A Computer Controlled Coordinate Measuring Machine

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(Manuscript received June 29, 1970)

In development and operation of the mask-making laboratory, a precise positional measurement system is needed. This paper describes a system based on a Do-all coordinate measurement machine, controlled by a PDP-8 computer. The computer handles all sequential operations as well as computation necessary for coordinate transformation and feature location. The result is a system which can measure an array of 208 points to an accuracy of ±1 μm in less than two hours. Without computer control, measurement of such an array is not feasible.

I. INTRODUCTION

In the design of the mask-making laboratory, the need for a precise positional-measurement system was recognized. This system is needed for alignment and adjustment of the primary pattern generator (PPG), the reduction cameras and the step-and-repeat camera. It is also needed for mask inspection. The measurement system should be at least ten times more precise than the tolerance on the masks being measured, and it should be capable of measuring a large number of points in a reasonable time. For example, the test pattern to align the PPG is an array of 208 points, and this should require no more than two hours to measure. Table I summarizes the requirements on the measurement system.

1.1 *System Description*

A Do-all Coordinate Measurement Machine (CMM) controlled by a PDP-8 computer forms the basis for the measurement system to meet these needs. This is shown schematically in Fig. 1. The Do-all machine consists of two air-bearing slides at 90° on black granite ways. The plate to be measured is mounted on one slide (x-axis) and

TABLE I—PERFORMANCE OBJECTIVES FOR CMM SYSTEM

Field X	18 CM
Y	22 CM
Optical Power	250
Projected Field	400 μm
Feature Location	±200 μm
System Precision	±0.08 μm
Slew Rate (Both Axes)	0.5 CM/SEC
Plate Measurement Time (208 Points)	<2 hrs.

a microscope with projection screen is mounted above the plate on the other slide (y-axis). The range of travel on the x and y axes is 18 cm and 22 cm respectively; by appropriate adjustment of the x- and y-axes slides, the microscope can be positioned above any point on a plate within an 18-cm by 22-cm range. Stepping motors move the x and y slides through taut wire capstan drives. Fine manual positional adjustment is provided for by two torque transmitter and receiver pairs on a separate control panel. Fringe counting interferometers using a HeNe laser source provide precise positional information on the x and y axes. The counters display the total counts (1

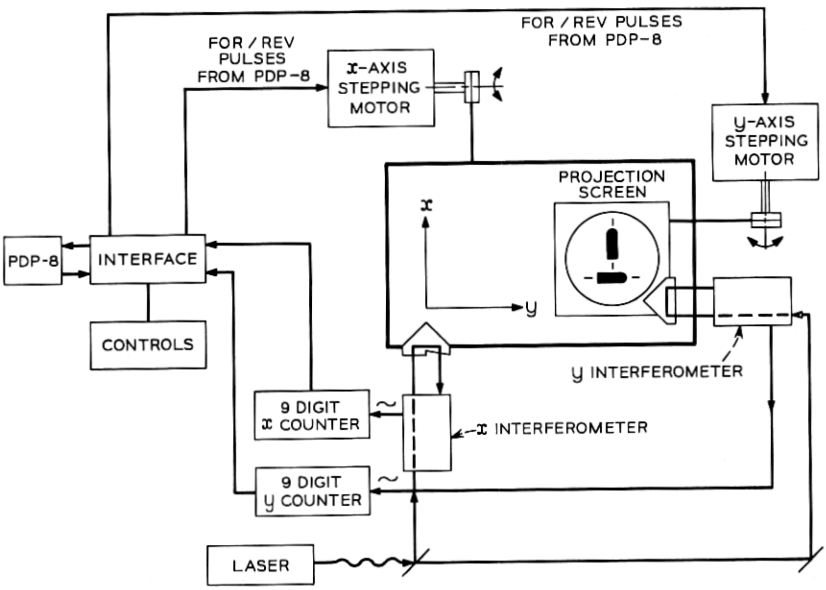

Fig. 1—Block diagram of measurement system.

count = 0.0791 μm) that the x and y slides have moved from some predetermined origin. Plate features to be measured are optically projected onto a screen to allow the operator, operating as a feedback element, to trim the location of the plate feature with respect to a reticle on the projection screen. The interface provides an interaction channel between the CMM, the PDP-8 and the operator.

