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THE SCANNING AND MEASURING PROJECTOR*

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FOREWORD

This report is a revision and expansion of a Ph.D. thesis written by John H. Munson. It is intended to be an adaptation of the material given in Dr. Munson's thesis for the scanning, measuring and projecting installations at the University of Illinois.

ABSTRACT

The Scanning and Measuring Projector (SMP) is a semi-automatic device for making rapid and accurate measurements of particle interactions from photographs of these events as they occurred within a bubble chamber. The SMP and a general purpose digital computer, CSX 1, work together in an integrated system. The operator scans the film and guides a detector approximately (± 0.5 cm) along the path of the points to be measured. The points are accurately digitized by an apparatus that sweeps the selected portion of the image across a fixed pattern of reference marks.

This paper generally describes the overall layout of the SMP system and specifically explains the SMP digitizing mechanism and process. Also discussed are the pattern-recognition and time-sharing aspects of the corresponding computer program, and its error-correction capabilities.

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I. INTRODUCTION

The Scanning and Measuring Projector (SMP) is a device for making accurate and relatively rapid measurements of events on bubble chamber photographs. The SMP employs a method of digitization in which points of the image are located relative to a pattern of accurately positioned reference marks. The method is analogous to a surveyor's use of bench marks as accurate local reference points. The coordinates of a point (a bubble image) on the SMP are found by specifying a "bench mark" (whose coordinates are already known) and incremental coordinates relative to the bench mark. Thus the SMP combines two measurements: one of relatively low precision and one of high precision. This combination replaces a single high-precision measurement usually made with a costly high-precision element.

One of the features of the design of the SMP is that the filmed events to be measured may be visually scanned by the operator prior to, or during, the measurement. Another feature is the tracing, by the operator, of only the approximate location of points to be measured. The precise digitization (essentially location) of points is left to the SMP digitizing apparatus. The operator and the SMP thus supplement each other in obtaining the measurement of points on those parts of the image selected by the operator.

The SMP operates on-line to a general purpose digital computer. The computer is incorporated directly into the system with the SMP(s) and the operator(s). The computer is immediately able to process, examine, and certify data generated and relayed by the SMP. Immediate feedback of results to the SMP operator increases the operating efficiency and reliability of the SMP.

II. THE DIGITIZING MECHANISM

The SMP table is a desk-sized structure at which the operator sits; the projection apparatus and the typewriter are located to the operator's left and right respectively. (See photographs) The image of the event to be measured or scanned is projected to an overhead mirror and then focused onto the top surface of the SMP table. On this flat, white surface, the operator is able to scan the image. The operator uses the projection controls to position the film, and uses the typewriter to communicate with the CSX throughout the measuring sequence. The SMP table, projector, typewriter, and associated electronics comprise the complete SMP.

Enclosed within the light-tight SMP table, below the white scanning surface, is the SMP digitizing apparatus. The digitizing apparatus has four parts (Fig. 1): 1) the curtains; 2) the detecting head; 3) the bench-mark plate; and 4) the light collector.

A. THE CURTAINS

The curtains form the horizontal scanning surface of the SMP table, as well as the top of the light-tight enclosure. The curtains are of sheet Mylar, aluminized for opacity and painted white on top. The larger (Y) curtain is mounted on rollers so that it is free to move in one dimension, away from

Cross-sectional View of Digitizing Apparatus

C. Schaad

Fig. 1

and toward the operator. The larger curtain covers the entire scanning surface, 55X70 cm, except for a gap 10 cm wide extending across the curtain from the operator's left to his right (Fig. 2). Mounted in this gap is a second, smaller (X) curtain. This transverse curtain is free to roll in the left and right directions, and is also carried with the motion of the larger curtain. Mounted in a gap in the smaller curtain is a 10 cm X 10 cm carriage. The top of this carriage is white and flush with the two curtains; it is broken only by a small aperture whose structure and dimensions are given in Fig. 3.

The effect of these mountings is that the two curtains can roll so as to permit the aperture to be positioned anywhere in the scanning plane. The aperture in the carriage becomes, in effect, a moveable hole in an opaque viewing surface. In measuring, the operator moves this aperture along the straight line or curved track of bubbles to be measured. Only that portion of the image striking the aperture passes into the light-tight volume below.

