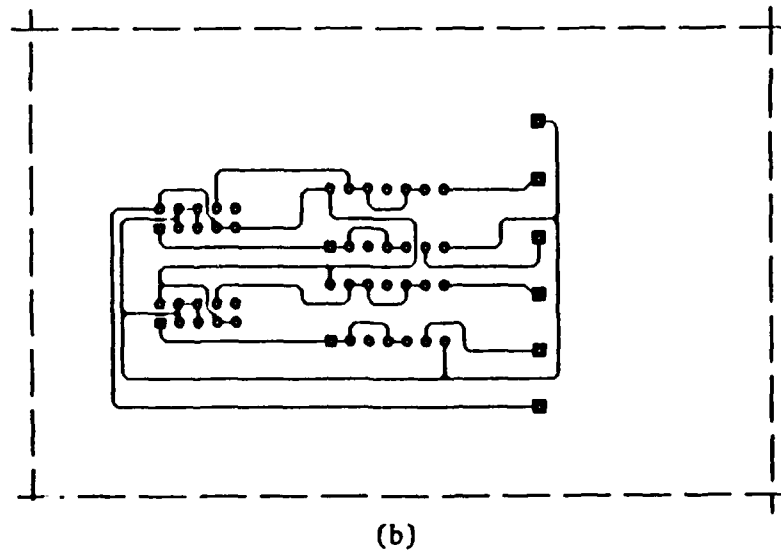
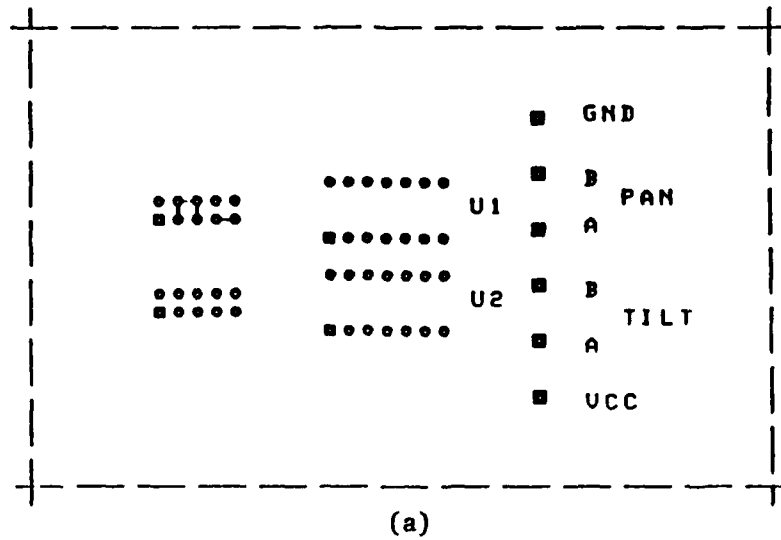
camera power supply and AC

Size Document Number
A camera power supply

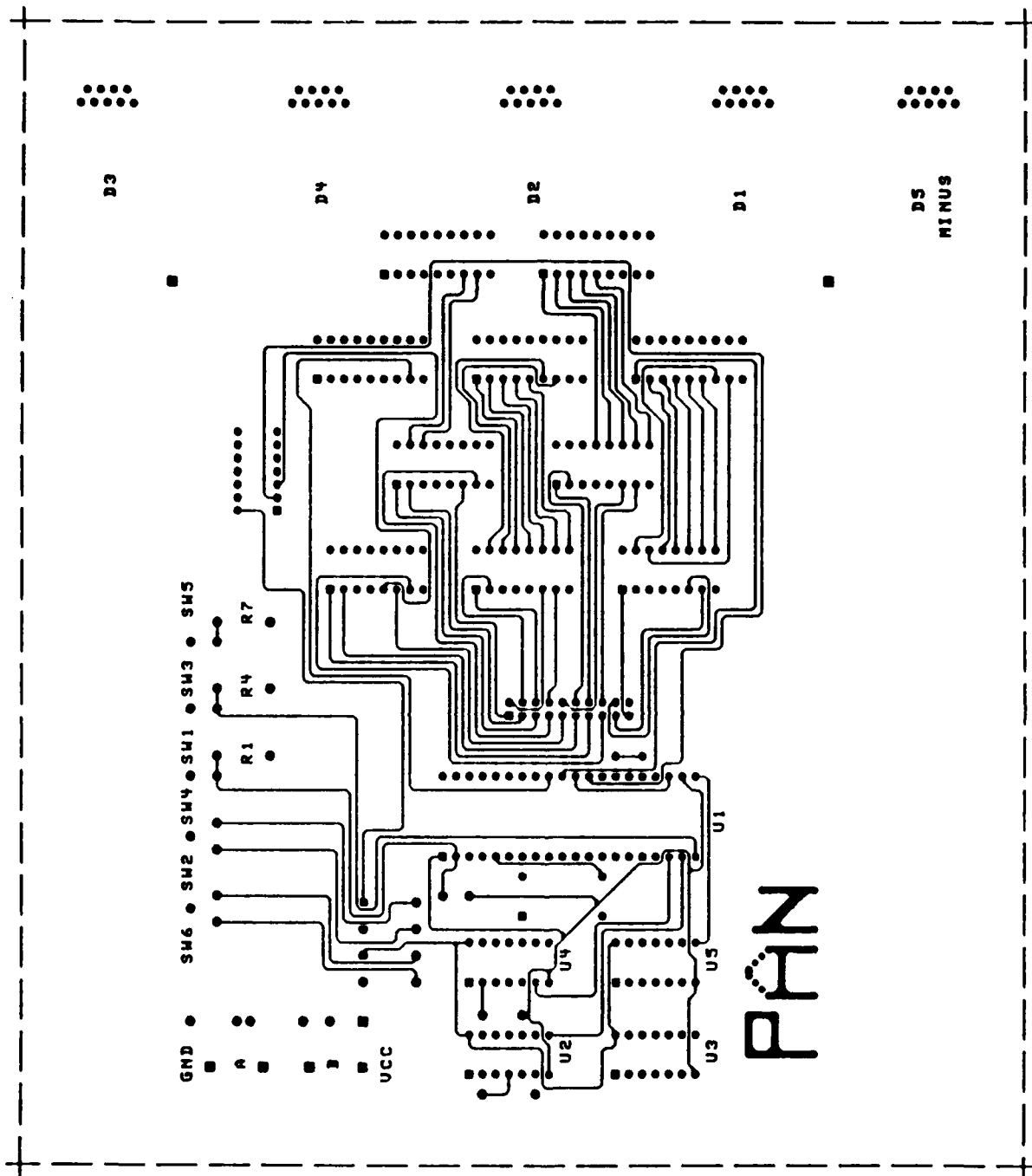
REV

Date: JANUARY 1980 Sheet 1 of 1

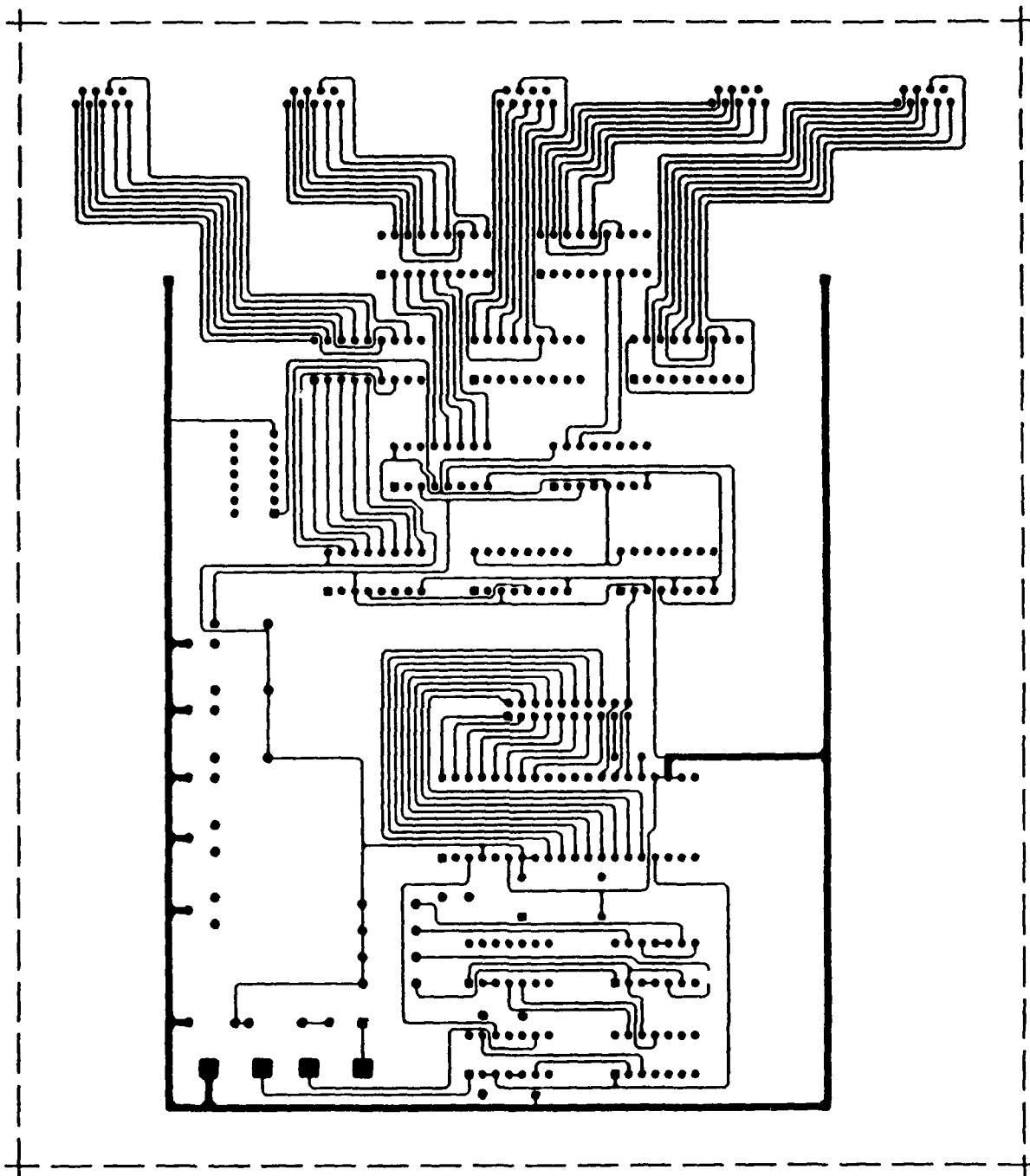
APPENDIX B. PRINTED CIRCUIT BOARD PLANS



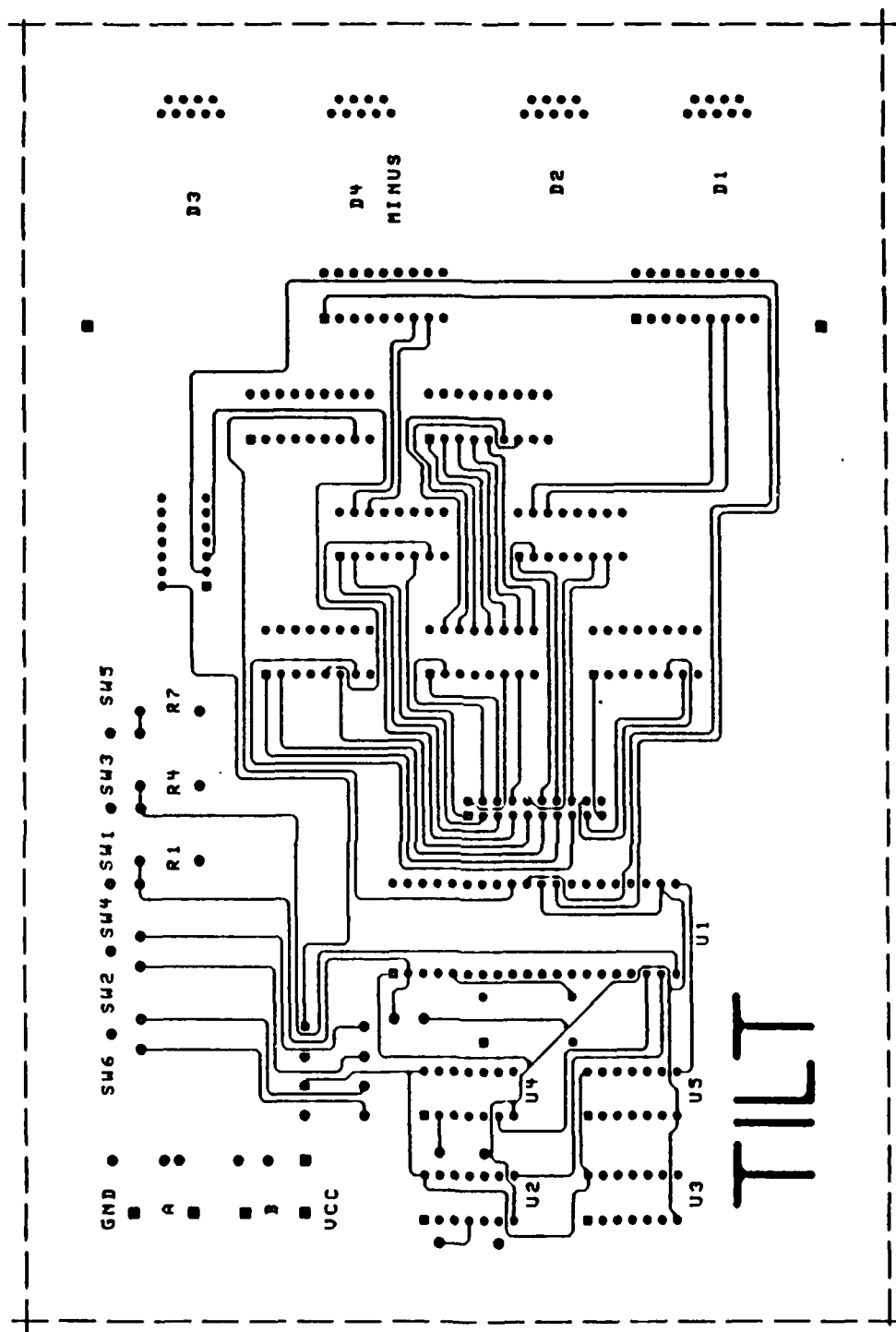
Line Driver, (a) Front and (b) Back. Full scale.



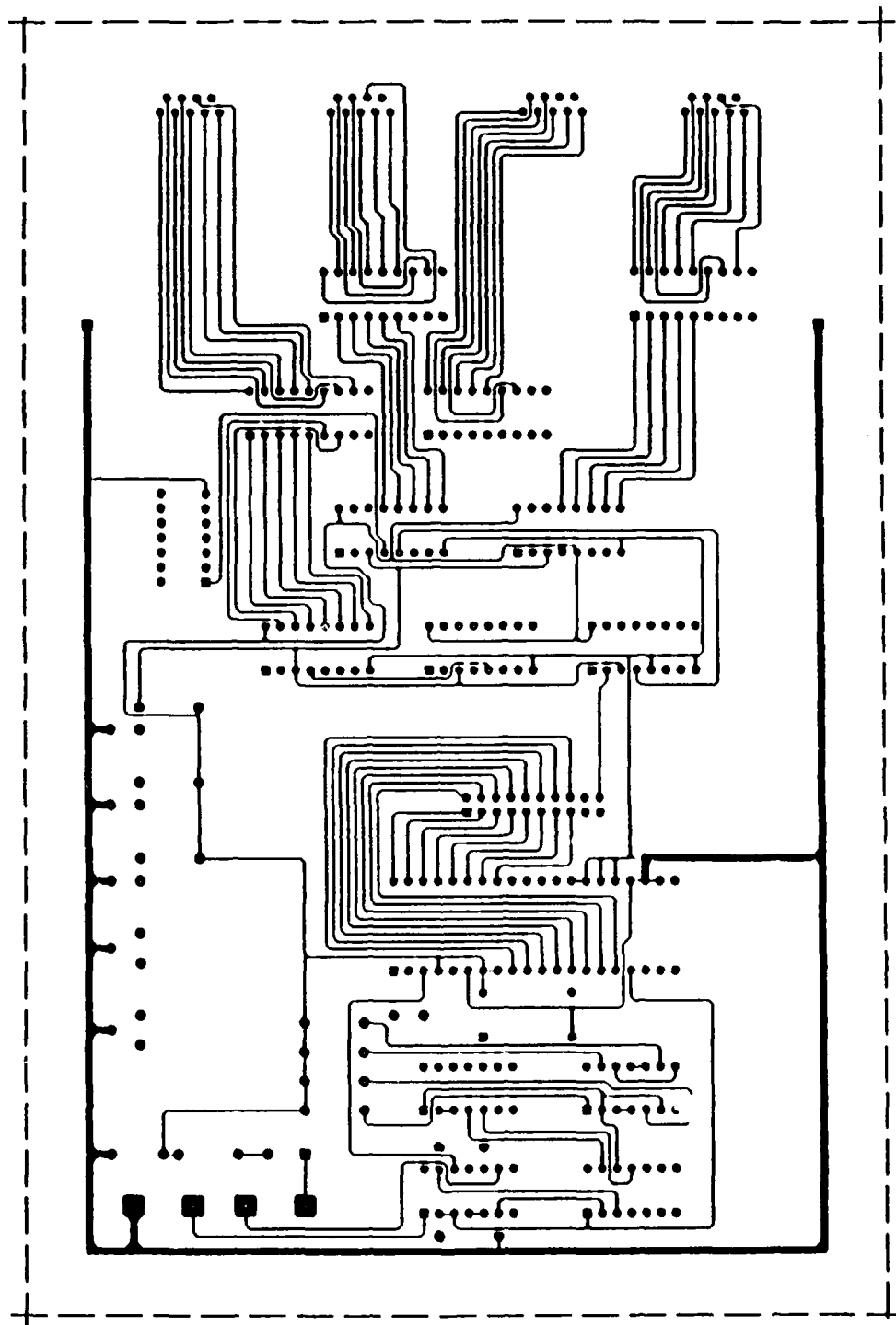
Pan MPU, Front. 90 % of full scale.