II. ADVANTAGES OF COMPUTER CONTROL

The use of a general purpose computer as a control element for the measurement system has a number of advantages over a "hard wired" controller. First, there is the flexibility that the stored program allows. Modifications of the control functions and correction of errors are done by changing the program, not wiring. Very often this involves changing just a few instructions in memory and can be done right at the computer console in a matter of minutes. Second, the computer offers much greater input-output capacity; the system can be expanded to use disk or magnetic tape if required for future needs. The third advantage is that the computer can transform the coordinate system of a plate to the CMM coordinate system. This transformation can take into account (*i*) plate rotation with respect to the CMM, (*ii*) the deviation of the angle between the x and y axes of the CMM from 90° (skew angle), and (*iii*) conversion of units of counts to metric units or address units of the plate. A fourth advantage is that the computer allows feature location on a plate. Since the computer is interfaced to read the x and y counters and to pulse the x- and y-stepping motors, a computer program can be written to position the CMM microscope over any desired point on a plate.

III. MEASUREMENT SYSTEM DESIGN

The two basic areas of design in the CMM system—design of the interface and program design—are discussed in the following paragraphs.

3.1 *Interface*

The interface was designed with simplicity as the objective, at the possible expense of more programming. This is feasible because of the high speed of the PDP-8 relative to the mechanical speed of the CMM. The block diagram for the interface is shown in Fig. 2. The interface allows the computer to read information (counter readings, control switches and data inputs) into its accumulator, and allows the com-

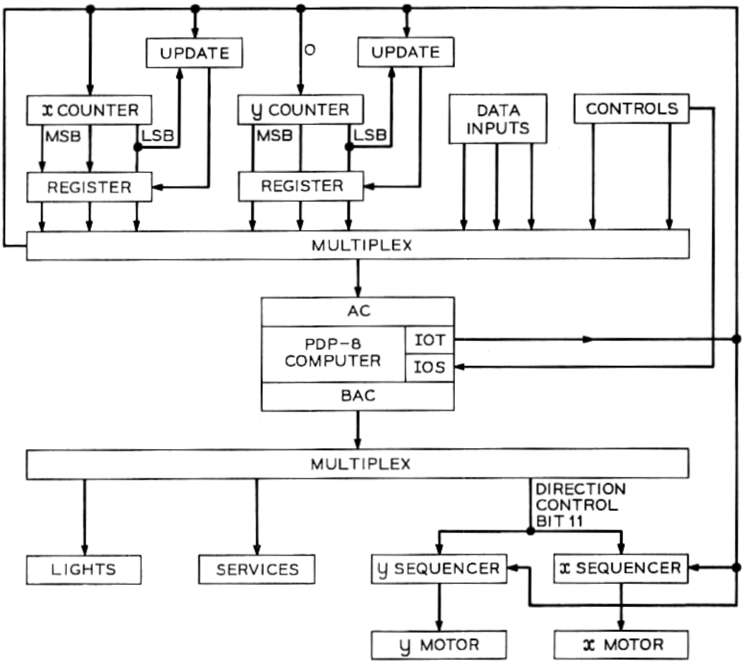

Fig. 2—Interface block diagram.

puter to transfer data from its accumulator to external devices. It also allows input-output transfer (IOT) pulses to be output by the computer.

The x- and y-axes stepping motors are driven by IOT pulses which occur in response to IOT instructions in the computer program. The direction of the step is controlled by the accumulator. One step of the motor causes a displacement of about 250 counts (20 μm) on either the x- or y-axis. The maximum rate of the motors is 200 steps per second giving a slew rate of 4 mm per second.