The two curtains are kept under tension to resist deformation due to gravity and touching by the operator. Along one edge of each curtain is a punched row of small rectangular slots (dimensions: $1/16$ cm X $1/2$ cm) called a picket fence. A small bulb is mounted below the row of slots, and two photodiodes above. As the curtains move, the signals from the photodiodes indicate the motion and direction of the curtains. The

SMP Curtain Arrangement

C. Schaad

Fig. 2

1. The periscope aperture is a sector of a circle whose mean radius is 2.406 cm.
2. This "pie" shaped sector then acquires an annular ring shape when rotating on its periscope mounting.

* Drawing not to scale.

Fig. 3

photodiode pulses for each curtain are counted in a reversible scaler in the electronics rack. The scalers for the two curtains always contain the current values X_C and Y_C (in centimeters) of the position of the aperture in the detecting head, as it moves with the curtains. X_C and Y_C are coarse measurements; they have a least count of $1/32$ cm and accuracy of $1/8$ cm. Each time a curtain passes the center of its travel, a special punched slot and corresponding photodiode are used to reset the scaler to a fixed number. This prevents the coarse scaler from accumulating large errors in the measuring process.

B. THE DETECTING HEAD

The aperture in the detecting head is essentially a window to a periscope mounted in a rotating drum within it. At any instant, the portion of the image falling into the aperture is displaced laterally by a vector $\underline{R}$ as it traverses the periscope and projects downward. The displacement is a perfect translation; that is, any point P in the aperture is displaced to (P, R) .

The periscope drum is the rotor of a synchronous motor that spins at a constant 1800 rpm. As the drum spins, the displacement vector $\underline{R}(t)$ traces out a circle. The fixed magnitude R of $\underline{R}$ is the lateral "length" of the periscope (2.406 cm), and the angle θ changes linearly with time. Thus, $\underline{R}$ has components:

$$\begin{aligned} X_D &= R \cos \theta = R \cos \omega t \\ &\text{and} \\ Y_D &= R \sin \theta = R \sin \omega t \end{aligned}$$

On the outer rim of the periscope drum are magnetic recordings giving X_D and Y_D directly in centimeters. Pulses from the heads reading these two recordings are shipped to two reversible scalers, which keep a running count of X_D and Y_D . The least count of the X_D and Y_D recordings is $1/128$ cm. Special "quadrant pulses" from the other two magnetic recordings on the drum are used to reset the X_D and Y_D scalers for each revolution, as an initializing procedure for guarding against possible cumulative errors in the scalers.

C. THE BENCH-MARK PLATE

The next element in the digitizing apparatus to be considered is the bench-mark plate. The bench-mark plate is a fixed, horizontal plate of glass that extends beneath the entire measuring surface. The detecting head carriage moves just above the bench-mark plate. The portion of the image passing through the aperture, and displaced by the periscope, strikes the bench-mark plate as it leaves the periscope.

The plate is opaque and has small, clear holes placed accurately on the vertices of a lattice 1 cm square. These holes are the accurate reference points for SMP measurements, and are called "bench marks." The diameter of the clear holes (0.5 mm) approximately matches the projected image of a single bubble.

Structurally, the bench-mark plate is in the form of a photographic emulsion on a glass plate, and the pattern of clear bench marks on an opaque background is reproduced by contact printing from a master. In this way, the bench-mark plate can be produced at relatively low cost. The master bench-mark plate consists of a Lucite sheet, into which conical holes for the bench marks have been milled to a positional tolerance of better than 25 microns.

D. THE LIGHT COLLECTOR

Below the bench mark plate is the light collector consisting of an annular lens and a photomultiplier tube. The light collector is mounted with a pulley arrangement so that it always travels directly beneath the detecting head. The annular lens is precisely positioned in order to receive the image that has been displaced in a ring by the periscope. No matter what the orientation, θ , of the periscope, any light of the displaced image passing through a bench mark will be collected by the annular lens for the photomultiplier tube. (A tilted mirror is placed below the lens so that the photomultiplier tube may be mounted on a horizontal axis, taking up less space.)