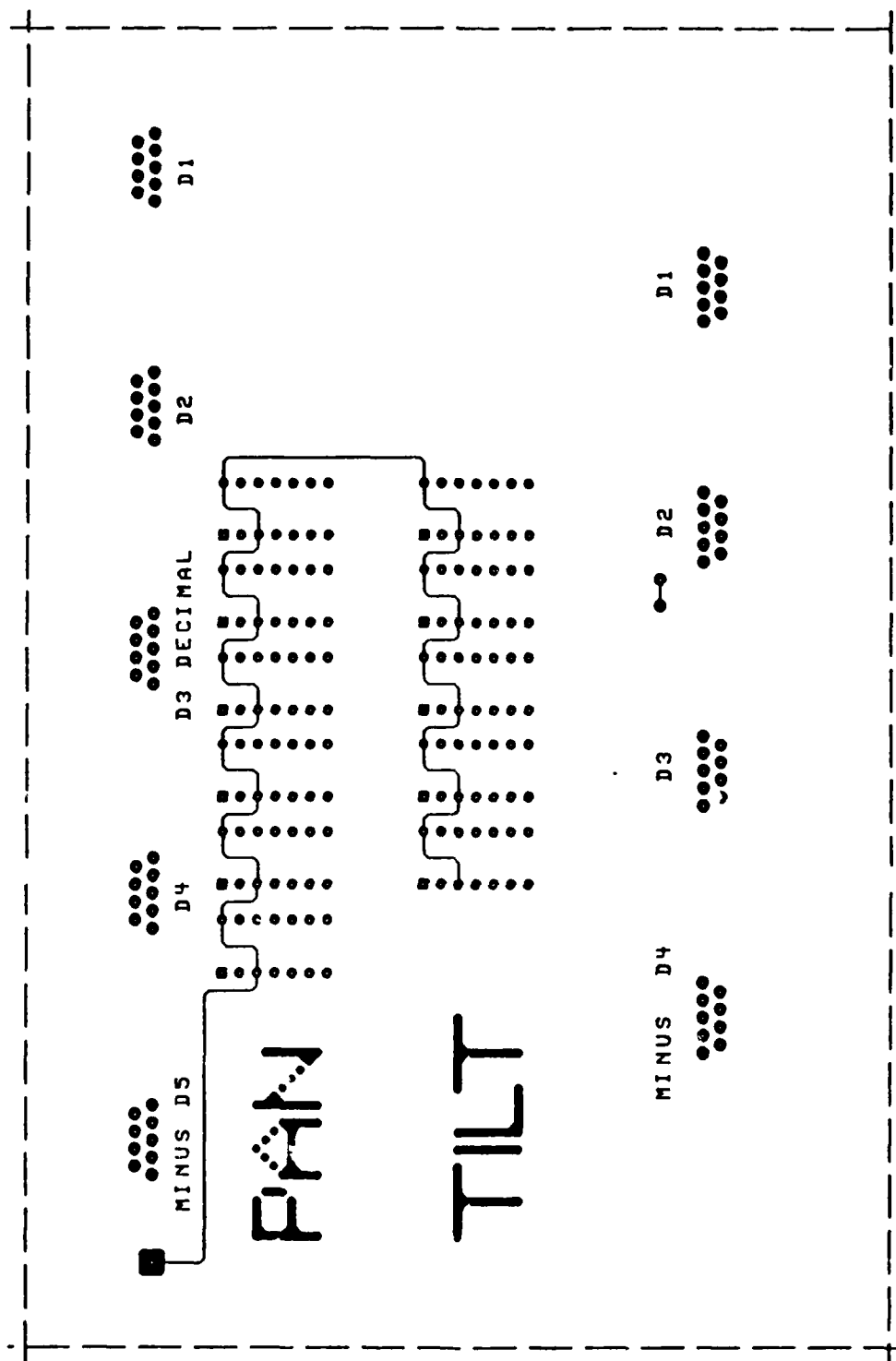
Pan MPU, Back. 90 % of full scale.



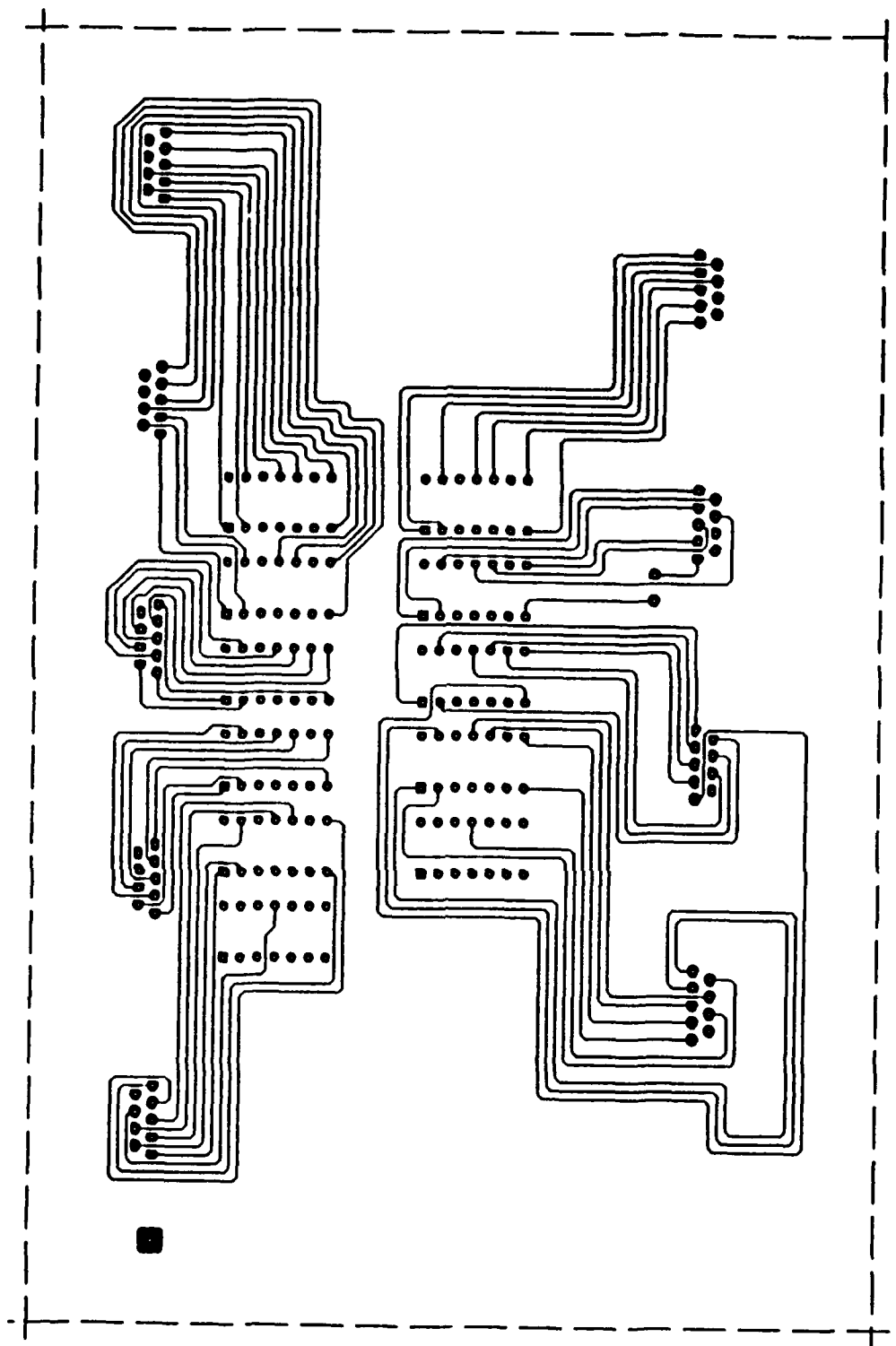
Tilt MPU, Front. 85 % of full scale.



Tilt MPU, Back. 85 % of full scale.



Display, Front. Full scale.



Display, Back. Full scale.

APPENDIX C. MICROPROCESSOR PROGRAMS

A. GENERAL

Sections B and C of this Appendix are the listing files for the two MPU programs written for the signal processor subsystems. The theory of operation of the two programs is identical and is most clearly described by Figure 31. The detailed operation of the Initialization , Mode Change, Blink, Output Display and Hysteresis Modify routines is described by the comments which accompany each of the programs. In addition to the detailed description provided by the program comments, the operation of the Count Routine is also explained in Chapter IV.

B. PAN

```

1          TTL          POSITION DETERMINING PROGRAM (AZIMUTH)
2          *            LATEST REVISION          9 MAY 89
3          *            FILE NAME                PAN.ASH
4          **
5          ** PROGRAM DESCRIPTION
6          **
7          **
8          **
9          ** I/O REGISTER ADDRESSES
10         **
11         0000          PORTA EQU $0000 I/O PORT A
12         0001          PORTB EQU $0001 I/O PORT B
13         0002          PORTC EQU $0002 I/O PORT C
14         0003          PORTD EQU $0003 INPUT PORT D
15         **
16         ** DATA DIRECTION REGISTER OFFSET
17         **
18         0004          DDR EQU 4 (eg. DDR FOR PORT A IS PORTA+DDR )
19         **
20         ** OTHERS
21         **
22         0008          TIMER EQU $0008 EIGHT BIT TIMER REGISTER.
23         0009          TCR EQU $0009 TIMER CONTROL REGISTER.
24         000A          MR EQU $000A MISCELLANEOUS REGISTER.
25         0010          RAM EQU $0010 START OF ON-CHIP RAM(112 - 31 FOR STACK)
26         0080          ZROM EQU $0080 PAGE ZERO OF ROM.
27         0100          ROM EQU $0100 START OF MAIN ROM.
28         0F38          MOR EQU $0F38 MASK OPTION REGISTER.
29         0FF8          INTRPT EQU $0FF8 LOCATION OF INTERRUPT VECTORS.
30         1000          MEMSIZ EQU $1000 MEMORY ADDRESS SIZE.
31         **
32         ** EQUATES
33         **
34         0001          BIT0 EQU 1
35         0002          BIT1 EQU 2
36         0004          BIT2 EQU 4
37         0008          BIT3 EQU 8
38         0010          BIT4 EQU 16
39         0020          BIT5 EQU 32
40         0040          BIT6 EQU 64
41         0080          BIT7 EQU 128
42         **
43         0000          B0 EQU 0
44         0001          B1 EQU 1
45         0002          B2 EQU 2
46         0003          B3 EQU 3
47         0004          B4 EQU 4
48         0005          B5 EQU 5
49         0006          B6 EQU 6
50         0007          B7 EQU 7
51         **
52         ** EQUATES FOR THE TIMER CONTROL REGISTER
53         **
54         ***
55         0007          TIR EQU 7 TIMER INTERRUPT REQUEST. 1 = REQUEST, 0 = NO REQ.
56         0006          TIM EQU 6 TIMER INTERRUPT MASK. 1 = DISABLED, 0 = ENABLED.
57         0005          TIN EQU 5 EXTERNAL OR INTERNAL CLOCK SOURCE. 1 = EXT, 0 = INT.
58         0004          TEE EQU 4 EXTERNAL CLOCK ENABLE. NOT USED.
59         0003          PSC EQU 3 PRESCALER CLEAR. NOT USED.
60         0002          PS2 EQU 2 (PS2) --
61         0001          PS1 EQU 1 (PS1) |-- PRESCALER SELECT BITS.

```

```

62          0000      PS0    EQU    0      (PS0)  --
63          **
64          ** EQUATES FOR THE STATUS BYTE, 'STAT'.
65          ***
66          ***
67          **
68          0007      UD      EQU    7      COUNT DIRECTION? 1 = UP, 0 = DOWN.
69          0006      MOD_32 EQU    6      IS 'BINCT' MODULO 32? 1 = YES, 0 = NO.
70          0005      FLASH EQU    5      BLINK THE DISPLAY? 1 = YES, 0 = NO.
71          0004      POSCT EQU    4      DISPLAY POSITION OR COUNT? 1 = POS, 0 = COUNT.
72          0003      L_SET EQU    3      VALUE OF 'MODE,PORTD' LAST TIME.
73          0002      NEGTV EQU    2      IS 'BCDCT' NEGATIVE NUMBER? 1 = YES, 0 = NO.
74          ***          1      NOT USED.
75          ***          0      NOT USED.
76          ***
77          ***
78          ** I/O EQUATES AND DESCRIPTIONS.
79          ***
80          ***
81          ***      PORT A (I/O)
82          ***
83          ***      +-----+-----+-----+-----+-----+-----+-----+-----+
84          ***      |          BCD DIGIT #4          |          BCD DIGIT #3          |
85          ***      +-----+-----+-----+-----+-----+-----+-----+-----+
86          ***      | D4 | C4 | B4 | A4 | D3 | C3 | B3 | A3 |
87          ***      +-----+-----+-----+-----+-----+-----+-----+-----+
88          *** BIT      7      6      5      4      3      2      1      0
89          ***
90          ***
91          ***      PORT B (I/O)
92          ***
93          ***      +-----+-----+-----+-----+-----+-----+-----+-----+
94          ***      |          DISPLAY CONTROL          | BCD DIGIT #5 (MOST SIGNIFICANT) |
95          ***      +-----+-----+-----+-----+-----+-----+-----+-----+
96          ***      | DECPT | POSTIV |          | BLANK | D5 | C5 | B5 | A5 |
97          ***      +-----+-----+-----+-----+-----+-----+-----+-----+
98          *** BIT      7      6      5      4      3      2      1      0
99          ***
100         0007      DECPT EQU    7      TO DISPLAY THE DECIMAL POINT...DECPT IS CLEARED
101         0006      POSTIV EQU    6      USED TO DISPLAY NEGATIVE SIGN...CLEARED TO SHOW
102         ***                                     MINUS SIGN.
103         0004      BLANK EQU    4      TO BLANK DIGITS 2 AND 3...CLEAR BLANK.
104         ***                                     DIGITS 4 AND 5 ARE ALWAYS BLANKED.
105         ***                                     DIGIT 1 IS NEVER BLANKED.
106         ***
107         ***      PORT C (I/O)
108         ***
109         ***      +-----+-----+-----+-----+-----+-----+-----+-----+
110         ***      |          BCD DIGIT #2          | BCD DIGIT #1(LEAST SIGNIFICANT) |
111         ***      +-----+-----+-----+-----+-----+-----+-----+-----+
112         ***      | D2 | C2 | B2 | A2 | D1 | C1 | B1 | A1 |
113         ***      +-----+-----+-----+-----+-----+-----+-----+-----+
114         *** BIT      7      6      5      4      3      2      1      0
115         ***
116         ***
117         ***      PORT D (INPUT ONLY)
118         ***
119         ***      +-----+-----+-----+-----+-----+-----+-----+-----+
120         ***      | CH_A | INT2 | CH_B | FUNCT | SET |          |          |          |
121         ***      +-----+-----+-----+-----+-----+-----+-----+-----+
122         *** BIT      7      6      5      4      3      2      1      0
123         ***
124         0007      CH_A EQU    7      INDICATES THE STATUS OF CHANNEL A.
125         0006      INT2 EQU    6      INTERRUPT #2. USED TO CHANGE DISPLAY MODES.
126         0005      CH_B EQU    5      INDICATES THE STATUS OF CHANNEL B.
127         0004      FUNCT EQU    4      USED TO PUT THE PROGRAM IN A MODE THAT WILL ALLOW

```

```

128      ***
129      0003  SET      EQU      3      'HYST' TO BE INCREMENTED.
130      ***
131      ***
132      *****
133      **
134      **
135      **
136      *****
137      **
138      ** RESERVE MEMORY SPACE FOR THE PROGRAM VARIABLES.
139      **
140      0000      DATA
141      **
142      **
143      0000      ABSOLUTE (ABSOLUTE ADDRESSING USED HERE TO RELATIVE DIRECTIVE)
144      **
145      0010      ORG      RAM      START OF RAM.
146      **
147      *** BINARY COUNT.
148      0010      BINCT  RMB      3
149      0010      NIBIN  EQU      BINCT  HI BYTE.
150      0011      MIDBIN EQU      BINCT+1 MIDDLE BYTE.
151      0012      LOBIN  EQU      BINCT+2 LO BYTE.
152      **
153      *** POSITION POINTERS.
154      0013      PTR    RMB      4      EACH BYTE POINTS TO A POSITION IN THE
155      **
156      **
157      0013      PTR4   EQU      PTR    MOST SIGNIFICANT DIGITS.
158      0014      PTR3   EQU      PTR+1
159      0015      PTR2   EQU      PTR+2
160      0016      PTR1   EQU      PTR+3 LEAST SIGNIFICANT DIGIT.
161      **
162      *** COUNT POINTERS.
163      0017      CTPTR  RMB      3      EACH BYTE POINTS TO A POSITION IN THE
164      **
165      **
166      0017      CTPTR3 EQU      CTPTR  MOST SIGNIFICANT DIGITS.
167      0018      CTPTR2 EQU      CTPTR+1
168      0019      CTPTR1 EQU      CTPTR+2 LEAST SIGNIFICANT DIGITS.
169      **
170      *** BCD POSITION IN DEGREES.
171      001A      DEGRES RMB      4
172      001A      HUNDEG EQU      DEGRES  CONTENTS X 100.000
173      001B      ONEDEG EQU      DEGRES+1 CONTENTS X 1.000
174      001C      HUNDTH EQU      DEGRES+2 CONTENTS X 0.010
175      001D      THOUTH EQU      DEGRES+3 + CONTENTS X 0.001
176      ***
177      ***
178      ***
179      *** BCD COUNT.
180      001E      BCDCT  RMB      3
181      001E      TENTHO EQU      BCDCT  CONTENTS X 10,000
182      001F      HUNDRO EQU      BCDCT+1 CONTENTS X 100
183      0020      TENONE EQU      BCDCT+2 + CONTENTS X 1
184      ***
185      ***
186      ***
187      *** HYSTERESIS COUNTER. POINTS TO A NUMBER IN THE TABLE THAT IS THE
188      *** AMOUNT OF HYSTERESIS PRESENT IN THE SYSTEM. INITIALIZED TO 7.
189      0021      HYSTPT RMB      1
190      **
191      *** POSITION INCREMENT. CONTAINS A NUMBER, THAT WHEN MULTIPLIED BY 0.001
192      *** IS THE NUMBER OF DEGREES THAT THE POSITION COUNTER (BCDPOS) IS
193      *** TO BE INCREMENTED OR DECREMENTED DURING PROGRAM EXECUTION.