The x and y counters are nine-digit counters with binary-coded decimal (BCD) output. Since one computer word is only 12 bits, it is necessary to provide a 36-bit storage register for each counter. This register is read into the computer in three 12-bit bytes. Care must be exercised in transferring the outputs of a counter to its storage register, in that the transfer must not occur when the counter is in a transition. This is taken care of by an update circuit which transfers the counter outputs to the register only at a fixed time delay after a change in the least-significant bit (LSB). This time delay is chosen to be less than the time between input transitions to the counter. The routine to read one counter and store its BCD output in memory requires 33 μs.

There are a number of manual controls available for the operator. These are operable only when the program is in the manual control mode (Fig. 3). These controls consist of switches whose state is sensed by the computer through the accumulator bus. A toggle switch MANL allows the operator to enter the manual mode. Push-button switches X+, X−, Y+, Y−, allow the operator to manually position the microscope by pulsing the x- or y-stepping motors at a 200 pps rate. Push button switch CLEAR causes a present counter reading to be stored in core and then both counters to bet set to zero. Push button switch OUTPUT causes the present position in address units to

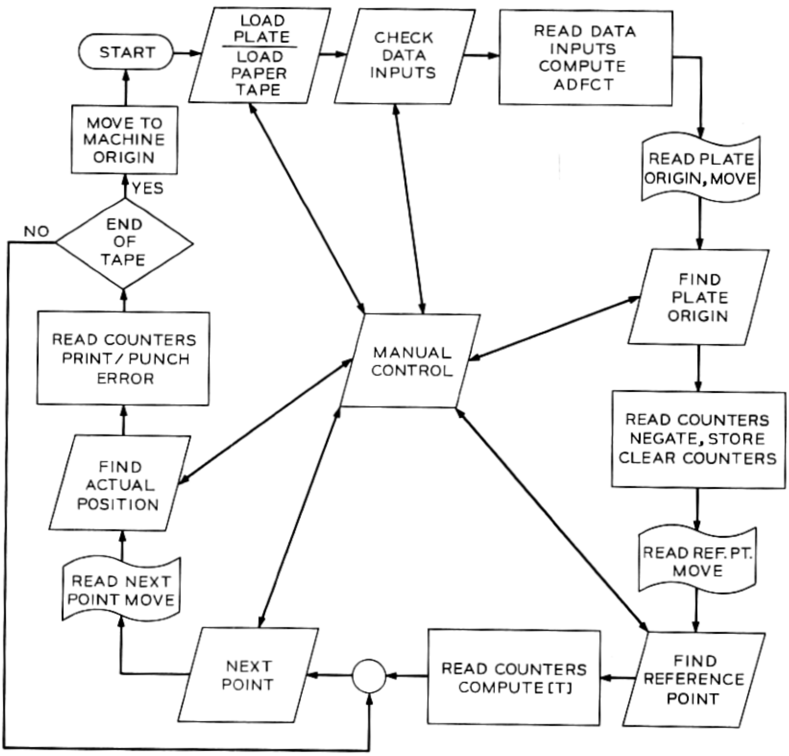

Fig. 3—Flowchart of control program.

be output on the teletype. Toggle switch TTY allows the operator to input x-y coordinates in plate-address units; the MOVE routine, described later, is then entered and causes the desired coordinates to be located.

3.2 *The Computer Program*

A simplified flow chart for the control program is shown in Fig. 3. The function of the control program is to provide a proper sequence of steps that will result in measurement of a plate. The slanted side boxes represent message lights that are illuminated when that point of the program is reached. The program progresses from one slanted side box to the next as the operator presses a continue push button on the control panel. The computer cycles in a loop while waiting for this operation. The manual mode can be accessed from any of the waiting loops, and is represented by the slanted side box in the center of Fig. 3. The boxes with curved tops and bottoms represent paper-tape input from the high-speed reader. In reading coordinates from the paper tape, a program XYINPT is called to transform plate coordinates to CMM coordinates. This is accomplished by the following matrix equation:

$$\begin{bmatrix} x_m \\ y_m \end{bmatrix} = \frac{ADFCT}{\cos\varphi} \begin{bmatrix} \cos(\theta-\varphi) & -\sin(\theta-\varphi) \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} x_p \\ y_p \end{bmatrix}. \tag{1}$$