III. THE DIGITIZING PROCESS

The events leading to the digitization of points may now be traced. As the image falls onto the scanning surface, a portion of the image, centered approximately at (X_C, Y_C) , falls into the aperture and enters the periscope. In the spinning periscope, the image portion is translated so that it is centered approximately at $(X_C + X_D, Y_C + Y_D)$. As the periscope executes one revolution, the displaced portion of the image sweeps out a circular path over the bench-mark plate (Fig. 4) and passes in turn over a number of bench marks. The output signal from the photomultiplier thus consists of 6 to 8 bucket signals during one periscope revolution, each of which is generated as light passes through a bench mark and reaches the photomultiplier tube. Such a signal has a duration of 2 msec. (The image field is light, the bubbles are dark.)

If a dark image of a bubble were to lie within the range of the periscope aperture exactly at periscope radius R from one of the bench marks, then this bubble image, displaced by the periscope, would eclipse a bench mark. This eclipse would cause a rise in the center of the bucket signal from the photomultiplier tube.

At a point approximately 75 usec after the peak of the photomultiplier signal, the circuitry generates a digitizing signal which indicates that a dark image point is crossing a

Motion of Displaced Image

C. Schaad

Fig. 4

bench mark and is to be digitized. Since this signal is delayed from the real bubble center, the recording is set back by some amount to compensate for the delay.

Fig. 5 shows the signals generated in the digitizing process. Also shown here is the logic followed by the electronics to insure that only bubble sized objects are digitized.

At the beginning of the periscope revolution, the coordinates X_C and Y_C from the picket fences are shipped from the SMP to the CSX. When a digitizing signal occurs, the coordinates X_D and Y_D are sent to the computer. The computer then forms $(X_C + X_D)$ and $(Y_C + Y_D)$. These numbers are the approximate coordinates of the center of the displaced image portion, near the bench mark through which the digitization occurred.

Since the bench marks are spaced exactly at the intersections of a 1 cm square grid, they may be taken as lying at integral centimeter values in X and Y. The bench mark eclipsed by a dark point to be digitized may be precisely determined, therefore, by rounding $(X_C + X_D)$ and $(Y_C + Y_D)$ to the nearest integers. In practice, an equivalent process is used: X_C and Y_C are set 0.5 cm too high, and the CSX performs a truncation rather than a rounding, forming (X_{BM}, Y_{BM}) as the coordinates of the bench mark causing the digitization.

At the instant of digitization, the vector $\underline{R} = (X_D, Y_D)$ is known to have exactly displaced the digitized point so that it

1. Track signal to be digitized.

2. Track signal with 150 usec. delayed signal.

3. Transitions from comparator.

4. Original track signal with 75 usec. delayed signal.

5. Transitions from second comparator.

6. Gates generated from 5.

7. 75 usec. delayed signal with 150 usec. delayed signal into comparator

8. Transitions from third comparator.

9. Gates generated from 8.

10. 75 usec. delayed signal with stretched signal (level of stretch. signal may be adjusted for sensitivity to certain pulse height tracks).

11. Transitions from fourth comparator.

12. Gates generated from 11.

13. Track strobe out. 3 is nanded with 6, 9, and 12.

Fig. 5

eclipses the bench mark just found. So the calculation for the exact coordinates of the undisplaced image point is $(X_{BM} - X_D)$ and $(Y_{BM} - Y_D)$. The complete calculation follows:

1)	X_C, Y_C	X_D, Y_D	Original pair of coordinates.
2)	$X_C + X_D = X'$
$Y_C + Y_D = Y'$		
3)	$(X' + 1/2 \text{ cm}) = X_{BM} \text{ cm.}$
$(Y' + 1/2 \text{ cm}) = Y_{BM} \text{ cm.}$
Truncate		Here, the precise bench mark (X,Y) has been determined, where X and Y are integers.
4)	$X_{BM} - X_D = X$
$Y_{BM} - Y_D = Y$		Here, the precise bubble coordinate (X,Y) have been determined.

This calculation of X and Y for each point is carried out in the CSX.