```

```

194
195
196
197
198
199
200
201
202 0022
203
204
205
206
207 0023
208
209 0024
210
211
212
213 0025
214 0026
215
216
217
218
219
220
221
222
223
224 0027
225
226
227
228
229
230
231
232
233
234
235
236
237
238 0000
239
240 0080
241
242 0080
243
244 0080
245
246
247
248
249
250
251
252 0080 98
253 0081 9C
254
255 0082 AE 10
256 0084 7F
257 0085 5C
258 0086 A3 27
259 0088 23 FA

*** THE VALUE OF 'POSINC', DETERMINED EXPERIMENTALLY, SHOULD BE
*** 7.0312. SINCE THE PROGRAM IS DESIGNED WORK WITH INTEGERS ONLY
*** THIS NUMBER IS ROUNDED TO 7. TO REDUCE THE CUMULATIVE EFFECT OF
*** THE ROUND OFF, EVERY 32 COUNTS 'POSINC' IS SET EQUAL TO 8. THIS
*** AGAIN LEADS TO SOME CUMULATIVE ERROR THAT IS ACCOUNTED FOR BY
*** SETTING 'POSINC' TO 7 INSTEAD OF 8 WHEN THE COUNT REACHES A
*** VALUE OF 16384 (2^14).
***
POSINC RMB 1
***
*** HYSTERESIS VARIABLES. USED TO ELIMINATE THE EFFECTS OF BACKLASH ON
*** THE POSITION MEASUREMENTS.
***
HYST RMB 1 THE THRESHOLD VALUE DETERMINED
*** EXPERIMENTALLY.
HYSTCT RMB 1 CURRENT AMOUNT OF HYSTERESIS MEASURED.
***
*** STATUS BYTE. USED TO KEEP TRACK OF WHAT IS GOING ON.
***
STAT RMB 1 CURRENT STATUS.
LSTAT RMB 1 PREVIOUS/LAST STATUS. USED TO KEEP TRACK OF
*** L_SET ONLY.
***
*** TIMER COUNTER. USED IN CONJUNCTION WITH THE TIMER PRESCALER AND THE
*** TDR TO KEEP TRACK OF ONE SEC. INTERVALS. USED IN BLINKING THE
*** DISPLAY. INITIALLY SET TO 31, WHEN THE 'FLASH' BIT OF 'STAT'
*** IS SET. TIMCT IS DECREMENTED EACH CLOCK INTERRUPT (APPROX. 31
*** TIMES PER SEC). RESET TO 31 WHEN CONTENTS GO TO ZERO.
*** WHEN (TIMCT)=0 THE DISPLAY WILL TOGGLE.
***
TIMCT RMB 1
**
ENDS
**
***
*****
**
** PAGE ZERO ROM
**
*****
**
** INITIALIZATION ROUTINE.
**
**
** CODE
**
** ORG ZROM PAGE ZERO ROM.
**
** RELATIVE RELATIVE ADDRESSING MUST BE USED FOR THE BRANCH.
**
RESTRT EQU $ THIS IS THE ENTRY POINT WHEN THE RESET
*** SWITCH IS PUSHED.
***
*****
**
*** INITIALIZE THE PC AND CLEAR RAM.
***
***
SEI SET INTERRUPT TO AVOID INTERRUPTION AND
RSP RESET THE STACK POINTER. JUST IN CASE!
***
LDX #BINCT CLEAR ALL OF THE VARIABLES BETWEEN
CLRIT CLR ,X 'BINCT' AND 'TIMCT' (INCLUSIVE).NOTE
INCX THAT THIS SETS THE COUNTER AND THE POS-
CPX #TIMCT ITION TO ZERO. THIS MEANS THAT ROTATION
BLS CLRIT SHOULD START IN AN INCREASING (CW)

```

260			***	DIRECTION FROM THE MOST CCW POSITION
261			***	AFTER A RESET.
262			***	
263	008A		***	ABSOLUTE BACK TO ABSOLUTE ADDRESSING.
264			***	
265			*****	
266			***	
267			***	ESTABLISH I/O PORTS.
268			***	
269	008A	A6 FF	LDA	#-1 PORTS A,B,C ARE CONFIGURED AS
270	008C	B7 04	STA	PORTA+DDR ALL OUTPUT. PORT D IS ALL INPUT
271	008E	B7 05	STA	PORTB+DDR SO THERE IS NO MASK TO SET.
272	0090	B7 06	STA	PORTC+DDR
273			***	
274			***	
275	0092	CD 03 4E	JSR	OUTCT COUNT IS TO BE DISPLAYED INITIALLY.
276			***	
277			*****	
278			***	SET UP THE STATUS REGISTER.
279			***	
280	0095	A6 08	LDA	#X00001000 --
281	0097	B4 03	AND	PORTD --> SET UP 'L_SET' BIT OF 'STAT'.
282	0099	B7 25	STA	STAT --
283			***	
284	0098	1C 25	BSET	MOD_32,STAT 0 IS MODULO 32.
285			**	
286			*****	
287			***	
288			***	INITIALIZE HYSTCT.
289			***	
290	009D	A6 08	LDA	#08
291	009F	B7 23	STA	HYST
292	00A1	B7 21	STA	HYSTPT
293			***	
294			*****	
295			**	
296			**	SET UP THE TIMER FOR A 4 MHZ CRYSTAL / 4 = 1 MHZ CLOCK.
297			***	
298			***	NOTE: THE MASK OPTION REGISTER IS IN ROM. IT IS SET UP AT
299			***	THE END OF THE PROGRAM.
300			***	
301			*****	SET UP THE TCR. *****
302			***	
303	00A3	A6 47	LDA	#BIT6+BIT2+BIT1+BIT0
304				(TIM) (PS2)(PS1)(PS0)
305			***	(DISABLE INTERRUPT) (PRESCALE BY 128)
306			***	
307	00A5	B7 09	STA	TCR
308			***	
309			***	
310			***	SET UP THE TIMER.
311			***	
312	00A7	A6 FF	LDA	#255 1 MHZ/(128*255) = 30.6 (APPROX. 31)
313	00A9	B7 08	STA	TIMER
314			***	
315			*****	INITIALIZE THE TIMER COUNTER. *****
316			***	
317	00AB	A6 1F	LDA	#31 PROVIDES FOR 1 SEC. BLINK INTERVAL.
318	00AD	B7 27	STA	TIMCT FOR 2 SEC. INTERVAL JUST USE TIMECT=62, etc.
319			***	
320			***	
321			*****	
322			**	
323			**	SET UP MISCELLANEOUS REGISTER.
324			**	
325	00AF	1D 0A	BCLR	B6,MR ENABLES THE SECOND INTERRUPT.

```

326
327
328 00B1 9A          **          CLI          CLEAR THE INTERRUPT MASK TO GET STARTED.
329
330 00B2          ***          RELATIVE          RELATIVE ADDRESSING MUST BE USED FOR THE
331          ***          REMAINDER OF THE PROGRAM.
332          ***
333          ****
334          **
335          ** WAIT LOOP. EXECUTES, UNTIL AN INTERRUPT OCCURS.
336          **
337 00B2 09 03 0B    PAUSE  BRCLR  FUNCT,PORTD,CHHYST WANT TO CHANGE HYST?
338          **                                YES...GO TO CHHYST.
339 00B5 06 03 04    BRSET  SET,PORTD,SBIT  NO...'SET,PORTD' SET?
340 00B8 17 25    BCLR  L_SET,STAT  NO...CLEAR 'L_SET,STAT'
341 00BA 20 F6    BRA  PAUSE  AND LOOP.
342 00BC 16 25    SBIT  BSET  L_SET,STAT  YES...SET 'L_SET,STAT'
343 00BE 20 F2    BRA  PAUSE  AND...LOOP
344          **
345          ****
346          **
347          ** HYSTERESIS MODIFICATION ROUTINE. PERMITS MODIFICATION OF THE
348          ** HYSTERESIS BUFFER WITHOUT REPROGRAMMING.
349          **
350 00C0 A6 40    CHHYST  LDA  #BIT6          DISABLE TIMER INTERRUPT.
351 00C2 B7 09    STA  TCR
352          ***
353 00C4 A6 08    LDA  #X00001000          SAVE 'L_SET'
354 00C6 B4 25    AND  STAT          INTO
355 00C8 B7 26    STA  LSTAT          'LSTAT'.
356 00CA A6 08    LDA  #X00001000
357 00CC B4 03    AND  PORTD          'SET,PORTD' --> ACCUMULATOR
358 00CE B1 26    CMP  LSTAT          HAS THE SET SWITCH BEEN CHANGED?
359 00D0 27 15    BEQ  DISPLA
360          ***
361 00D2 A6 08    LDA  #X00001000          YES...
362 00D4 B8 25    EOR  STAT          --
363 00D6 B7 25    STA  STAT          |-->CHANGE 'L_SET,STAT',
364 00D8 3C 23    INC  HYST          --
365 00DA 3C 21    INC  HYSTPT          THEN INCREMENT THE HYSTERESIS
366          ***                                POINTER AND 'HYST'...
367 00DC B6 21    LDA  HYSTPT          --
368 00DE A1 19    CMP  #25          --
369 00E0 23 05    BLS  DISPLA          --
370          ***
371 00E2 4F          CLRA          -- BUT NOT ABOVE 25.
372 00E3 B7 23    STA  HYST          -- THEN-->
373 00E5 B7 21    STA  HYSTPT          --
374          ***
375 00E7 A6 00    DISPLA  LDA  #X00000000          NO... JUST----->
376 00E9 B7 00    STA  PORTA          --
377 00EB A6 C0    LDA  #X11000000          --
378 00ED B7 01    STA  PORTB          --
379          ***                                \ /
380 00EF BE 21    LDX  HYSTPT          -- DISPLAY CURRENT 'HYST'.
381 00F1 D6 03 BE    LDA  TABLE,X          --
382 00F4 B7 02    STA  PORTC          --
383          ***
384 00F6 09 03 C7    BRCLR  FUNCT,PORTD,CHHYST IS 'HYST' SETTING COMPLETE?
385 00F9 08 25 05    BRSET  POSCT,STAT,SHOPOS NO... KEEP CHECKING 'SET'.
386 00FC CD 03 4E    JSR  OUTCT          YES... RESET THE DISPLAY.
387 00FF 20 03    BRA  DUNCHG
388          ***
389 0101 CD 03 68    SHOPOS  JSR  OUTPOS
390          ***
391 0104 0B 25 04    DUNCHG  BRCLR  FLASH,STAT,NO_INT  IF THE DISPLAY IS TO BLINK...

```

```

392 0107 A6 07          LDA    #BIT2+BIT1+BIT0    ENABLE TIMER INTERRUPT AND RESET
393 0109 B7 09          STA    TCR                TIMER PRESCALER
394 0108 20 A5          NO_INT BRA    PAUSE        PRIOR TO RETURNING.
395                    ***
396                    **
397                    *****
398                    ** MAXIMUM EXECUTION TIME FOR THE REMAINDER OF THE PROGRAM OCCURS
399                    ** IF THE COUNTER ROTATES THROUGH ZERO AS THE DISPLAY MODE IS CHANGED
400                    ** FROM THE BLINKING MODE TO THE COUNT MODE AT THE SAME TIME THAT THE
401                    ** BLINKING ROUTINE IS CAUSING THE DISPLAY TO TOGGLE TO SHOW THE
402                    ** POSITION IN DEGREES.
403                    ** MAXIMUM EXECUTION TIME = 140 + 184 + 708 = 1032 CLOCK CYCLES.
404                    *****
405                    **
406                    ** MODE CHANGE ROUTINE. CHANGES THE DISPLAY MODE FROM
407                    ** COUNT -> POSITION -> BLINKING -> COUNT ->....(ETC.)
408                    ** MAXIMUM EXECUTION TIME OF 181 CLOCK CYCLES OCCURS WHEN THE
409                    ** DISPLAY MODE IS CHANGED FROM DISPLAYING THE COUNT TO DISPLAYING
410                    ** THE POSITION (IN DEGREES).
411                    ** IF THE DISPLAY IS CHANGED FROM BLINKING TO A COUNT DISPLAY
412                    ** EXECUTION TIME IS 140 CLOCK CYCLES.
413                    **
414 0100 1F 0A          CHMODE BCLR    B7,NR                AVOID REPEATED INTERRUPTS.
415                    **
416 010F 0A 25 10        BRSET    FLASH,STAT,DIS_CT    IF FLASHING, DISPLAY COUNT...
417 0112 09 25 07        BRCLR    POSCT,STAT,DISPOS    IF SHOWING COUNT, DISPLAY POSITION...
418 0115 1A 25          BSET      FLASH,STAT            ELSE, BLINK.
419                    **
420 0117 A6 07          LDA    #BIT2+BIT1+BIT0    ENABLE TIMER INTERRUPT AND RESET
421 0119 B7 09          STA    TCR                TIMER PRESCALER.
422 0118 80          RTI
423                    **
424 011C 18 25          DISPOS BSET    POSCT,STAT        --
425 011E CD 03 68        JSR      OUTPOS                |-- DISPLAY CURRENT POSITION, AND WAIT.
426 0121 80          RTI                                --
427                    **
428 0122 A6 47          DIS_CT LDA    #BIT6+BIT2+BIT1+BIT0  DISABLE TIMER INTERRUPT AND RESET
429 0124 B7 09          STA    TCR                TIMER PRESCALER.
430 0126 19 25          BCLR    POSCT,STAT        --
431 0128 18 25          BCLR    FLASH,STAT        |-- DISPLAY CURRENT COUNT, AND WAIT.
432                    **
433 012A CD 03 4E        JSR      OUTCT                |
434 012D 80          RTI                                --
435                    **
436                    *****
437                    **
438                    ** BLINK ROUTINE. INTERRUPT ROUTINE TO CHANGE THE DISPLAY FROM POSITION
439                    ** TO COUNT OR VICE VERSA EVERY 31 ST TIMER INTERRUPT IF THE
440                    ** 'FLASH' BIT OF 'STAT' IS SET.
441                    ** MAXIMUM EXECUTION TIME OF 184 CLOCK CYCLES OCCURS WHEN THE
442                    ** DISPLAY IS TOGGLED FROM A COUNT DISPLAY TO A POSITION DISPLAY.
443                    **
444                    BLINK EQU    $
445 012E 0F 09 DC        BRCLR    TIR,TCR,CHMODE        IF THE INTERRUPT WAS NOT A TIMER
446                    **                                INTERRUPT IT MUST BE FROM INT2.
447                    **
448 0131 1F 09          BCLR    TIR,TCR                AVOID REPEATED TIMER INTERRUPTS.
449                    **
450 0133 3A 27          DEC      TIMCT                IF THERE HAVE BEEN 31 TIMER
451 0135 27 01          BEQ      CHGDIS                INTERRUPTS (1 SEC), IT'S TIME TO
452                    **                                CHANGE THE DISPLAY.
453 0137 80          RTI                                OTHERWISE, IT'S BACK TO WORK.
454                    **
455 0138 A6 1F          CHGDIS LDA    #31                RESET TIMCT TO 31 (1 SEC. INTERVAL).
456 013A B7 27          STA    TIMCT
457                    **