Figure 4 shows the plate and CMM coordinates systems. The rotation of the plate with respect to the CMM is denoted by θ, while φ denotes the skew angle. The quantity $ADFCT$ is a constant to convert address units of a plate to counts of the CMM.

$$ADFCT = 8\,N/\lambda \text{ counts/address.} \tag{2}$$

N is the address size in μm, and λ is the wavelength ($\approx .6328\ \mu$m) of the HeNe laser.

To compute positional errors, it is necessary to convert the CMM coordinates to plate coordinates. This is done by inverting the transformation (1)

$$\begin{bmatrix} x_p \\ y_p \end{bmatrix} = \frac{1}{ADFCT} \begin{bmatrix} \cos\theta & \sin(\theta-\varphi) \\ -\sin\theta & \cos(\theta-\varphi) \end{bmatrix} \begin{bmatrix} x_m \\ y_m \end{bmatrix}. \tag{3}$$

3.2.1 *Feature Location*

When the coordinates of a feature on a plate are known, a routine called MOVE can be used to cause the microscope to be positioned over

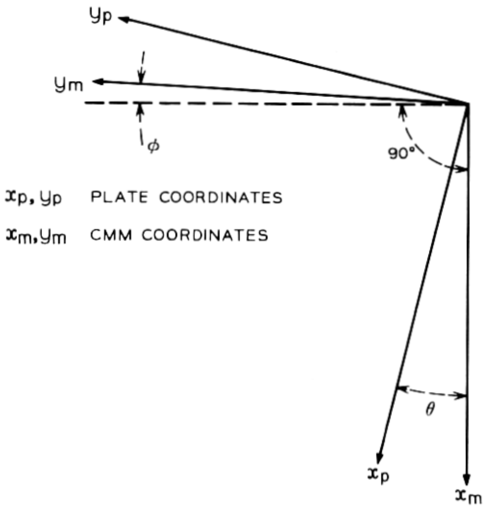

Fig. 4—CMM and plate coordinate systems.

the feature. This is done through the stepping motors. Since one step is 20 μm, the positioning accuracy is ± 20 μm on each axis, which is well within the field of the microscope. Thus, to locate a feature, the following procedure takes place for each axis:

(*i*) The desired counter reading is computed using equation (1) and is stored in the PDP-8 memory.

(*ii*) The quantity Δ, which is the difference between the desired counter reading and the present counter reading, is computed.

(*iii*) If $|\Delta| < 500$ counts, the feature is located and the procedure terminates; otherwise go to (*iv*).

(*iv*) A pulse is applied to the stepping motor; the sign of Δ determines the direction of the step. After a 5-ms delay (to allow the motor to complete its step) go to (*ii*).

Thus, while slewing to a position over a feature, the x- and y-stepping motors are pulsed continuously, and between pulses, the counters are read to see if the desired readings are obtained. The sequencing of MOVE insures that the first time the desired condition of being within 500 counts (40 μm) of the feature is obtained, then the motion of that axis is complete. No more pulses are output to that stepping motor. This eliminates hunting that would occur due to the time lag between application of a pulse to a stepping motor and motion of the slide.

IV. MEASUREMENT OF A PLATE

The process of measurement of a plate is illustrated by the flow chart of Fig. 3. Initially, the microscope is positioned over a fixed point that is the CMM origin. Prior to measurement of a plate, a paper tape is made containing the distance from the CMM origin to to the origin of the plate coordinate system. Following on the tape are the coordinates of a reference point on the x-axis, followed by the coordinates of all points to be measured; these points are expressed in the plate coordinate system. This paper tape is placed in the high-speed reader of the PDP-8, and is read under program control. Also prior to measurement, three data-input thumbwheel switches are set. These contain the CMM skew angle in seconds of arc, the factor N which is the address size in microns and the three least-significant digits of the wavelength of the HeNe laser. The wavelength of the HeNe laser is represented to an accuracy of seven digits in the PDP-8 —0.6328XXX μm, where XXX is read in on thumbwheel switches.