As the periscope makes one complete revolution, several digitizing signals may occur, one for each bench mark crossed by a portion of the track image. For each digitizing signal, a fine coordinate pair, X_D and Y_D is read out into the computer. Each of these fine (delta) coordinate pairs is combined with the X_C and Y_C for the entire revolution to form point coordinates X and Y as described above. Two image points may even eclipse the same bench mark and cause two distinct digitizations during the same 2 msec photomultiplier signal. The minimum time interval between two such signals is on the order of 200 usec, corresponding to a "peak instantaneous data rate" of 5 kc on the SMP.

The selection of the correct bench mark by truncation to integers depends on the circumstance that the uncertainty in position of the digitized point is less than the 1 cm spacing between adjacent bench marks. This uncertainty is the sum of the width of the aperture (0.5 cm) and the error in X_C (or Y_C), which must therefore be kept less than 1/8 cm. It is possible for the operator to move the carriage so rapidly that the X_C and Y_C established at the beginning of a periscope revolution become invalid during the 33 msec of the revolution. In other words, it is possible for the operator to move the carriage more than 1/8 cm in either X or Y direction before one periscope revolution has been completed. Sensing a change in these coordinates, then, the SMP reads out to the computer a new X_C and Y_C , which are used for the remainder of the revolution.

The digitization of a point does not depend on the precise location of the periscope carriage; as long as the point falls into the aperture, the displacement vector $\underline{R}$ carries it in the same circle on the bench mark plate. Thus, the operator only has to guide the carriage accurately enough to keep the image to be measured somewhere within the aperture. By the same token, however, if the operator moved the carriage slowly, or stopped it, the same points would be repeatedly digitized as long as they fell into the aperture, uselessly overloading the computer. To avoid this repetition, the transmission of coordinates to the computer is gated to occur for only one periscope

revolution, each time the aperture is moved by 0.5 cm in X or Y. In this way, a "snapshot" is taken each time the aperture moves by approximately its own diameter.

In order to be digitized, a dark point in the image must be able to eclipse some bench mark; that is, it must lie at distance R from some bench mark, to within a fraction of a bench mark diameter. In other words, the loci of all possible digitizations in the image plane are circles of radius R centered on every bench mark. The uniformity with which these circles cover the image plane is a critical factor in choosing the exact periscope radius R (Appendix A).

A point not lying on any of the circles of radius R cannot be digitized by the SMP. Thus, the SMP is not directly able to measure any arbitrarily chosen point. Such a point may be called a dead spot. (Indirect and special methods of single point measurement are discussed in Sec. VII.) If a dense bubble chamber track is thought of as being composed of adjacent bubbles of 0.04 cm image diameter, then about one bubble in three can be digitized. In other words, the SMP digitizes some six to eight points per centimeter on a dark track.

In measuring, the SMP does produce useful bubble-density information. As noted above, the SMP digitizes a statistical sampling of the bubbles on a track. If the density of bubbles varies, so too does the density of the digitizations. The observed density must be corrected for track dip angle and

IV. LEAST COUNT AND ACCURACY

The bit lengths of the various SMP coordinates are given in Table I.

Table I. Bit Lengths of SMP Coordinates

<u>COORDINATES</u>	<u>INTEGRAL BITS</u>	<u>FRACTIONAL BITS</u>	<u>TOTAL BITS</u>
X_C and Y_C	6	5	11
X_D and Y_D	3	7	10
X and Y	6	7	13

The least count of the SMP, (2^{-7} cm on the SMP table), corresponds to 5 microns (on an SMP with 15X magnification) on the film. This least count applies to the individual digitizations, not to the SMP output points.

We take the accuracy of the SMP to mean the magnitude of the spatial differences between the output points of the SMP program and the corresponding points in the nearest "true" transformation from the film plane, which involves only translation, rotation, and magnification. All such true transformations are acceptable, since the fiducial marks measured provide the four parameters necessary to specify the transformation. In adopting this definition of accuracy, the computer processing is considered to be an integral part of the SMP measurement.

Two special considerations apply to the discussion of accuracy on the SMP. First, optical distortions may be neglected as sources of inaccuracy if they are corrected later. The distortions due to the optics of projection may be found directly by making SMP measurements of an accurately ruled grid placed in the projector. The distortion corrections are then found by fitting the measured grid points to their known positions. In the present program, for example, a polynomial correction is applied for cubic radial distortion of the lens, and for key-stoning as a result of mirrors.