```

```

458 013C B6 25          LDA  STAT          --
459 013E A8 10          EOR  #%00010000    |-- CHANGE 'POSCT' BIT OF 'STAT'.
460 0140 B7 25          STA  STAT          --
461
462 0142 08 25 04      BRSET POSCT,STAT,POSOUT  DECIDE ON CORRECT DISPLAY.
463
464 ***** CHANGE THE DISPLAY TO SHOW THE COUNT..... *****
465
466 0145 CD 03 4E      JSR  OUTCT
467 0148 80            RTI
468
469 ***** OR HAVE THE DISPLAY SHOW THE POSITION. *****
470
471 0149 CD 03 68      POSOUT JSR  OUTPOS
472 014C 80            RTI
473
474 *****
475
476          COUNT ROUTINE.
477          WHEN A COUNT IS RECEIVED THIS IS THE ENTRY POINT .
478          MAXIMUM EXECUTION TIME OF 708 CLOCK CYCLES OCCURS WHEN THE
479          COUNTER ROTATES CCW THROUGH ZERO AND THE POSITION (IN DEGREES)
480          IS BEING DISPLAYED.
481
482
483          CURRENT DIRECTION OF ROTATION IS DETERMINED BY INSPECTING THE STATUS
484          OF 'CH_A' AND 'CH_B'. THE FOUR POSSIBILITIES AND THE ASSOCIATED
485          DIRECTION OF ROTATION ARE AS SHOWN BELOW. NOTE THAT THIS SCHEME
486          PREVENTS MULTIPLE OSCILLATIONS ABOUT A SINGLE POINT FROM
487          REPEATEDLY INCREMENTING OR DECREMENTING THE COUNTER.
488
489          +-----+-----+-----+-----+
490          | CH_A | CH_B | DIRECTION | COUNT THE PULSE? |
491          |-----|-----|-----|-----|
492          |     |     | OF ROTATION |                   |
493          |-----|-----|-----|-----|
494          | LO  | LO  |    CW    |        NO        |
495          | LO  | HI  |   CCW   |        YES       |
496          | HI  | LO  |   CCW   |        NO        |
497          | HI  | HI  |    CW    |        YES       |
498          +-----+-----+-----+-----+
499
500 ***** FIRST SEE IF WE ARE SUPPOSED TO COUNT THIS INTERRUPT. *****
501
502 014D 0A 03 01      COUNT EQU  $
503 0150 80            BRSET CH_B,PORTD,OKCT  IF CH_B IS LO WE DON'T COUNT THE
504                                     INTERRUPT.
505                                     RTI
506
507 ***** IF THE INTERRUPT IS VALID UPDATE 'STAT'. *****
508
509 OKCT  LDA  #%01111111
510      AND  STAT          SAVE ALL OF THE OLD 'STAT' EXCEPT THE
511      STA  STAT          DIRECTION OF ROTATION.
512      LDA  #%10000000
513      AND  PORTD         'CH_A,PORTD' INDICATES THE DIRECTION
514      ORA  STAT          OF ROTATION AND BECOMES 'UD,STAT'.
515      STA  STAT          ADD THE RESULTS TO GET
516                                     THE NEW 'STAT'.
517
518 ***** DECIDE IF THE "SLACK" DUE TO BACKLASH/HYSTERESIS HAS BEEN TAKEN OUT.
519
520 BRSET UD,STAT,HYSTCK IF ROTATING CW SEE BELOW.
521 LDA  HYSTCT          ELSE, SEE IF WE DECREMENT THIS TIME.
522 BEQ  CCW            IF HYSTCT=0, GO TO THE COUNT DOWN
523                                     ROUTINE.
524
525 SUB  #1             ELSE, DECREMENT THE HYSTERESIS COUNTER,
526 STA  HYSTCT

```

524	016A	80	RTI	AND WAIT FOR THE NEXT INTERRUPT.
525			**	
526	0168	B6 23	HYSTCK LDA HYST	IF ROTATING CW....
527	016D	B1 24	CMP HYSTCT	AND HYST = HYSTCT
528	016F	27 03	BEQ CW	COUNT THE PULSE .
529	0171	3C 24	INC HYSTCT	ELSE, INCREMENT THE HYSTERESIS COUNTER,
530	0173	80	RTI	AND WAIT FOR ANOTHER PULSE.
531			**	
532			**	
533			*****	
534			**	
535			**	CLOCKWISE ROUTINE.
536			**	
537		0174	CW EQU \$	
538			**	
539			***	
540			*****	INCREMENT THE BINARY COUNTER (BINCT). *****
541			***	
542	0174	B6 12	LDA LOBIN	BEGIN AT THE LSB OF THE BINARY COUNTER.
543	0176	AB 01	ADD #1	LOBIN = LOBIN + 1 ; CARRY -> C,CCR
544	0178	B7 12	STA LOBIN	
545			***	
546	017A	B6 11	LDA MIDBIN	
547	017C	A9 00	ADC #0	ADD THE CARRY TO THE MIDDLE BYTE.
548	017E	B7 11	STA MIDBIN	
549			***	
550	0180	B6 10	LDA HIBIN	
551	0182	A9 00	ADC #0	ADD THE CARRY TO THE HIGH BYTE.
552	0184	B7 10	STA HIBIN	
553			***	
554			***	
555			*****	CLR/SET MOD_32 APPROPRIATELY. *****
556			***	
557			***	THE FOLLOWING SEVERAL LINES OF CODE ARE PRETTY MESSY. ALL THAT
558			***	IS BEING DONE IS TO ENSURE THAT THE SCALE FACTOR IS SET PROPERLY.
559			***	FOR THE PAN AXIS THE SCALE FACTOR IS;
560			***	
561			***	1 PULSE => 0.007097 DEGREES
562			***	
563	0186	B6 12	LDA LOBIN	IF THE LOW FIVE BITS OF 'LOBIN' ARE NOT
564	0188	A4 1F	AND #X00011111	ZERO THEN THE NUMBER ISN'T A MODULO 32 NUMBER.
565	018A	26 0F	BNE NOT_32	
566	018C	B6 11	LDA MIDBIN	IF THE LOW SIX BITS OF 'MIDBIN' ARE ZERO
567	018E	27 07	BEQ MOD	AND 'HIBIN' .NE. ZERO
568	0190	A4 3F	AND #X00111111	THEN THE NUMBER IS MODULO 16,384, AND WE
569	0192	26 03	BNE MOD	DON'T WANT TO SET 'MOD_32,STAT', UNLESS
570	0194	0D 11 04	BRCLR B6,MIDBIN,NOT_32	THE NUMBER IS ALSO MODULO 32,768.
571			***	
572	0197	1C 25	MOD BSET MOD_32,STAT	
573	0199	20 02	BRA DIRCHK	
574			***	
575	019B	1D 25	NOT_32 BCLR MOD_32,STAT	
576			***	
577			***	
578	019D	B6 10	DIRCHK LDA HIBIN	
579	019F	2B 1D	CMPI CWNEG	IF HIBIN < 0 , WE'RE ROTATING CCW TOWARD
580			***	THE ORIGIN.
581			***	
582	01A1	26 14	BNE CWPOS	
583	01A3	B6 11	LDA MIDBIN	ELSE IF BINCT .NE. 0
584	01A5	26 10	BNE CWPOS	WE'RE ROTATING CW
585	01A7	B6 12	LDA LOBIN	AWAY FROM THE ORIGIN.
586	01A9	26 0C	BNE CWPOS	
587			***	
588			***	ELSE, WE'VE ROTATED CW THROUGH THE ORIGIN.
589	01AB	15 25	BCLR NEGTV,STAT	CLR NEGATIVE SIGN.

590	01AD	AE 13	LDX	#PTR4	--	
591	01AF	7F	CLRIT2	CLR	,X	--
592	0180	5C	INX			--RESET ALL COUNTERS AND DEGRES TO ZERO.
593	0181	A3 1D	CPX	#THOUTH	--	
594	0183	23 FA	BLS	CLRIT2	--	
595	0185	20 68	BRA	UPOUT		UPDATE OUTPUT.
596			***			
597	0187	AD 74	CMPOS	BSR	ADDBCD	
598	0189	CD 02 6A		JSR	INCP0S	
599	018C	20 64		BRA	UPOUT	
600			***			
601	018E	CD 02 CA	CMNEG	JSR	SUBBCD	
602	01C1	CD 02 6A		JSR	INCP0S	
603	01C4	20 5C		BRA	UPOUT	
604			***			
605			**			
606			*****			
607			**			
608			**			COUNTER-CLOCKWISE ROUTINE.
609			**			
610		01C6	CCW	EQU	\$	
611			**			
612			***			
613			*****			CLR/SET MOD_32 APPROPRIATELY. *****
614			***			
615			***			AGAIN SET THE SCALE FACTOR TO;
616			***			
617			***			1 PULSE => 0.007097 DEGREES
618			***			
619	01C6	B6 12	LDA	LOBIN		IF THE LOW FIVE BITS OF 'LOBIN' ARE NOT
620	01C8	A4 1F	AND	#X00011111		ZERO THEN THE NUMBER ISN'T A MODULO 32 NUMBER.
621	01CA	26 0F	BNE	NO_32		
622	01CC	B6 11	LDA	MIDBIN		IF THE LOW SIX BITS OF 'MIDBIN' ARE ZERO
623	01CE	27 07	BEQ	MODLO		AND 'HIBIN' .NE. ZERO
624	01D0	A4 3F	AND	#X00111111		THEN THE NUMBER IS MODULO 16,384, AND WE
625	01D2	26 03	BNE	MODLO		DON'T WANT TO SET 'MOD_32,STAT', UNLESS
626	01D4	0D 11 04	BRLCL	B6,MIDBIN,NO_32		THE NUMBER IS ALSO MODULO 32,768.
627			***			
628	01D7	1C 25	MODLO	BSET	MOD_32,STAT	
629	01D9	20 02		BRA	DECBIN	
630			***			
631	01DB	1D 25	NO_32	BCLR	MOD_32,STAT	
632			***			
633			***			
634			*****			DECREMENT THE BINARY COUNTER (BINCT). *****
635			***			
636	01DD	B6 12	DECBIN	LDA	LOBIN	BEGIN AT THE LSB OF THE BINARY COUNTER.
637	01DF	A0 01		SUB	#1	LOBIN = LOBIN - 1 ; BORROW -> C,CCR
638	01E1	B7 12		STA	LOBIN	
639			***			
640	01E3	B6 11		LDA	MIDBIN	
641	01E5	A2 00		SBC	#0	SUBTRACT THE CARRY FROM THE MIDDLE BYTE.
642	01E7	B7 11		STA	MIDBIN	
643			***			
644	01E9	B6 10		LDA	HIBIN	
645	01EB	A2 00		SBC	#0	SUBTRACT THE CARRY FROM THE HIGH BYTE.
646	01ED	B7 10		STA	HIBIN	
647			***			
648	01EF	B6 10		LDA	HIBIN	
649	01F1	2A 29		BPL	CCWPOS	IF HIBIN .GE. 0 , WE'RE ROTATING CCW TOWARD THE ORIGIN.
650			***			
651	01F3	A6 FF		LDA	#-1	--
652	01F5	B1 10		CMP	HIBIN	--
653	01F7	26 1C		BNE	CCWNEG	-- ELSE IF BINCT .NE. -1 ,
654	01F9	B1 11		CMP	MIDBIN	-- WE'RE ROTATING CCW AWAY
655	01FB	26 18		BNE	CCWNEG	-- FROM THE ORIGIN.

656	01FD	B1 12		CMP	LOBIN	--	
657	01FF	26 14		BNE	CCWNEG	--	
658			***				
659	0201	14 25		BSET	NEGTV,STAT	ELSE, WE'VE GONE THROUGH ORIGIN IN CCW	
660			***			DIRECTION. SET NEGATIVE SIGN.	
661			***			AND SET ALL COUNTERS APPROPRIATELY.	
662	0203	A6 03		LDA	#03	--	
663	0205	B7 13		STA	PTR4	--	
664	0207	B7 1A		STA	MUNDEG	-- DEGES = 360.00	
665	0209	A6 3C		LDA	#60	--	
666	0208	B7 14		STA	PTR3	--	
667	020D	AE 15		LDX	#PTR2	--	
668	020F	7F	CLREM	CLR	,X	--	
669	0210	5C		INX		-- EVERYTHING ELSE IS ZERO BEFORE CHANGE.	
670	0211	A3 19		CPX	#CTPTR1	--	
671	0213	23 FA		BLS	CLREM	--	
672			***				
673	0215	AD 16	CCWNEG	BSR	ADDBCD		
674	0217	CD 02 FD		JSR	DECPOS		
675	021A	20 06		BRA	UPOUT		
676			***				
677	021C	CD 02 CA	CCWPOS	JSR	SUBBCD		
678	021F	CD 02 FD		JSR	DECPOS		
679			***				
680			***				
681			**				
682			*****				
683			**				
684			**				
685			**				
686			**				
687			**				
688		0222	UPOUT	EQU	\$		
689			**				
690	0222	09 25 04		BRCLR	POSCT,STAT,PUTCT		
691			**				
692	0225	CD 03 68		JSR	OUTPOS		
693	0228	80		RTI			
694			**				
695	0229	CD 03 4E	PUTCT	JSR	OUTCT		
696	022C	80		RTI			
697			**				
698			*****				
699			*****				
700			*****				
701	022D	B6 19	ADDBCD	LDA	CTPTR1		
702	022F	AB 01		ADD	#1		
703	0231	A1 63		CMP	#99	CTPTR > 99 ?	
704	0233	23 05		BLS	OK1	NO, WE'RE OK HERE. LOOK UP THE FIRST TWO DIGITS.	
705	0235	A0 64		SUB	#100	YES... MODIFY THE CTPTR,	
706	0237	99		SEC		SET THE CARRY, AND	
707	0238	20 01		BRA	OK1A	USE TABLE LOOK UP.	
708			***				
709	023A	98	OK1	CLC		NO CARRY EXISTS IF WE ENTER AT THIS POINT.	
710	023B	B7 19	OK1A	STA	CTPTR1	--	
711	023D	97		TAX		--	
712			***			-- LOOK UP THE TWO LEAST SIGNIFICANT DIGITS.	
713	023E	D6 03 BE		LDA	TABLE,X	--	
714	0241	B7 20		STA	TENONE	--	
715	0243	24 24		BCC	NOMO	AND CONTINUE ONLY IF THERE WAS A CARRY.	
716			***				
717			***				
718	0245	B6 18		LDA	CTPTR2		
719	0247	A9 00		ADC	#0	ADD THE CARRY.	
720	0249	A1 63		CMP	#99	CTPTR > 99 ?	
721	024B	23 05		BLS	OK2	NO, WE'RE OK HERE. LOOK UP THE NEXT TWO DIGITS.	

722	0240	A0 64	SUB	#100	YES... MODIFY THE CTPTR,
723	024F	99	SEC		SET THE CARRY, AND
724	0250	20 01	BRA	OK2A	USE TABLE LOOK UP.
725			***		
726	0252	98	OK2	CLC	NO CARRY EXISTS IF WE ENTER AT THIS POINT.
727	0253	B7 18	OK2A	STA	CTPTR2 --
728	0255	97		TAX	--
729			***		-- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
730	0256	D6 03 BE		LDA	TABLE,X --
731	0259	B7 1F		STA	HUNDRO --
732	025B	24 0C		BCC	NOMO AND CONTINUE ONLY IF THERE WAS A CARRY.
733			***		
734	025D	B6 17		LDA	CTPTR3
735	025F	A9 00		ADC	#0 ADD THE CARRY.
736	0261	B7 17		STA	CTPTR3 --
737	0263	97		TAX	--
738			***		-- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
739	0264	D6 03 BE		LDA	TABLE,X --
740	0267	B7 1E		STA	TENTHO --
741			***		
742	0269	81	NOMO	RTS	
743			***		
744			*****		*****
745			*****		SUBROUTINE TO INCREMENT THE POSITION COUNTER (DEGRES). *****
746			***		
747			****		FIRST CHECK TO SEE IF THE BINARY COUNTER HAS REACHED A MODULO 32
748			****		NUMBER.
749			****		
750	026A	0D 25 04	INCP0S	BRCLR	MOD_32,STAT,INC7 'MOD_32,STAT' SET ?
751			****		
752	026D	A6 08		LDA	#8 YES ...
753	026F	20 02		BRA	INC INCREMENT THE POSITION BY 0.008 DEGREES.
754			****		
755	0271	A6 07	INC7	LDA	#7 NO
756	0273	B7 22	INC	STA	POSINC INCREMENT THE POSITION BY 0.007 DEGREES.
757			****		
758			****		ROUTINE TO INCREMENT THE POSITION COUNTER , 'DEGRES', BY A
759			****		PREDETERMINED AMOUNT, 'POSINC'.
760			****		
761	0275	B6 16		LDA	PTR1
762	0277	B8 22		ADD	POSINC
763	0279	A1 09		CMF	#9 PTR1 > 9 ?
764	027B	23 05		BLS	OK3 NO, WE'RE OK HERE. LOOK UP THE FIRST DIGIT.
765	027D	A0 0A		SUB	#10 YES... MODIFY THE CTPTR,
766	027F	99		SEC	SET THE CARRY, AND
767	0280	20 01		BRA	OK3A USE TABLE LOOK UP.
768			****		
769	0282	98	OK3	CLC	NO CARRY EXISTS IF WE ENTER AT THIS POINT.
770	0283	B7 16	OK3A	STA	PTR1 --
771	0285	97		TAX	--
772			****		-- LOOK UP THE LEAST SIGNIFICANT DIGIT.
773	0286	D6 03 BE		LDA	TABLE,X --
774	0289	B7 1D		STA	THOUTH --
775	028B	24 3C		BCC	DONE AND CONTINUE ONLY IF THERE WAS A CARRY.
776			****		
777			****		
778	028D	B6 15		LDA	PTR2
779	028F	A9 00		ADC	#0 ADD THE CARRY.
780	0291	A1 63		CMF	#99 PTR2 > 99 ?
781	0293	23 05		BLS	OK4 NO, WE'RE OK HERE. LOOK UP THE NEXT TWO DIGITS.
782	0295	A0 64		SUB	#100 YES...MODIFY THE CTPTR,
783	0297	99		SEC	SET THE CARRY,
784	0298	20 01		BRA	OK4A AND USE TABLE LOOK UP.
785			****		
786	029A	98	OK4	CLC	NO CARRY EXISTS IF WE ENTER AT THIS POINT.
787	029B	B7 15	OK4A	STA	PTR2 --

```

788 0290 97
789
790 029E D6 03 BE
791 02A1 B7 1C
792 02A3 24 24
793
794
795 02A5 B6 14
796 02A7 A9 00
797 02A9 A1 63
798 02AB 23 05
799 02AD A0 64
800 02AF 99
801 02B0 20 01
802
803 02B2 98
804 02B3 B7 14
805 02B5 97
806
807 02B6 D6 03 BE
808 02B9 B7 1B
809 02BB 24 0C
810
811 02BD B6 13
812 02BF A9 00
813 02C1 B7 13
814 02C3 97
815
816 02C4 D6 03 BE
817 02C7 B7 1A
818
819 02C9 81
820
821
822
823
824
825 02CA B6 19
826 02CC A0 01
827 02CE 24 03
828 02D0 AB 64
829 02D2 99
830
831 02D3 B7 19
832 02D5 97
833
834 02D6 D6 03 BE
835 02D9 B7 20
836 02DB 24 1F
837
838
839 02DD B6 18
840 02DF A2 00
841 02E1 24 03
842 02E3 AB 64
843 02E5 99
844
845 02E6 B7 18
846 02E8 97
847
848 02E9 D6 03 BE
849 02EC B7 1F
850 02EE 24 0C
851
852 02F0 B6 17
853 02F2 A2 00

**** TAX --
-- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.

LDA TABLE,X --
STA HUNDTH --
BCC DONE AND CONTINUE ONLY IF THERE WAS A CARRY.

****
****
LDA PTR3
ADC #0 ADD THE CARRY.
CMP #99 PTR3 > 99 ?
BLS OK5 NO, WE'RE OK HERE. LOOK UP THE NEXT TWO DIGITS.
SUB #100 YES... MODIFY THE CTPTR,
SEC SET THE CARRY, AND
BRA OK5A USE TABLE LOOK UP.

****
OK5 CLC NO CARRY EXISTS IF WE ENTER AT THIS POINT.
OK5A STA PTR3 --
TAX --
-- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.

LDA TABLE,X --
STA ONEDEG --
BCC DONE AND CONTINUE ONLY IF THERE WAS A CARRY.

****
LDA PTR4
ADC #0 ADD THE CARRY.
STA PTR4 --
TAX --
-- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.

LDA TABLE,X --
STA HUNDEG --
DONE RTS
***
**
***** SUBROUTINE TO DECREMENT THE BCD COUNTER (BCDCT). *****
***
SUBBCD LDA CTPTR1
SUB #1 CTPTR > 99 ?
BCC OK6 NO, WE'RE OK HERE. LOOK UP THE FIRST TWO DIGITS.
ADD #100 YES, MODIFY THE CTPTR, AND
SEC GENERATE A BORROW.

***
OK6 STA CTPTR1 --
TAX --
-- LOOK UP THE TWO LEAST SIGNIFICANT DIGITS.

LDA TABLE,X --
STA TENONE --
BCC COMPT AND CONTINUE ONLY IF THERE WAS A BORROW.

***
***
LDA CTPTR2
SBC #0 SUBTRACT THE CARRY. CTPTR > 99 ?
BCC OK7 NO, WE'RE OK HERE. LOOK UP THE NEXT TWO DIGITS.
ADD #100 YES, MODIFY THE CTPTR, AND
SEC GENERATE A BORROW.

***
OK7 STA CTPTR2 --
TAX --
-- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.

LDA TABLE,X --
STA HUNDRD --
BCC COMPT AND CONTINUE ONLY IF THERE WAS A CARRY.

***
LDA CTPTR3
SBC #0 SUBTRACT THE BORROW.