During the preliminary steps of the measurement, the plate origin is located and both counters are cleared. Prior to being cleared, both counters are read and the negative of their readings are stored in the PDP-8 memory. This enables the program to return the CMM microscope to the CMM origin at the end of the measurement. The reference point on the x-axis is located next. This enables the PDP-8 to compute the angle θ, $\theta = \tan^{-1} (y_{ref}/x_{ref})$, where (x_{ref}, y_{ref}) are the coordinates of the reference point on the x-axis as read from the CMM counters. The program now has enough information to compute the coordinate transformations (1) and (3). The program then proceeds to measure points as they are read from the tape, printing the errors on the ASR 33. An end of tape character signals the last point to be measured and causes the programs to terminate with the microscope positioned over the CMM origin.

V. CONCLUSIONS

The measurement system as described has been successfully used to measure plates from the PPG, the 3.5X reduction camera and the step-and-repeat camera. The main limitation on accuracy is the ability of the operator to align the desired feature with the reticle of the microscope. This in turn depends very much on the line-edge definition. For example, features generated by the PPG have been measured with ± 1-μm accuracy; the PPG generates line edges that are typically defined over a 5-μm distance.

The objectives on measurement time also have been met. A test array of 208 points for alignment of the PPG can be measured in less than two hours. Without computer control, the measurement time would be so long that drift problems and operator fatigue would make the measurement unfeasible.

VI. ACKNOWLEDGMENTS

The authors are grateful to A. Zacharias and K. M. Poole whose guidance and support provided the basis for this work. J. W. Stafford and L. Rongved provided consultation on mechanical problems. Thanks also are due to Mrs. E. E. Yamin for the use of her assembly program written on the GE 635 to assemble code for the PDP-8.

APPENDIX A

Skew Angle Measurements

The skew angle Φ as defined in Fig. 4 is the deviation from 90° of the x and y CMM axes. To measure Φ, a glass plate having three marks is used. An origin mark and marks on lines approximately 90° apart define the xp and yp axes as shown in Fig. 5. First the plate is placed on the CMM as shown in Fig. 5a with the axis of the plate roughly aligned with the CMM axis. Angles A and B may now be accurately measured by use of the CMM counters resulting in the following equation:

$$A + 90° + \Phi = B + 90° + \Phi p. \tag{4}$$

The measurement is then repeated with the plate rotated approxi-

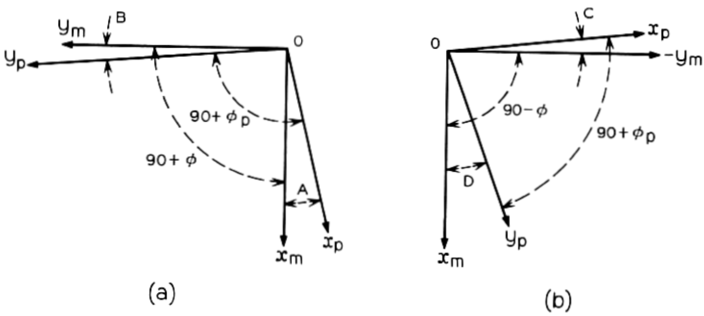

Fig. 5—Skew angle measurements. (a) Plate aligned with CMM axes. (b) Plate rotated 90° from CMM axes.

mately 90° with respect to the CMM axis as shown in Fig. 5b. Angles C and D are now measured resulting in the equation:

$$C + 90° - \Phi = D + 90° + \Phi p. \tag{5}$$

Equations (4) and (5) may be solved simultaneously to give the equation:

$$\Phi = \frac{(B + C) - (A + D)}{2}. \tag{6}$$

Measurements of this type indicate that Φ is about 11.5 seconds of arc. Φ must be measured after any disassembly of the y-axis support.