The second consideration pertaining to accuracy is that all other sources of inaccuracy are either sources of statistical error, or enter into the measurement as if they were sources of statistical error. There are two sources of true statistical error: 1) the least count quantization; and 2) the jitter in the electronic signal marking the instant of digitization. The remaining sources of inaccuracy in the digitizations are misalignments causing errors in the periscope radius and azimuth, and inaccuracies in the positioning of the individual bench marks. These are systematic errors. It is to be noted, however, that nearby points on a track are digitized through many different bench marks and at all angles of periscope orientation. Since 10 digitizations on the track are averaged together to give one output point, the contributions of the above errors will tend to average out over the ten points.

Measurements of tightly stretched shadow wires (simulating straight tracks) typically show an rms scatter off the track of approximately 5 microns on the film (one SMP least count) for individual digitizations. The rms scatter off the track of the averaged output points is then reduced by a factor of $1/\sqrt{10}$, to about 2 microns on the film. Periodic maintenance tests consisting of straight line measurements on the SMP(s) typically yield rms scatter points of 2 microns. Theoretically, the minimum attainable rms scatter of single measurements of a uniformly distributed variable, measured with a quantization of least count L , can be shown to be $L/\sqrt{12}$.

V. AUXILIARY HARDWARE

A. THE PROJECTOR AND FILM TRANSPORT

The detailed description of the projector and film transport for the SMP depends on the format of the photographic data being analyzed, and will vary among installations. (See Table II.)

The optical system must have a long light path, so that the rays passing through the SMP digitizing apparatus will have small divergence and so that the image will be well focused both on the scanning surface and on the bench mark plate. This long light path (approximately 16') necessitates bending of the light path in rooms with typical ceiling heights. It is also desirable to give the operator direct access to the film transport. For these reasons, the projector is mounted at the side of the SMP table, and the image is projected to a ceiling mirror, which in turn projects the image onto the scanning surface. The ceiling mirror is a rigid, yet lightweight construction of two glass plates, separated by cylindrical glass columns; the outer surface of one plate is ground optically flat and then silvered.

The film is vacuum-clamped onto a single platen carriage, which moves in one dimension to bring any region of the chamber into view. (The SMP's that examine Argonne film have a stationary carriage as the entire chamber is visible.) The

Typical SMP Setup

C. Schaad

Fig. 6

Table II

There are three types of projectors in operation:

1. Argonne
2. Berkeley (Lawrence Radiation Laboratory)
3. Brookhaven

Below is a table, listing specifications for each type.

Projector	Magnif.	Focal Lnth	Chamber	Image	View Arrangement
1. Argonne	10 X	450 mm	30" Circ	.8 Life Size	4 views. Entire chamber visible on table in any one view.
2. Berkeley	15 X	305 mm	72"	1.0 Life Size	3 views. 40% of view visible on table.
3. Brookhaven	10 X	450 mm	80"	.8 Life Size	3 views. 40% of view visible on table.

platen carriage has an electromagnetic brake which serves primarily to hold the carriage in place during the measuring sequence. Any combination of views may be turned on at once, and the views superimposed by controlling the objective lenses. The operator may use this superimposition to determine whether the tracks end in the plane of a bubble chamber window (leaving) or in the body of liquid hydrogen (stopping). The views are turned on and off by individual switches that control 500 watt projection lamps.

The operator has fast film forward and rewind controls, with an automatic, approximate frame finder. The film may conveniently be positioned by unclamping it and manipulating the feed reel at the operator's left hand (Fig. 6) and finally by adjusting the platen carriage.

The projection axes are placed as close together as is possible to minimize the divergence of light paths in the digitizing apparatus. In the present design using three views, two of the paths are folded close to the third with mirrors.

B. THE TYPEWRITER

The SMP typewriter is located at the operator's right, within convenient reach. The operator uses the typewriter to communicate with the CSX in order to progress through the measuring sequence. The typewriter paper constitutes a permanent record of the entire measuring procedure (Fig. 7).