```

854	02F4	B7 17	STA	CTPTR3	--	
855	02F6	97	TAX		--	
856			***			-- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
857	02F7	D6 03 BE	LDA	TABLE,X	--	
858	02FA	B7 1E	STA	TENTHO	--	
859			***			
860	02FC	81	COMPLT	RTS		
861			***			
862			*****			*****
863			*****			SUBROUTINE TO DECREMENT THE POSITION COUNTER (DEGRES). *****
864			***			
865			****			FIRST CHECK TO SEE IF THE BINARY COUNTER HAS REACHED A MODULO 32
866			****			NUMBER.
867			****			
868	02FD	00 25 04	DECPOS	BRCLR	MOD_32,STAT,DEC7	'MOD_32,STAT' SET ?
869			****			
870	0300	A6 08	LDA	#8		YES...
871	0302	20 02	BRA	DEC		DECREMENT THE POSITION BY 0.008 DEGREES.
872			****			
873	0304	A6 07	DEC7	LDA	#7	NO
874	0306	B7 22	DEC	STA	POSINC	DECREMENT THE POSITION BY 0.007 DEGREES.
875			****			
876			****			ROUTINE TO DECREMENT THE POSITION COUNTER, 'DEGREES', BY A
877			****			PREDETERMINED AMOUNT, 'POSINC'.
878			****			
879	0308	B6 16	LDA	PTR1		
880	030A	B0 22	SUB	POSINC	PTR1 < 0 ?	
881	030C	24 03	BCC	OK8	NO, WE'RE OK HERE. LOOK UP THE FIRST DIGIT.	
882	030E	AB 0A	ADD	#10	YES, MODIFY THE CTPTR, AND	
883	0310	99	SEC		GENERATE A BORROW.	
884			****			
885	0311	B7 16	OK8	STA	PTR1	--
886	0313	97	TAX		--	
887			****			-- LOOK UP THE LEAST SIGNIFICANT DIGIT.
888	0314	D6 03 BE	LDA	TABLE,X	--	
889	0317	B7 10	STA	THOUTH	--	
890	0319	24 32	BCC	DUNSUB	AND CONTINUE ONLY IF THERE WAS A BORROW.	
891			***			
892			***			
893	031B	B6 15	LDA	PTR2		
894	031D	A2 00	SBC	#0	SUBTRACT THE BORROW. PTR2 < 0 ?	
895	031F	24 03	BCC	OK9	NO, WE'RE OK HERE. LOOK UP THE NEXT TWO DIGITS.	
896	0321	AB 64	ADD	#100	YES, MODIFY THE CTPTR, AND	
897	0323	99	SEC		GENERATE A BORROW.	
898			***			
899	0324	B7 15	OK9	STA	PTR2	--
900	0326	97	TAX		--	
901			***			-- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
902	0327	D6 03 BE	LDA	TABLE,X	--	
903	032A	B7 1C	STA	HUNDTH	--	
904	032C	24 1F	BCC	DUNSUB	AND CONTINUE ONLY IF THERE WAS A CARRY.	
905			***			
906			***			
907	032E	B6 14	LDA	PTR3		
908	0330	A2 00	SBC	#0	SUBTRACT THE BORROW. PTR3 < 0 ?	
909	0332	24 03	BCC	OK10	NO, WE'RE OK HERE. LOOK UP THE NEXT TWO DIGITS.	
910	0334	AB 64	ADD	#100	YES, MODIFY THE CTPTR, AND	
911	0336	99	SEC		GENERATE A BORROW.	
912			****			
913	0337	B7 14	OK10	STA	PTR3	--
914	0339	97	TAX		--	
915			****			-- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
916	033A	D6 03 BE	LDA	TABLE,X	--	
917	033D	B7 18	STA	ONEDEG	--	
918	033F	24 0C	BCC	DUNSUB	AND CONTINUE ONLY IF THERE WAS A CARRY.	
919			****			

920	0341	B6 13	LDA	PTR4	
921	0343	A2 00	SBC	#0	SUBTRACT THE BORROW.
922	0345	B7 13	STA	PTR4	--
923	0347	97	TAX		--
924			****		-- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
925	0348	D6 03 BE	LDA	TABLE,X	--
926	0348	B7 1A	STA	HUNDEG	--
927			****		
928	0340	81	DUNSUB	RTS	
929			***		
930			**		
931			**		
932			*****		
933			**		
934			**		OUTPUT COUNT (OUTCT). SUBROUTINE TO MOVE THE CURRENT COUNT (BCDCT)
935			**		TO THE OUTPUT PORTS. REMOVES THE DECIMAL POINT FROM THE
936			**		DISPLAY AND BLANKS ALL BUT THE LEAST SIGNIFICANT DIGIT. ALSO
937			**		SETS THE MINUS SIGN IF APPROPRIATE.
938			**		
939		034E	OUTCT	EQU	\$
940			**		
941	034E	B6 20	LDA	TENONE	
942	0350	B7 02	STA	PORTC	
943			**		
944	0352	B6 1F	LDA	HUNDRD	
945	0354	B7 00	STA	PORTA	
946			**		
947	0356	B6 1E	LDA	TENTHO	
948	0358	B7 01	STA	PORTB	
949			**		
950	035A	1E 01	BSET	DECPY,PORTB	
951	035C	19 01	BCLR	BLANK,PORTB	
952			**		
953	035E	04 25 04	BRSET	NEGTV,STAT,MINUS	
954	0361	1C 01	BSET	POSTIV,PORTB	
955	0363	20 02	BRA	ALLDUN	
956			**		
957	0365	1D 01	MINUS	BCLR	POSTIV,PORTB
958			**		
959	0367	81	ALLDUN	RTS	
960			**		
961			**		
962			**		OUTPUT POSITION (OUTPOS). SUBROUTINE TO MOVE THE CURRENT POSITION
963			**		COUNT (BCDCT) TO THE OUTPUT PORTS. THE DECIMAL POINT IS
964			**		DISPLAYED , AND ONLY THE MOST SIGNIFICANT DIGIT IS BLANKED.
965			**		
966		0368	OUTPOS	EQU	\$
967			**		
968	0368	B6 1D	LDA	THOUTH	--
969	036A	A1 05	CMF	#5	--
970	036C	25 38	BLO	TRUNC	-- IF 5 > 'THOUTH' SIMPLY TRUNCATE THE
971	036E	B6 1C	LDA	HUNDTH	-- DISPLAY. OTHERWISE...
972	0370	A4 09	AND	#9	-- IF THE LAST DIGIT ISN'T A NINE IT IS
973	0372	A1 09	CMF	#9	-- EASY TO ROUND UP. JUST ADD A ONE.
974	0374	26 28	BNE	DECIMAL	--
975	0376	B6 1C	LDA	HUNDTH	-- BUT IF THE LAST DIGIT IS A NINE CHECK TO
976	0378	A1 99	CMF	#99	-- SEE IF IT'S 99. IF SO IT GETS GRIM.
977	037A	27 04	BEQ	UGLY	--
978	037C	AB 07	ADD	#7	-- IF THE NUMBER IS X9 AND X.NE. 9, THEN
979	037E	20 28	BRA	PCOUT	-- JUST ADD SEVEN TO ROUND UP. DUE TO
980			**		-- HEXIDECIMAL.
981			**		-- IF THE LOW TWO DIGITS ARE BOTH NINES
982	0380	A6 00	UGLY	LDA	#00 -- AND WE NEED TO ROUND UP....
983	0382	B7 02	STA	PORTC	-- MAKE THE LOW TWO DIGITS BOTH ZEROS
984	0384	99	SEC		-- AND SET THE CARRY.
985			**		

986	0385	B6 18	LDA	ONEDEG	--	CHECK THE LAST DIGIT AS BEFORE.
987	0387	A4 09	AND	#9	--	IF USING THIS PORTION OF THE CODE
988	0389	A1 09	CMP	#9	--	THERE HAD TO BE A CARRY.
989	0388	26 1E	BNE	NEXT	--	IF THE LAST DIGIT IS NOT A NINE USE THE
990	038D	B6 18	LDA	ONEDEG	--	ADC INSTRUCTION BELOW.
991	038F	A1 99	CMP	\$999	--	IF IT IS A NINE, IS THE NEXT ONE A NINE
992	0391	27 04	BEG	RLUGLY	--	ALSO?
993	0393	AB 07	ADD	#7	--	IF NOT JUST ADD SEVEN,
994	0395	20 18	BRA	PAOUT	--	AND DISPLAY THE OUTPUT.
995			**			
996	0397	A6 00	RLUGLY LDA	#00	--	
997	0399	B7 00	STA	PORTA	--	IF SO ROUND UP THE MOST SIGNIFICANT
998	039B	99	SEC		--	DIGIT AND SET EVERYTHING ELSE TO ZERO.
999	039C	20 13	BRA	NEXT1	--	
1000			**			
1001	039E	B6 1C	DECIMAL LDA	HUNDTH	--	
1002	03A0	AB 01	ADD	#1	--	
1003			**		--	THIS IS ALL THAT NEEDS TO BE DONE IF
1004	03A2	B7 02	STA	PORTC	--	THE LAST DIGIT IS NOT A NINE.
1005	03A4	20 05	BRA	NEXT	--	
1006			**			
1007	03A6	B6 1C	TRUNC LDA	HUNDTH	--	
1008	03A8	B7 02	PCOUT STA	PORTC	--	AND IF THERE IS NO CARRY IT'S EVEN EASIER.
1009	03AA	98	CLC		--	
1010			**			
1011	03AB	B6 18	NEXT LDA	ONEDEG		
1012	03AD	A9 00	ADC	#0		
1013	03AF	B7 00	PAOUT STA	PORTA		
1014			**			
1015	03B1	B6 1A	NEXT1 LDA	HUNDEG		
1016	03B3	A9 00	ADC	#0		
1017	03B5	B7 01	STA	PORTB		
1018			**			
1019	03B7	1C 01	BSET	POSTIV,PORTB		
1020	03B9	18 01	BSET	BLANK,PORTB		
1021	03BB	1F 01	BCLR	DECPT,PORTB		
1022			**			
1023	03BD	81	RTS			
1024			**			
1025			**			
1026			*****			
1027			**			
1028			** SET UP THE TABLE TO BE USED WITH BCD INCREMENT/DECREMENT ROUTINES.			
1029			**			
1030			* ENDS			
1031			* DATA			
1032	03BE	00 01 02 03 04	TABLE FCB	\$00,\$01,\$02,\$03,\$04,\$05,\$06,\$07,\$08,\$09		
	03C3	05 06 07 08 09				
1033	03C8	10 11 12 13 14	FCB	\$10,\$11,\$12,\$13,\$14,\$15,\$16,\$17,\$18,\$19		
	03CD	15 16 17 18 19				
1034	03D2	20 21 22 23 24	FCB	\$20,\$21,\$22,\$23,\$24,\$25,\$26,\$27,\$28,\$29		
	03D7	25 26 27 28 29				
1035	03DC	30 31 32 33 34	FCB	\$30,\$31,\$32,\$33,\$34,\$35,\$36,\$37,\$38,\$39		
	03E1	35 36 37 38 39				
1036	03E6	40 41 42 43 44	FCB	\$40,\$41,\$42,\$43,\$44,\$45,\$46,\$47,\$48,\$49		
	03EB	45 46 47 48 49				
1037	03F0	50 51 52 53 54	FCB	\$50,\$51,\$52,\$53,\$54,\$55,\$56,\$57,\$58,\$59		
	03F5	55 56 57 58 59				
1038	03FA	60 61 62 63 64	FCB	\$60,\$61,\$62,\$63,\$64,\$65,\$66,\$67,\$68,\$69		
	03FF	65 66 67 68 69				
1039	0404	70 71 72 73 74	FCB	\$70,\$71,\$72,\$73,\$74,\$75,\$76,\$77,\$78,\$79		
	0409	75 76 77 78 79				
1040	040E	80 81 82 83 84	FCB	\$80,\$81,\$82,\$83,\$84,\$85,\$86,\$87,\$88,\$89		
	0413	85 86 87 88 89				
1041	0418	90 91 92 93 94	FCB	\$90,\$91,\$92,\$93,\$94,\$95,\$96,\$97,\$98,\$99		
	041D	95 96 97 98 99				

```

1042      *      ENDS
1043      *      CODE
1044      *****
1045      **
1046      **
1047      **          SET UP MASK OPTION REGISTER.
1048      **
1049      0422      ABSOLUTE
1050      **
1051      **
1052      0F38      ORG      NOR
1053      0F38      FCB      #BIT2+BIT1+BIT0
1054      **
1055      **          COMMENTS:
1056      **          BIT 7  CLOCK SOURCE 0 = CRYSTAL.
1057      **          BIT 6  TIMER OPTION 0 = INTERNAL.
1058      **          BIT 5  TIMER/CLOCK SOURCE 0 = INTERNAL.
1059      **          BIT 4  NOT USED.
1060      **          BIT 3  NOT USED.
1061      **          BIT 2  SET  -
1062      **          BIT 1  SET  -  PRESCALE SELECT 111 => 128
1063      **          BIT 0  SET  -
1064      **
1065      *****
1066      **
1067      **          ASSIGN INTERRUPT VECTORS.
1068      **
1069      0FF8      ORG      INTRPT
1070      **
1071      0FF8      FDB      BLINK  TIMER/INT2 INTERRUPT VECTOR.
1072      0FFA      FDB      COUNT  EXTERNAL INTERRUPT VECTOR.
1073      0FFC      FDB      COUNT  SOFTWARE INTERRUPT VECTOR, NOT USED.
1074      0FFE      FDB      RESTRY RESET VECTOR.
1075      **
1076      **
1077      **
1078      1000      ENDS
1079      END

```

Lines Assembled : 1079

Assembly Errors : 0

C. TILT

```

1          TTL                                POSITION DETERMINING PROGRAM (ELEVATION)
2          *                                LATEST REVISION          9 MAY 89
3          *                                FILE NAME              TILT.ASM
4          **
5          ** PROGRAM DESCRIPTION
6          **
7          **
8          **
9          ** I/O REGISTER ADDRESSES
10         **
11         0000    PORTA    EQU    $0000    I/O PORT A
12         0001    PORTB    EQU    $0001    I/O PORT B
13         0002    PORTC    EQU    $0002    I/O PORT C
14         0003    PORTD    EQU    $0003    INPUT PORT D
15         **
16         ** DATA DIRECTION REGISTER OFFSET
17         **
18         0004    DDR      EQU    4        (eg. DDR FOR PORT A IS  PORTA+DDR )
19         **
20         ** OTHERS
21         **
22         0008    TIMER    EQU    $0008    EIGHT BIT TIMER REGISTER.
23         0009    TCR      EQU    $0009    TIMER CONTROL REGISTER.
24         000A    MR       EQU    $000A    MISCELLANEOUS REGISTER.
25         0010    RAM      EQU    $0010    START OF ON-CHIP RAM(112 - 31 FOR STACK)
26         0080    ZROM     EQU    $0080    PAGE ZERO OF ROM.
27         0100    ROM      EQU    $0100    START OF MAIN ROM.
28         0F38    MOR      EQU    $0F38    MASK OPTION REGISTER.
29         0FF8    INTRPT   EQU    $0FF8    LOCATION OF INTERRUPT VECTORS.
30         1000    MEMSIZ   EQU    $1000    MEMORY ADDRESS SIZE.
31         **
32         ** EQUATES
33         **
34         0001    BIT0     EQU    1
35         0002    BIT1     EQU    2
36         0004    BIT2     EQU    4
37         0008    BIT3     EQU    8
38         0010    BIT4     EQU    16
39         0020    BIT5     EQU    32
40         0040    BIT6     EQU    64
41         0080    BIT7     EQU    128
42         **
43         0000    B0       EQU    0
44         0001    B1       EQU    1
45         0002    B2       EQU    2
46         0003    B3       EQU    3
47         0004    B4       EQU    4
48         0005    B5       EQU    5
49         0006    B6       EQU    6
50         0007    B7       EQU    7
51         **
52         ** EQUATES FOR THE TIMER CONTROL REGISTER
53         **
54         ***
55         0007    TIR      EQU    7        TIMER INTERRUPT REQUEST. 1 = REQUEST, 0 = NO REQ.
56         0006    TIM      EQU    6        TIMER INTERRUPT MASK. 1 = DISABLED, 0 = ENABLED.
57         0005    TIN      EQU    5        EXTERNAL OR INTERNAL CLOCK SOURCE. 1 = EXT, 0 = INT.
58         0004    TEE      EQU    4        EXTERNAL CLOCK ENABLE. NOT USED.
59         0003    PSC      EQU    3        PRESCALER CLEAR. NOT USED.
60         0002    PS2      EQU    2        (PS2)  --
61         0001    PS1      EQU    1        (PS1)  |-- PRESCALER SELECT BITS.

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62      0000      PS0      EQU      0      (PS0)  --
63      **
64      ** EQUATES FOR THE STATUS BYTE, 'STAT'.
65      ***
66      ***
67      **
68      0007      UD      EQU      7      COUNT DIRECTION? 1 = UP, 0 = DOWN.
69      0006      MOD_32  EQU      6      IS 'BINCT' MODULO 32? 1 = YES, 0 = NO.
70      0005      FLASH  EQU      5      BLINK THE DISPLAY? 1 = YES, 0 = NO.
71      0004      POSCT  EQU      4      DISPLAY POSITION OR COUNT? 1 = POS, 0 = COUNT.
72      0003      L_SET  EQU      3      VALUE OF 'MODE,PORTD' LAST TIME.
73      0002      NEGTV  EQU      2      IS 'BCDCT' NEGATIVE NUMBER? 1 = YES, 0 = NO.
74      ***
75      ***          1      NOT USED.
76      ***          0      NOT USED.
77      ***
78      ** I/O EQUATES AND DESCRIPTIONS.
79      ***
80      ***
81      ***      PORT A (I/O)
82      ***
83      ***      +-----+-----+-----+-----+-----+-----+-----+-----+
84      ***      |          BCD DIGIT #4          |          BCD DIGIT #3          |
85      ***      +-----+-----+-----+-----+-----+-----+-----+-----+
86      ***      | D4 | C4 | B4 | A4 | D3 | C3 | B3 | A3 |
87      ***      +-----+-----+-----+-----+-----+-----+-----+-----+
88      *** BIT      7      6      5      4      3      2      1      0
89      ***
90      ***
91      ***      PORT B (I/O)
92      ***
93      ***      +-----+-----+-----+-----+-----+-----+-----+-----+
94      ***      |          DISPLAY CONTROL          |          NOT USED          |
95      ***      +-----+-----+-----+-----+-----+-----+-----+-----+
96      ***      | DECP | POSIV |          BLANK          |          |          |          |
97      ***      +-----+-----+-----+-----+-----+-----+-----+-----+
98      *** BIT      7      6      5      4      3      2      1      0
99      ***
100     0007      DECP   EQU      7      TO DISPLAY THE DECIMAL POINT...DECP IS CLEARED
101     0006      POSIV  EQU      6      USED TO DISPLAY NEGATIVE SIGN...CLEARED TO SHOW
102     ***                                     MINUS SIGN.
103     0004      BLANK  EQU      4      TO BLANK DIGITS 2 AND 3...CLEAR BLANK.
104     ***                                     DIGITS 4 AND 5 ARE ALWAYS BLANKED.
105     ***                                     DIGIT 1 IS NEVER BLANKED.
106     ***
107     ***      PORT C (I/O)
108     ***
109     ***      +-----+-----+-----+-----+-----+-----+-----+-----+
110     ***      |          BCD DIGIT #2          | BCD DIGIT #1(LEAST SIGNIFICANT) |
111     ***      +-----+-----+-----+-----+-----+-----+-----+-----+
112     ***      | D2 | C2 | B2 | A2 | D1 | C1 | B1 | A1 |
113     ***      +-----+-----+-----+-----+-----+-----+-----+-----+
114     *** BIT      7      6      5      4      3      2      1      0
115     ***
116     ***
117     ***      PORT D (INPUT ONLY)
118     ***
119     ***      +-----+-----+-----+-----+-----+-----+-----+-----+
120     ***      | CH_A | INT2 | CH_B | FUNCT | SET |          |          |          |
121     ***      +-----+-----+-----+-----+-----+-----+-----+-----+
122     *** BIT      7      6      5      4      3      2      1      0
123     ***
124     0007      CH_A   EQU      7      INDICATES THE STATUS OF CHANNEL A.
125     0006      INT2   EQU      6      INTERRUPT #2. USED TO CHANGE DISPLAY MODES.
126     0005      CH_B   EQU      5      INDICATES THE STATUS OF CHANNEL B.
127     0004      FUNCT  EQU      4      USED TO PUT THE PROGRAM IN A MODE THAT WILL ALLOW

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128          0003      ***      'HYST' TO BE INCREMENTED.
129          SET      EQU      3      INCREMENTS 'HYST' WHEN TOGGLED AND FUNCT IS LOW.
130          ***
131          ***
132          *****
133          **
134          **      RAM VARIABLES
135          **
136          *****
137          **
138          ** RESERVE MEMORY SPACE FOR THE PROGRAM VARIABLES.
139          **
140          0000      DATA
141          **
142          **
143          0000      ABSOLUTE (ABSOLUTE ADDRESSING USED HERE TO RELATIVE DIRECTIVE)
144          **
145          0010      ORG      RAM      START OF RAM.
146          **
147          *** BINARY COUNT.
148          0010      BINCT RMB      2
149          0010      HIBIN EQU      BINCT      HI BYTE.
150          0011      LOBIN EQU      BINCT+1      LO BYTE.
151          **
152          *** POSITION POINTERS.
153          0012      PTR      RMB      3      EACH BYTE POINTS TO A POSITION IN THE
154          **      TABLE THAT CONTAINS ONE OR TWO DIGITS
155          **      OF THE BCD POSITION.
156          0012      PTR3 EQU      PTR      MOST SIGNIFICANT DIGITS.
157          0013      PTR2 EQU      PTR+1
158          0014      PTR1 EQU      PTR+2      LEAST SIGNIFICANT DIGIT.
159          **
160          *** COUNT POINTERS.
161          0015      CTPTR RMB      2      EACH BYTE POINTS TO A POSITION IN THE
162          **      TABLE THAT CONTAINS TWO OF THE DIGITS
163          **      IN THE BCD COUNT.
164          0015      CTPTR2 EQU      CTPTR      MOST SIGNIFICANT DIGITS.
165          0016      CTPTR1 EQU      CTPTR+1      LEAST SIGNIFICANT DIGITS.
166          **
167          *** BCD POSITION IN DEGREES.
168          0017      DEGRES RMB      3
169          0017      ONEDEG EQU      DEGRES      CONTENTS X      1.000
170          0018      HUNDTH EQU      DEGRES+1      CONTENTS X      0.010
171          0019      THOUTH EQU      DEGRES+2      + CONTENTS X      0.001
172          ***
173          ***      POSITION IN DEGREES
174          **
175          *** BCD COUNT.
176          001A      BCDCT RMB      2
177          001A      HUNDRD EQU      BCDCT      CONTENTS X      100
178          001B      TENONE EQU      BCDCT+1      + CONTENTS X      1
179          ***
180          ***      NUMBER OF PULSES COUNTED
181          ***
182          *** HYSTERESIS COUNTER. POINTS TO A NUMBER IN THE TABLE THAT IS THE
183          *** AMOUNT OF HYSTERESIS PRESENT IN THE SYSTEM. INITIALIZED TO 6.
184          001C      HYSTPT RMB      1
185          **
186          *** POSITION INCREMENT. CONTAINS A NUMBER, THAT WHEN MULTIPLIED BY 0.001
187          *** IS THE NUMBER OF DEGREES THAT THE POSITION COUNTER (BCDPOS) IS
188          *** TO BE INCREMENTED OR DECREMENTED DURING PROGRAM EXECUTION.
189          *** THE VALUE OF 'POSINC', DETERMINED EXPERIMENTALLY, SHOULD BE
190          *** 7.0452. SINCE THE PROGRAM IS DESIGNED WORK WITH INTEGERS ONLY
191          *** THIS NUMBER IS ROUNDED TO 7. TO REDUCE THE CUMULATIVE EFFECT OF
192          *** THE ROUND OFF, EVERY 32 COUNTS 'POSINC' IS SET EQUAL TO 8. THIS
193          *** AGAIN LEADS TO SOME CUMULATIVE ERROR, BUT THE SMALL ANGULAR RANGE

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194      ***      OF THE TILT ANGLE (10.5 DEGREES) ALLOWS US TO NEGLECT ANY FURTHER
195      ***      MODIFICATIONS.
196      ***
197      POSINC RMB      1
198      ***
199      *** HYSTERESIS VARIABLES. USED TO ELIMINATE THE EFFECTS OF BACKLASH ON
200      ***      THE POSITION MEASUREMENTS.
201      ***
202      HYST      RMB      1      THE THRESHOLD VALUE DETERMINED
203      ***      EXPERIMENTALLY.
204      HYSTCT RMB      1      CURRENT AMOUNT OF HYSTERESIS MEASURED.
205      ***
206      *** STATUS BYTE. USED TO KEEP TRACK OF WHAT IS GOING ON.
207      ***
208      STAT      RMB      1      CURRENT STATUS.
209      LSTAT      RMB      1      PREVIOUS/LAST STATUS. USED TO KEEP TRACK OF
210      ***      L_SET ONLY.
211      ***
212      *** TIMER COUNTER. USED IN CONJUNCTION WITH THE TIMER PRESCALER AND THE
213      ***      TDR TO KEEP TRACK OF ONE SEC. INTERVALS. USED IN BLINKING THE
214      ***      DISPLAY. INITIALLY SET TO 31, WHEN THE 'FLASH' BIT OF 'STAT'
215      ***      IS SET. TIMCT IS DECREMENTED EACH CLOCK INTERRUPT (APPROX. 31
216      ***      TIMES PER SEC). RESET TO 31 WHEN CONTENTS GO TO ZERO.
217      ***      WHEN (TIMCT)=0 THE DISPLAY WILL TOGGLE.
218      ***
219      TIMCT      RMB      1
220      **
221      ENDS
222      **
223      ***
224      *****
225      **
226      PAGE ZERO ROM
227      **
228      *****
229      **
230      INITIALIZATION ROUTINE.
231      **
232      **
233      CODE
234      **
235      ORG      ZROM      PAGE ZERO ROM.
236      **
237      RELATIVE      RELATIVE ADDRESSING MUST BE USED FOR THE BRANCH.
238      **
239      RESTRT EQU      $      THIS IS THE ENTRY POINT WHEN AN EXTERNAL
240      ***      INTERRUPT OCCURS.
241      **
242      *****
243      **
244      INITIALIZE THE PC AND CLEAR RAM.
245      ***
246      ***
247      0080 9B      SEI      SET INTERRUPT TO AVOID INTERRUPTION AND
248      0081 9C      RSP      RESET THE STACK POINTER. JUST IN CASE!
249      ***
250      0082 AE 10      LDX      #BINCT CLEAR ALL OF THE VARIABLES BETWEEN
251      0084 7F      CLRIT CLR      ,X      'BINCT' AND 'TIMCT' (INCLUSIVE).NOTE
252      0085 5C      INCX      THAT THIS SETS THE COUNTER AND THE POS-
253      0086 A3 22      CPX      #TIMCT ITION TO ZERO. THIS MEANS THAT ROTATION
254      0088 23 FA      BLS      CLRIT SHOULD START IN AN INCREASING (CW)
255      ***      DIRECTION FROM THE MOST CCW POSITION
256      ***      AFTER A RESET.
257      ***
258      008A      ABSOLUTE      BACK TO ABSOLUTE ADDRESSING.
259      ***

```

```

260
261
262
263
264 008A A6 FF
265 008C B7 04
266 008E B7 05
267 0090 B7 06
268
269
270
271
272 0092 A6 08
273 0094 B4 03
274 0096 B7 20
275
276 0098 1C 20
277
278
279
280
281
282 009A A6 06
283 009C B7 1E
284 009E B7 1C
285
286
287
288
289
290
291
292
293
294
295 00A0 A6 47
296
297
298
299 00A2 B7 09
300
301
302
303
304 00A4 A6 FF
305 00A6 B7 08
306
307
308
309 00A8 A6 1F
310 00AA B7 22
311
312
313
314
315
316
317 00AC 1D 0A
318
319
320
321
322
323 00AE CD 02 D8
324 00B1 1C 01
325

```

```

*****
***
***          ESTABLISH I/O PORTS.
***
          LDA    #-1          PORTS A,B,C ARE CONFIGURED AS
          STA    PORTA+DDR    ALL OUTPUT. PORT D IS ALL INPUT
          STA    PORTB+DDR    SO THERE IS NO MASK TO SET.
          STA    PORTC+DDR
***
*****
***          SET UP THE STATUS REGISTER.
***
          LDA    #X00001000    --
          AND    PORTD          |--> SET UP 'L_SET' BIT OF 'STAT'.
          STA    STAT          --
***
          BSET    MOD_32,STAT  0 IS MODULO 32.
**
*****
***          INITIALIZE HYSTCT.
***
          LDA    #06
          STA    HYST
          STA    HYSTPT
***
*****
**
**          SET UP THE TIMER FOR A 4 MHZ CRYSTAL / 4 = 1 MHZ CLOCK.
***
***          NOTE: THE MASK OPTION REGISTER IS IN ROM. IT IS SET UP AT
***          THE END OF THE PROGRAM.
***
*****          SET UP THE TCR. *****
***
          LDA    #BIT6+BIT2+BIT1+BIT0
          (TIM)|(PS2)|(PS1)|(PS0)
***          (DISABLE INTERRUPT)|(PRESCALE BY 128)
***
          STA    TCR
***
***          SET UP THE TIMER.
***
          LDA    #255          1 MHZ/(128*255) = 30.6 (APPROX. 31)
          STA    TIMER
***
*****          INITIALIZE THE TIMER COUNTER. *****
***
          LDA    #31          PROVIDES FOR 1 SEC. BLINK INTERVAL.
          STA    TIMCT        FOR 2 SEC. INTERVAL JUST USE TIMECT=62, etc.
***
***
*****
**
**          SET UP MISCELLANEOUS REGISTER.
**
          BCLR    B6,MR        ENABLES THE SECOND INTERRUPT.
**
*****
**
**          COUNT = 0 IS DISPLAYED INITIALLY.
**
          JSR    OUTCT
          BSET    POSTIV,PORTB
**

```

```

326
327 0083 9A
328
329 0084
330
331
332
333
334
335
336 0084 09 03 08
337
338 0087 06 03 04
339 008A 17 20
340 008C 20 F6
341 008E 16 20
342 00C0 20 F2
343
344
345
346
347
348
349 00C2 A6 40
350 00C4 B7 09
351
352 00C6 A6 08
353 00C8 B4 20
354 00CA B7 21
355 00CC A6 08
356 00CE B4 03
357 00D0 B1 21
358 00D2 27 15
359
360 00D4 A6 08
361 00D6 B8 20
362 00D8 B7 20
363 00DA 3C 1E
364 00DC 3C 1C
365
366 00DE B6 1C
367 00E0 A1 19
368 00E2 23 05
369
370 00E4 4F
371 00E5 B7 1E
372 00E7 B7 1C
373
374 00E9 A6 00
375 00EB B7 00
376 00ED A6 C0
377 00EF B7 01
378
379 00F1 BE 1C
380 00F3 D6 03 28
381 00F6 B7 02
382
383 00F8 09 03 C7
384 00FB 04 20 04
385 00FE 1C 01
386 0100 20 02
387 0102 1D 01
388 0104 08 20 05
389
390 0107 CD 02 D8
391 010A 20 03