Fig. 7

/S/
 BEGIN 2/2
 MO 8/8/DAY 9/9/YR 6/6
 OP 74/74
 INT 1/1
 EXP 7/7
 ROLL 2019/2019
 PRI ET 22/22
 FRAME 41/41
 MEAS 1/1

Operator's typed comments are underlined; typed requests of the computer are not. (Ordinarily the operator's comments are in black and the typed requests of the computer are in red.) Slash S "Square Root" is the operator's request to begin measuring. Typed data is transmitted by typing a square root sign; measured data is transmitted by typing the character pi. 2 square root is the request for SMP format; then follows the date, operator number, interpretation type, frame number, and measurement number. The computer then requests View 1 fiducial.

VW 1
 F, II, ERR A → Trouble on lower crossarm or possible need in adjustment of light intensity.
 F, II,
 V1, II, → Vertex measurement requested, in this instance, vertex was measured by intersecting track method.
 T1, II,
 T2, P, P, P, P, P, P, P, P, P, P, II, → Track 2 was measured in point mode.
 T3, II, ERRA → Track 3 measurement did not pass filter program.
 T3, II, , , Too few points recognized.
 VW2
 F, II, ERR 4 → Trouble in area 4 of fiducial mast.
 F, II, ERR H → Too many points taken.
 F, II,
 V1, P, P, P, P, ERR CP, P This vertex measured in point mode.
 T1, P, P, P, P, P, P, P, P, P, P, P, P, II,
 T2, II, ERRD, → Track failed to start; may indicate poor vertex measurement.
 T2, II, ERR D,
 T2, II,
 T3, P, P, P, P, P, P, P, P, P, P, P, , ,
 VW 3
 F, II, ERR F → Trouble on fiducial mast near upper crossarm.
 F, II, ERR E → Trouble on fiducial mast near lower crossarm.
 F, II,

Fig. 7, cont'd.

V1, II,

T1, II, ERR H —————> Too many points taken.

T1, II, ERR B —————> This error may indicate SMP scaler malfunction.

T1, II,

T2, P, P, P, P, P, P, P, P, P, II,

T3, II, ERR H —————> Too many points taken.

T3, II, RESTART —————> At the end of measuring sequence, the computer forwards a RESTART request to enable the operator to progress to another measurement.

Automatic color shift of the typewriter ribbon separates those messages typed by computer control from those typed by the operator.

The SMP typewriter is an electric typewriter equipped with encoders and decoders for transforming characters into six-bit codes, and vice versa. As the operator strikes a character key, the corresponding code is then relayed to the main typewriter multiplexer. A signal is sent to the CSX; this signal informs the CSX that typed data is ready for transmission (Fig. 8b). It is the function of the special program section reached by this signal to accept the character and process it within a few milliseconds. (Here it is to be noted that measured data has a priority of 1, while typed data has a priority of 2. In other words, the computer will accept all measured information before it will accept any typed information.) After approximately 10 msec, the code on the sense lines is removed by the typewriter multiplexer, and may be replaced with another typed character from the SMP typewriter.

If the computer is transmitting a typewriter message to the operator, a computer instruction presents a character code on 6 output lines. The character is immediately passed to a buffer in the SMP allowing the CSX to proceed to other operations. Upon receiving the character in the buffer, the typewriter initiates a stroke cycle to print the character. At the completion of the stroke cycle, the typewriter again signals the

CSX stating that the character has been completed and that the typewriter is ready for another character. Codes for nonexistent characters on the typewriter are used for special functions controlled by the computer.

The typewriter's electronics includes the buffer for character transmission from the CSX, and the control circuitry required between the typewriter and the multiplexer. The main typewriter circuitry is contained within a few rows of printed circuit boards mounted below the typewriter table.

C. THE ELECTRONICS RACKS

Two floor-standing racks contain the bulk of the electronics for the SMP. The majority of the logical electronics consists of four reversible scalars for holding the coordinates X_C , Y_C , X_D and Y_D . The coarse scalars hold twelve bits each, whereas the delta scalars hold ten bits each, including sign. Associated with each scalar is a register of equal bit length used for transferring data to the multiplexer and subsequently into the CSX.