```

```

**
**      CLI      CLEAR THE INTERRUPT MASK TO GET STARTED.
***
**      RELATIVE  RELATIVE ADDRESSING MUST BE USED FOR THE
***      REMAINDER OF THE PROGRAM.
***
*****
**
** WAIT LOOP.  EXECUTES, UNTIL AN INTERRUPT OCCURS.
**
PAUSE  BRCLR  FUNCT,PORTD,CHHYST  WANT TO CHANGE HYST?
**                                     YES...GO TO CHHYST.
**      BRSET  SET,PORTD,SBIT      NO... 'SET,PORTD' SET?
**      BCLR   L_SET,STAT          NO... CLEAR 'L_SET,STAT'
**      BRA    PAUSE              AND LOOP.
SBIT   BSET   L_SET,STAT          YES... SET 'L_SET,STAT'
**      BRA    PAUSE              AND LOOP.
**
*****
**
** HYSTERESIS MODIFICATION ROUTINE.  PERMITS MODIFICATION OF THE
** HYSTERESIS BUFFER WITHOUT REPROGRAMMING.
**
CHHYST LDA  #BIT6      YES...
STA     TCR            DISABLE TIMER INTERRUPT.
***
LDA     #X00001000    SAVE 'L_SET'
AND     STAT          INTO
STA     LSTAT         'LSTAT'.
LDA     #X00001000
AND     PORTD         'SET,PORTD' --> ACCUMULATOR
CMP     LSTAT         HAS THE SET SWITCH BEEN CHANGED?
BEQ     DISPLA
***
YES...
LDA     #X00001000    --
EOR     STAT          -- |-->CHANGE 'L_SET,STAT',
STA     STAT          --
INC     HYST          THEN INCREMENT THE HYSTERESIS
INC     HYSTPT        POINTER AND 'HYST'...
***
LDA     HYSTPT        --
CMP     #25           --
BLS     DISPLA        --
***
-- BUT NOT ABOVE 25.
-- THEN---->
CLRA
STA     HYST
STA     HYSTPT
--
***
DISPLA LDA  #X00000000  NO... JUST----->
STA     PORTA
LDA     #X11000000
STA     PORTB
--
***
-- DISPLAY CURRENT 'HYST'.
LDX     HYSTPT
LDA     TABLE,X
STA     PORTC
--
***
IS 'HYST' SETTING COMPLETE?
BRCLR  FUNCT,PORTD,CHHYST NO... KEEP CHECKING 'SET'.
BRSET  NEGTV,STAT,SIGN    YES... RESET THE DISPLAY.
BSET   POSTIV,PORTB
BRA    DIR
SIGN   BCLR  POSTIV,PORTB
DIR    BRSET POSCT,STAT,SHOPOS
**
JSR    OUTCT
BRA    DUNCHG

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392
393 010C CD 02 E5
394
395 010F 08 20 04
396 0112 A6 07
397 0114 B7 09
398 0116 20 9C
399
400
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419 0118 1F 0A
420
421 011A 0A 20 10
422 011D 09 20 07
423 0120 1A 20
424
425 0122 A6 07
426 0124 B7 09
427 0126 80
428
429 0127 18 20
430 0129 CD 02 E5
431 012C 80
432
433 012D A6 47
434 012F B7 09
435 0131 19 20
436 0133 1B 20
437
438 0135 CD 02 D8
439 0138 80
440
441
442
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444
445
446
447
448
449 0139
450 0139 0F 09 DC
451
452
453 013C 1F 09
454
455 013E 3A 22
456 0140 27 01
457

***
SHOPOS JSR OUTPOS
***
DUNCHG BRCLR FLASH,STAT,NO_INT IF THE DISPLAY IS TO BLINK...
LDA #BIT2+BIT1+BIT0 ENABLE TIMER INTERRUPT AND RESET
STA TCR TIMER PRESCALER
NO_INT BRA PAUSE PRIOR TO RETURNING.
***
**
*****
** MAXIMUM EXECUTION TIME FOR THE REMAINDER OF THE PROGRAM OCCURS
** IF THE COUNTER ROTATES THROUGH ZERO AS THE DISPLAY MODE IS CHANGED
** FROM THE BLINKING MODE TO THE COUNT MODE AT THE SAME TIME THAT THE
** BLINKING ROUTINE IS CAUSING THE DISPLAY TO TOGGLE TO SHOW THE
** POSITION IN DEGREES.
** MAXIMUM EXECUTION TIME = 67 + 140 + 618 = 825 CLOCK CYCLES.
**
*****
**
**MODE CHANGE ROUTINE. CHANGES THE DISPLAY MODE FROM
** COUNT -> POSITION -> BLINKING -> COUNT ->....(ETC.)
** MAXIMUM EXECUTION TIME OF 127 CLOCK CYCLES OCCURS WHEN THE
** DISPLAY MODE IS CHANGED FROM DISPLAYING THE COUNT TO DISPLAYING
** THE POSITION (IN DEGREES).
** IF THE DISPLAY IS CHANGED FROM BLINKING TO A COUNT DISPLAY
** EXECUTION TIME IS 67 CLOCK CYCLES.
**
CHMODE BCLR B7,MR AVOID REPEATED INTERRUPTS.
**
BRSET FLASH,STAT,DIS_CT IF FLASHING, DISPLAY COUNT...
BRCLR POSCT,STAT,DISPOS IF SHOWING COUNT, DISPLAY POSITION...
BSET FLASH,STAT ELSE, BLINK.
**
LDA #BIT2+BIT1+BIT0 ENABLE TIMER INTERRUPT AND RESET
STA TCR TIMER PRESCALER.
RTI
**
DISPOS BSET POSCT,STAT --
JSR OUTPOS -- DISPLAY CURRENT POSITION, AND WAIT.
RTI --
**
DIS_CT LDA #BIT6+BIT2+BIT1+BIT0 DISABLE TIMER INTERRUPT AND RESET
STA TCR TIMER PRESCALER.
BCLR POSCT,STAT --
BCLR FLASH,STAT --
**
JSR OUTCT -- DISPLAY CURRENT COUNT, AND WAIT.
RTI --
**
*****
**
** BLINK ROUTINE. INTERRUPT ROUTINE TO CHANGE THE DISPLAY FROM POSITION
** TO COUNT OR VICE VERSA EVERY 31 ST TIMER INTERRUPT IF THE
** 'FLASH' BIT OF 'STAT' IS SET.
** MAXIMUM EXECUTION TIME OF 140 CLOCK CYCLES OCCURS WHEN THE
** DISPLAY IS TOGGLED FROM A COUNT DISPLAY TO A POSITION DISPLAY.
**
BLINK EQU $
BRCLR TIR,TCR,CHMODE IF THE INTERRUPT WAS NOT A TIMER
INTERRUPT IT MUST BE FROM INT2.
**
BCLR TIR,TCR AVOID REPEATED TIMER INTERRUPTS.
**
DEC TIMCT IF THERE HAVE BEEN 31 TIMER
BEQ CHGDIS INTERRUPTS (1 SEC), IT'S TIME TO
CHANGE THE DISPLAY.
**

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```

458 0142 80
459
460 0143 A6 1F
461 0145 B7 22
462
463 0147 B6 20
464 0149 A8 10
465 0148 B7 20
466
467 0140 08 20 04
468
469
470
471 0150 CD 02 D8
472 0153 80
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476 0154 CD 02 E5
477 0157 80
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506 0158
507 015B 0A 03 01
508 015B 80
509
510
511
512 015C A6 7F
513 015E B4 20
514 0160 B7 20
515 0162 A6 80
516 0164 B4 03
517
518 0166 BA 20
519 0168 B7 20
520
521
522
523 016A 0E 20 09

```

```

RTI OTHERWISE, IT'S BACK TO WORK.
**
CHGDIS LDA #31 RESET TIMCT TO 31 (1 SEC. INTERVAL).
STA TIMCT
**
LDA STAT --
EOR #X00010000 |-- CHANGE 'POSCT' BIT OF 'STAT'.
STA STAT --
**
BRSET POSCT,STAT,POSOUT DECIDE ON CORRECT DISPLAY.
**
***** CHANGE THE DISPLAY TO SHOW THE COUNT..... *****
**
JSR OUTCT
RTI
**
***** OR HAVE THE DISPLAY SHOW THE POSITION. *****
**
POSOUT JSR OUTPOS
RTI
**
*****
**
COUNT ROUTINE.
**
WHEN A COUNT IS RECEIVED THIS IS THE ENTRY POINT .
**
MAXIMUM EXECUTION TIME OF 618 CLOCK CYCLES OCCURS WHEN THE
**
COUNTER ROTATES CCW THROUGH ZERO AND THE POSITION (IN DEGREES)
**
IS BEING DISPLAYED.
**
**
CURRENT DIRECTION OF ROTATION IS DETERMINED BY INSPECTING THE STATUS
**
OF 'CH_A' AND 'CH_B'. THE FOUR POSSIBILITIES AND THE ASSOCIATED
**
DIRECTION OF ROTATION ARE AS SHOWN BELOW. NOTE THAT THIS SCHEME
**
PREVENTS MULTIPLE OSCILLATIONS ABOUT A SINGLE POINT FROM
**
REPEATEDLY INCREMENTING OR DECREMENTING THE COUNTER.
**
**
+-----+-----+-----+-----+
| CH_A | CH_B | DIRECTION | COUNT THE PULSE? |
|-----|-----|-----|-----|
| LO | LO | CW | NO |
| LO | HI | CCW | YES |
| HI | LO | CCW | NO |
| HI | HI | CW | YES |
+-----+-----+-----+-----+
**
***** FIRST SEE IF WE ARE SUPPOSED TO COUNT THIS INTERRUPT. *****
**
COUNT EQU $
BRSET CH_B,PORTD,OKCT IF CH_B IS LO WE DON'T COUNT THE
RTI INTERRUPT.
**
***** IF THE INTERRUPT IS VALID UPDATE 'STAT'. *****
**
OKCT LDA #X01111111
AND STAT SAVE ALL OF THE OLD 'STAT' EXCEPT THE
STA STAT DIRECTION OF ROTATION.
LDA #X10000000
AND PORTD 'CH_A,PORTD' INDICATES THE DIRECTION
OF ROTATION AND BECOMES 'UD,STAT'.
* ORA STAT ADD THE RESULTS TO GET
STA STAT THE NEW 'STAT'.
**
** DECIDE IF THE "SLACK" DUE TO BACKLASH/HYSTERESIS HAS BEEN TAKEN OUT.
**
BRSET UD,STAT,HYSTCK IF ROTATING CW SEE BELOW.

```

524	0160	B6 1F	LDA	HYSTCT	ELSE, SEE IF WE DECREMENT THIS TIME.
525	016F	27 4B	BEQ	CCW	IF HYSTCT=0, GO TO THE COUNT DOWN ROUTINE.
526			**		
527	0171	A0 01	SUB	#1	ELSE, DECREMENT THE HYSTERESIS COUNTER,
528	0173	B7 1F	STA	HYSTCT	
529	0175	80	RTI		AND WAIT FOR THE NEXT INTERRUPT.
530			**		
531	0176	B6 1E	HYSTCK LDA	HYST	IF ROTATING CW....
532	0178	B1 1F	CMP	HYSTCT	AND HYST = HYSTCT
533	017A	27 03	BEQ	CW	COUNT THE PULSE .
534	017C	3C 1F	INC	HYSTCT	ELSE, INCREMENT THE HYSTERESIS COUNTER,
535	017E	80	RTI		AND WAIT FOR ANOTHER PULSE.
536			**		
537			**		
538			*****		
539			**		
540			**		
541			**		CLOCKWISE ROUTINE.
542		017F	CW EQU	\$	
543			**		
544			***		
545			*****		INCREMENT THE BINARY COUNTER (BINCT). *****
546			***		
547	017F	B6 11	LDA	LOBIN	BEGIN AT THE LSB OF THE BINARY COUNTER.
548	0181	A8 01	ADD	#1	LOBIN = LOBIN + 1 ; CARRY -> C,CCR
549	0183	B7 11	STA	LOBIN	
550			***		
551	0185	B6 10	LDA	HIBIN	
552	0187	A9 00	ADC	#0	ADD THE CARRY TO THE HIGH BYTE.
553	0189	B7 10	STA	HIBIN	
554			***		
555			***		
556			*****		CLR/SET MOD_32 APPROPRIATELY. *****
557			***		
558	0188	B6 11	LDA	LOBIN	IF THE LOW FIVE BITS OF 'LOBIN' ARE NOT
559	018D	A4 1F	AND	#X00011111	NOT THEN THE NUMBER ISN'T A MODULO 32 NUMBER.
560	018F	26 04	BNE	NOT_32	
561			***		
562	0191	1C 20	BSET	MOD_32,STAT	
563	0193	20 02	BRA	DIRCHK	
564			***		
565	0195	1D 20	NOT_32 BCLR	MOD_32,STAT	
566			***		
567			***		
568	0197	B6 10	DIRCHK LDA	HIBIN	
569	0199	2B 19	BMI	CWNEG	IF HIBIN < 0 , WE'RE ROTATING CW TOWARD THE ORIGIN.
570			***		
571			***		
572	019B	26 10	BNE	CWPOS	ELSE IF BINCT .NE. 0 ,
573	019D	B6 11	LDA	LOBIN	WE'RE ROTATING CW
574	019F	26 0C	BNE	CWPOS	AWAY FROM THE ORIGIN.
575			***		
576	01A1	15 20	BCLR	NEGTV,STAT	ELSE, WE'VE GONE THROUGH ORIGIN IN CW DIRECTION. CLR NEGATIVE SIGN.
577			***		
578	01A3	AE 12	LDX	#PTR3	--
579	01A5	7F	CLR	,X	--
580	01A6	5C	INCX		--RESET ALL COUNTERS AND DEGRES TO ZERO.
581	01A7	A3 19	CPX	#THOUTH	--
582	01A9	23 FA	BLS	CLRIT2	--
583	01AB	20 4C	BRA	UPOUT	UPDATE OUTPUT.
584			***		
585	01AD	AD 5E	CWPOS BSR	ADDBCD	
586	01AF	CD 02 32	JSR	INCPOS	
587	01B2	20 45	BRA	UPOUT	
588			***		
589	01B4	CD 02 7A	CWNEG JSR	SUBBCD	

```

590 01B7 CD 02 9A      JSR   DECPOS
591 01BA 20 3D      BRA   UPOUT
592
593
594 *****
595
596
597
598
599      01BC      CCW   EQU   $
600
601 ***** CLR/SET MOD_32 APPROPRIATELY. *****
602
603 01BC B6 11      LDA   LOBIN      ; IF THE LOW FIVE BITS OF 'LOBIN' ARE NOT
604 01BE A4 1F      AND   #X00011111 ZERO THEN THE NUMBER ISN'T A MODULO 32 NUMBER.
605 01C0 26 04      BNE   NO_32
606
607 01C2 1C 20      BSET  MOD_32,STAT
608 01C4 20 02      BRA   DECBIN
609
610 01C6 1D 20      NO_32 BCLR  MOD_32,STAT
611
612
613 ***** DECREMENT THE BINARY COUNTER (BINCT). *****
614
615 01C8 B6 11      DECBIN LDA  LOBIN      BEGIN AT THE LSB OF THE BINARY COUNTER.
616 01CA A0 01      SUB   #1          LOBIN = LOBIN - 1 ; BORROW -> C,CCR
617 01CC B7 11      STA   LOBIN
618
619 01CE B6 10      LDA   HIBIN
620 01D0 A2 00      SBC   #0          SUBTRACT THE CARRY FROM THE HIGH BYTE.
621 01D2 B7 10      STA   HIBIN
622
623 01D4 B6 10      LDA   HIBIN
624 01D6 2A 18      BPL   CCWPOS      IF HIBIN .GE. 0 , WE'RE ROTATING CCW TOWARD
625
626 01D8 A1 FF      CMP   #-1          --
627 01DA 26 10      BNE   CCWNEG      -- ELSE IF BINCT .NE. -1 ,
628 01DC B6 11      LDA   LOBIN      --WE'RE ROTATING CCW AWAY
629 01DE A1 FF      CMP   #-1          -- FROM THE ORIGIN.
630 01E0 26 0A      BNE   CCWNEG      --
631 01E2 14 20      BSET  NEGTV,STAT  ELSE, WE'VE GONE THROUGH ORIGIN IN CCW
632
633
634
635
636
637
638
639
640 01EC AD 1F      LDX   #PTR3      --
641 01EE CD 02 32   CLREM  CLR   ,X          --
642 01F1 20 06      INCK
643
644 01F3 CD 02 7A   CPX   #THOUTH      --
645 01F6 CD 02 9A   BLS   CLREM      --
646
647
648
649 *****
650
651
652 ** OUTPUT ROUTINE. ROUTINE TO PRINT DATA TO THE OUTPUT PORTS. BY
653 ** CALLING THE APPROPRIATE SUBROUTINE.('OUTCT' TO OUTPUT THE
654 ** THE COUNT AND 'OUTPOS' TO OUTPUT THE POSITION).
655
655      01F9      UPOUT EQU   $

```

656				**			
657	01F9	04 20 04		BRSET	NEGTV,STAT,MINUS	--	
658	01FC	1C 01		BSET	POSTIV,PORTB	--	
659	01FE	20 02		BRA	DISCHK	--	
660				**			SET THE NEGATIVE SIGN
661	0200	1D 01		MINUS	BCLR	POSTIV,PORTB	--
662				**			APPROPRIATELY.
663	0202	09 20 04		DISCHK	BRCLR	POSCT,STAT,PUTCT	
664				**			
665	0205	CD 02 E5			JSR	OUTPOS	
666	0208	80			RTI		
667				**			
668	0209	CD 02 D8		PUTCT	JSR	OUTCT	
669	020C	80			RTI		
670				**			
671				*****			
672				*****	SUBROUTINE TO INCREMENT THE BCD COUNTER (BCDCT). *****		
673				***			
674	0200	B6 16		ADDBCD	LDA	CTPTR1	
675	020F	AB 01			ADD	#1	
676	0211	A1 63			CMP	#99	CTPTR > 99 ?
677	0213	A3 05			BLS	OK1	NO, WE'RE OK HERE. LOOK UP THE FIRST TWO DIGITS.
678	0215	A0 64			SUB	#100	YES... MODIFY THE CTPTR,
679	0217	99			SEC		SET THE CARRY, AND
680	0218	20 01			BRA	OK1A	USE TABLE LOOK UP.
681				***			
682	021A	98		OK1	CLC		NO CARRY EXISTS IF WE ENTER AT THIS POINT.
683	021B	B7 16		OK1A	STA	CTPTR1	--
684	021D	97			TAX		--
685				***			-- LOOK UP THE TWO LEAST SIGNIFICANT DIGITS.
686	021E	D6 03 28			LDA	TABLE,X	--
687	0221	B7 1B			STA	TENONE	--
688	0223	24 0C			BCC	NOMO	AND CONTINUE ONLY IF THERE WAS A CARRY.
689				***			
690				***			
691	0225	B6 15			LDA	CTPTR2	
692	0227	A9 00			ADC	#0	ADD THE CARRY.
693	0229	B7 15			STA	CTPTR2	--
694	022B	97			TAX		--
695				***			-- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
696	022C	D6 03 28			LDA	TABLE,X	--
697	022F	B7 1A			STA	HUNDRD	--
698				***			
699	0231	81		NOMO	RTS		
700				***			
701				*****			
702				*****	SUBROUTINE TO INCREMENT THE POSITION COUNTER (DEGRES). *****		
703				***			
704				****	FIRST CHECK TO SEE IF THE BINARY COUNTER HAS REACHED A MODULO 32		
705				****	NUMBER.		
706				****			
707	0232	0D 20 04		INCPOS	BRCLR	MOD_32,STAT,INC7	'MOD_32,STAT' SET ?
708				****			
709	0235	A6 08			LDA	#8	YES ...
710	0237	20 02			BRA	INC	INCREMENT THE POSITION BY 0.008 DEGREES.
711				****			
712	0239	A6 07		INC7	LDA	#7	NO
713	023B	B7 1D		INC	STA	POSINC	INCREMENT THE POSITION BY 0.007 DEGREES.
714				****			
715				****	ROUTINE TO INCREMENT THE POSITION COUNTER , 'DEGREES', BY A		
716				****	PREDETERMINED AMOUNT, 'POSINC'.		
717				****			
718	023D	B6 14			LDA	PTR1	
719	023F	B8 1D			ADD	POSINC	
720	0241	A1 09			CMP	#9	PTR1 > 9 ?
721	0243	23 05			BLS	OK3	NO, WE'RE OK HERE. LOOK UP THE FIRST DIGIT.

722	0245	A0 0A	SUB	#10	YES... MODIFY THE CTPTR,
723	0247	99	SEC		SET THE CARRY, AND
724	0248	20 01	BRA	OK3A	USE TABLE LOOK UP.
725			****		
726	024A	98	OK3	CLC	NO CARRY EXISTS IF WE ENTER AT THIS POINT.
727	024B	87 14	OK3A	STA	PTR1 --
728	024D	97		TAX	--
729			****		-- LOOK UP THE LEAST SIGNIFICANT DIGIT.
730	024E	D6 03 28		LDA	TABLE,X --
731	0251	B7 19		STA	HUNDTH --
732	0253	24 24		BCC	DONE AND CONTINUE ONLY IF THERE WAS A CARRY.
733			****		
734			****		
735	0255	B6 13		LDA	PTR2
736	0257	A9 00		ADC	#0 ADD THE CARRY.
737	0259	A1 63		CMP	#99 PTR2 > 99 ?
738	025B	23 05		BLS	OK4 NO, WE'RE OK HERE. LOOK UP THE NEXT TWO DIGITS.
739	025D	A0 64		SUB	#100 YES...MODIFY THE CTPTR,
740	025F	99		SEC	SET THE CARRY,
741	0260	20 01		BRA	OK4A AND USE TABLE LOOK UP.
742			****		
743	0262	98	OK4	CLC	NO CARRY EXISTS IF WE ENTER AT THIS POINT.
744	0263	B7 13	OK4A	STA	PTR2 --
745	0265	97		TAX	--
746			****		-- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
747	0266	D6 03 28		LDA	TABLE,X --
748	0269	B7 18		STA	HUNDTH --
749	026B	24 0C		BCC	DONE AND CONTINUE ONLY IF THERE WAS A CARRY.
750			****		
751			****		
752	026D	B6 12		LDA	PTR3
753	026F	A9 00		ADC	#0 ADD THE CARRY.
754	0271	B7 12		STA	PTR3 --
755	0273	97		TAX	--
756			****		-- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
757	0274	D6 03 28		LDA	TABLE,X --
758	0277	B7 17		STA	ONEDEG --
759			****		
760	0279	81	DONE	RTS	
761			***		
762			**		
763			*****		*****
764			*****		SUBROUTINE TO DECREMENT THE BCD COUNTER (BCDCT). *****
765			***		
766	027A	B6 16	SUBBCD	LDA	CTPTR1
767	027C	A0 01		SUB	#1 CTPTR > 99 ?
768	027E	24 03		BCC	OK6 NO, WE'RE OK HERE. LOOK UP THE FIRST TWO DIGITS.
769	0280	A8 64		ADD	#100 YES, MODIFY THE CTPTR, AND
770	0282	99		SEC	GENERATE A BORROW.
771			***		
772	0283	B7 16	OK6	STA	CTPTR1 --
773	0285	97		TAX	--
774			***		-- LOOK UP THE TWO LEAST SIGNIFICANT DIGITS.
775	0286	D6 03 28		LDA	TABLE,X --
776	0289	B7 1B		STA	TENONE --
777	028B	24 0C		BCC	COMPLT AND CONTINUE ONLY IF THERE WAS A BORROW.
778			***		
779			***		
780	028D	B6 15		LDA	CTPTR2
781	028F	A2 00		SBC	#0 SUBTRACT THE CARRY. CTPTR > 99 ?
782	0291	B7 15		STA	CTPTR2 --
783	0293	97		TAX	--
784			***		-- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
785	0294	D6 03 28		LDA	TABLE,X --
786	0297	B7 1A		STA	HUNDRD --
787			***		

788	0299	81	COMPLT	RTS	
789			***		
790			*****		
791			*****	SUBROUTINE TO DECREMENT THE POSITION COUNTER (DEGREES).	*****
792			***		
793			****	FIRST CHECK TO SEE IF THE BINARY COUNTER HAS REACHED A MODULO 32	
794			****	NUMBER.	
795			****		
796	029A	00 20 04	DECPOS	BRCLR	MOD_32,STAT,DEC7 'MOD_32,STAT' SET ?
797			****		
798	029D	A6 08		LDA	#8 YES...
799	029F	20 02		BRA	DEC DECREMENT THE POSITION BY 0.008 DEGREES.
800			****		
801	02A1	A6 07	DEC7	LDA	#7 NO
802	02A3	B7 1D	DEC	STA	POSINC DECREMENT THE POSITION BY 0.007 DEGREES.
803			****		
804			****	ROUTINE TO DECREMENT THE POSITION COUNTER , 'DEGREES', BY A	
805			****	PREDETERMINED AMOUNT, 'POSINC'.	
806			****		
807	02A5	B6 14		LDA	PTR1
808	02A7	B0 1D		SUB	POSINC PTR1 < 0 ?
809	02A9	24 03		BCC	OK8 NO, WE'RE OK HERE. LOOK UP THE FIRST DIGIT.
810	02AB	AB 0A		ADD	#10 YES, MODIFY THE CTPTR, AND
811	02AD	99		SEC	GENERATE A BORROW.
812			****		
813	02AE	B7 14	OK8	STA	PTR1 --
814	02B0	97		TAX	--
815			****		-- LOOK UP THE LEAST SIGNIFICANT DIGIT.
816	02B1	D6 03 28		LDA	TABLE,X --
817	02B4	B7 19		STA	THOUTH --
818	02B6	24 1F		BCC	DUNSUB AND CONTINUE ONLY IF THERE WAS A BORROW.
819			***		
820			***		
821	02B8	B6 13		LDA	PTR2
822	02BA	A2 00		SBC	#0 SUBTRACT THE BORROW. PTR2 < 0 ?
823	02BC	24 03		BCC	OK9 NO, WE'RE OK HERE. LOOK UP THE NEXT TWO DIGITS.
824	02BE	AB 64		ADD	#100 YES, MODIFY THE CTPTR, AND
825	02C0	99		SEC	GENERATE A BORROW.
826			***		
827	02C1	B7 13	OK9	STA	PTR2 --
828	02C3	97		TAX	--
829			***		-- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
830	02C4	D6 03 28		LDA	TABLE,X --
831	02C7	B7 18		STA	MUNDTH --
832	02C9	24 0C		BCC	DUNSUB AND CONTINUE ONLY IF THERE WAS A CARRY.
833			***		
834			***		
835	02CB	B6 12		LDA	PTR3
836	02CD	A2 00		SBC	#0 SUBTRACT THE BORROW.
837	02CF	B7 12		STA	PTR3 --
838	02D1	97		TAX	--
839			****		-- LOOK UP THE NEXT TWO DIGITS IN THE TABLE.
840	02D2	D6 03 28		LDA	TABLE,X --
841	02D5	B7 17		STA	ONEDEG --
842			****		
843	02D7	81	DUNSUB	RTS	
844			***		
845			**		
846			**		
847			*****		
848			**		
849			**	OUTPUT COUNT (OUTCT). SUBROUTINE TO MOVE THE CURRENT COUNT (BCDCT)	
850			**	TO THE OUTPUT PORTS. REMOVES THE DECIMAL POINT FROM THE	
851			**	DISPLAY AND BLANKS ALL BUT THE LEAST SIGNIFICANT DIGIT. ALSO	
852			**	SETS THE MINUS SIGN IF APPROPRIATE.	
853			**		

```

854          02D8          OUTCT EQU $
855          **
856          02D8 B6 1B          LDA TENONE
857          02DA B7 02          STA PORTC
858          **
859          02DC B6 1A          LDA HUNDRO
860          02DE B7 00          STA PORTA
861          **
862          02E0 1E 01          BSET DECPT,PORTB
863          02E2 19 01          BCLR BLANK,PORTB
864          **
865          02E4 81          RTS
866          **
867          *****
868          **
869          ** OUTPUT POSITION (OUTPOS). SUBROUTINE TO MOVE THE CURRENT POSITION
870          ** COUNT (BCDCT) TO THE OUTPUT PORTS. THE DECIMAL POINT IS
871          ** DISPLAYED , AND ONLY THE MOST SIGNIFICANT DIGIT IS BLANKED.
872          **
873          02E5          OUTPOS EQU $
874          **
875          02E5 B6 19          LDA THOUTH --
876          02E7 A1 05          CMP #5 --
877          02E9 25 2D          BLO TRUNC -- IF 5 > 'THOUTH' SIMPLY TRUNCATE THE
878          02EB B6 18          LDA HUNDTH -- DISPLAY. OTHERWISE...
879          02ED A4 09          AND #9 -- IF THE LAST DIGIT ISN'T A NINE IT IS
880          02EF A1 09          CMP #9 -- EASY TO ROUND UP. JUST ADD A ONE.
881          02F1 26 1D          BNE DECIMAL --
882          02F3 B6 18          LDA HUNDTH -- BUT IF THE LAST DIGIT IS A NINE CHECK TO
883          02F5 A1 99          CMP #99 -- SEE IF IT'S 99. IF SO IT GETS GRIM.
884          02F7 27 04          BEQ UGLY --
885          02F9 AB 07          ADD #7 -- IF THE NUMBER IS X9 AND X.NE. 9, THEN
886          02FB 20 1D          BRA PCOUT -- JUST ADD SEVEN TO ROUND UP. DUE TO
887          ** -- HEXIDECIMAL.
888          ** -- IF THE LOW TWO DIGITS ARE BOTH NINES
889          02FD A6 00          UGLY LDA #00 -- AND WE NEED TO ROUND UP....
890          02FF B7 02          STA PORTC -- MAKE THE LOW TWO DIGITS BOTH ZEROS
891          0301 99          SEC -- AND SET THE CARRY.
892          **
893          0302 B6 17          LDA ONEDEG -- CHECK THE LAST DIGIT AS BEFORE.
894          0304 A4 09          AND #9 -- IF USING THIS PORTION OF THE CODE
895          0306 A1 09          CMP #9 -- THERE HAD TO BE A CARRY.
896          0308 26 13          BNE NEXT -- IF THE LAST DIGIT IS A NINE DO THE
897          030A B6 17          LDA ONEDEG -- CARRY HERE. IF NOT USE THE ADC
898          030C AB 07          ADD #7 -- INSTRUCTION TO TAKE CARE OF IT
899          030E 20 11          BRA PAOUT -- BELOW.
900          0310 B6 18          DECIMAL LDA HUNDTH --
901          0312 AB 01          ADD #1 --
902          ** -- THIS IS ALL THAT NEEDS TO BE DONE IF
903          0314 B7 02          STA PORTC -- THE LAST DIGIT IS NOT A NINE.
904          0316 20 05          BRA NEXT --
905          **
906          0318 B6 18          TRUNC LDA HUNDTH --
907          031A B7 02          PCOUT STA PORTC -- AND IF THERE IS NO CARRY IT'S EVEN EASIER.
908          031C 9B          CLC --
909          **
910          031D B6 17          NEXT LDA ONEDEG
911          031F A9 00          ADC #0
912          0321 B7 00          PAOUT STA PORTA
913          **
914          0323 18 01          BSET BLANK,PORTB
915          0325 1F 01          BCLR DECPT,PORTB
916          **
917          0327 81          RTS
918          **
919          *****

```

```

920
921
922
923
924
925 0328 00 01 02 03 04
    032D 05 06 07 08 09
926 0332 10 11 12 13 14
    0337 15 16 17 18 19
927 033C 20 21 22 23 24
    0341 25 26 27 28 29
928 0346 30 31 32 33 34
    034B 35 36 37 38 39
929 0350 40 41 42 43 44
    0355 45 46 47 48 49
930 035A 50 51 52 53 54
    035F 55 56 57 58 59
931 0364 60 61 62 63 64
    0369 65 66 67 68 69
932 036E 70 71 72 73 74
    0373 75 76 77 78 79
933 0378 80 81 82 83 84
    037D 85 86 87 88 89
934 0382 90 91 92 93 94
    0387 95 96 97 98 99
935
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941 038C
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945 0F38
946 0F38 07
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961
962
963 0FF8
964
965 0FF8 0139
966 0FFA 0158
967 0FFC 0158
968 0FFE 0080
969
970
971
972
973 1000

```

```

**
** SET UP THE TABLE TO BE USED WITH BCD INCREMENT/DECREMENT ROUTINES.
**
*      ENDS
*      DATA
*      TABLE FCB $00,$01,$02,$03,$04,$05,$06,$07,$08,$09
*
*      FCB $10,$11,$12,$13,$14,$15,$16,$17,$18,$19
*
*      FCB $20,$21,$22,$23,$24,$25,$26,$27,$28,$29
*
*      FCB $30,$31,$32,$33,$34,$35,$36,$37,$38,$39
*
*      FCB $40,$41,$42,$43,$44,$45,$46,$47,$48,$49
*
*      FCB $50,$51,$52,$53,$54,$55,$56,$57,$58,$59
*
*      FCB $60,$61,$62,$63,$64,$65,$66,$67,$68,$69
*
*      FCB $70,$71,$72,$73,$74,$75,$76,$77,$78,$79
*
*      FCB $80,$81,$82,$83,$84,$85,$86,$87,$88,$89
*
*      FCB $90,$91,$92,$93,$94,$95,$96,$97,$98,$99
*
*      ENDS
*      CODE
*****
**
**
** SET UP MASK OPTION REGISTER.
**
** ABSOLUTE JUST TO ENSURE THAT THE INTERRUPT VECTORS
** ARE CORECTLY LOCATED.
**
**
** ORG MOR
** FCB #BIT2+BIT1+BIT0
**
** COMMENTS:
** BIT 7 CLOCK SOURCE 0 = CRYSTAL.
** BIT 6 TIMER OPTION 0 = INTERNAL.
** BIT 5 TIMER/CLOCK SOURCE 0 = INTERNAL.
** BIT 4 NOT USED.
** BIT 3 NOT USED.
** BIT 2 SET -
** BIT 1 SET - PRESCALE SELECT 111 => 128
** BIT 0 SET -
**
*****
**
**
** ASSIGN INTERRUPT VECTORS.
**
** ORG INTRPT
**
** FDB BLINK TIMER/INT2 INTERRUPT VECTOR.
** FDB COUNT EXTERNAL INTERRUPT VECTOR.
** FDB COUNT SOFTWARE INTERRUPT VECTOR, NOT USED.
** FDB RESTRY RESET VECTOR.
**
**
**
** ENDS
** END

```

Lines Assembled : 973

Assembly Errors : 0

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