Additional logic circuitry consists of gating and control electronics, including a multiplexer to intersperse coarse and fine (delta) coordinate transmission. For transmission to the CSX, a partial coordinate pair, either X_C and Y_C or X_D and Y_D , are placed together in a single 36-bit data word. (Note: What actually gets shipped into the CSX, however, are two-16 bit sections.) These two data sections also contain a signal stating

whether the SMP is in point mode (see Sec. VII) or track mode, a signal designating the SMP number, and other information that enables the CSX to proceed through the measuring sequence.

One of the two floor-standing racks contains the control circuitry, main power supplies, and indicator circuitry. This rack contains all the major control circuitry with the exception of the film control chassis which is located beneath the projection table.

D. THE MULTIPLEXER UNIT

A multiplexer unit is used to intersperse the data generated by a number of SMP's and to present the data to the data channel as if from a single source. This multiplexer unit contains two independent multiplexers: one to receive the measured data from the SMP, and one to receive the typed data from the SMP typewriter.

Each of these two independent multiplexers is essentially an asynchronous ring circuit that circulates among the SMP's until it encounters a data ready signal. The multiplexer then remains switched to the requesting SMP until the data transmission is accomplished.

For a complete outline of SMP data transmission, see:

Fig. 8a: Measured Data Transmission

Fig. 8b: Typed Data Transmission (Normal)

Fig. 8c: Typed Data Transmission (CSX Controlled)

Measured Data Transmission:

1. SMP two channel multiplexer, when stopped, ships a DRM (Data Ready Measurement) signal to the Main Measurement Multiplexer.
2. When DRM (with corresponding SMP no.) is sensed, the main measurement multiplexer stops and transmits a RDM (Read Data Measurement) to that SMP. The RDM signal gates the measured data into the buffer. From the buffer, the data is shipped to the receiver and the step counter is set to 1.
3. At the end of one clock cycle ($2.5\mu\text{sec}$), the step counter is set to 2. This wait allows all the information to be serially shipped to the CSX. If the parity check at step 2 is correct, the step counter is then set to 3.
4. At step 3, an interrupt request signal is transmitted to the CSX.
5. The CSX then transmits an interrupt reply signal which resets the request channel. Then the measured data is gated into the CSX: first the X data, second, the Y data.
6. After all data transmission is accomplished (at the end of Y data transmission), the step counter is set to 0 and a spin signal is given to the main measurement multiplexer.

Fig. 8a

Typed Data Transmission:

1. The typewriter ships a DRT (Data Ready Typewriter) signal to the typewriter multiplexer.
2. When DRT signal (with corresponding SMP no.) is sensed, the typewriter multiplexer stops and transmits an RDT (Read Data Typewriter) to that SMP. The RDT signal gates the typed data into the buffer. The typed data is then shipped to the receiver and the step counter is set to 1.
3. At the end of one clock cycle, the step counter is set to 2. If the parity check at step 2 is correct, the step counter is set to 3.
4. At step 3, an interrupt request signal is transmitted to the CSX.
5. The CSX then transmits an interrupt reply signal which resets the request channel. At this point, the typed data is gated into the CSX.
6. After all typed data has been received, the step counter is set to 0 and a spin signal is transmitted to the typewriter multiplexer.

Step Counter

Fig. 8b

Typed Data Transmission (CSX Controlled):

1. If the CSX has data to ship to the SMP typewriter (i.e., requests control of typewriter), the computer transmits an output request signal to the typewriter which sets the step counter to 1.
2. At the end of one clock cycle, the step counter is set to 2.
3. If the parity check at step 2 is correct, the step counter is set to 3.
4. At step 3, a signal is transmitted to gate the typed data on. This is known as a WRT (write) signal.
5. After one clock cycle, the step counter is set to 0 and an output process reply is shipped to the CSX.

Fig. 8c

VI. THE SMP COMPUTER PROGRAM

A. THE PROGRAM IN GENERAL

The SMP program for the computer operates on two separate levels. On the processing level, the program does all the processing and checking of the data from a measured track for an individual SMP, assembling the data to pass on to subsequent programs. The program also performs a function on the executive level, making the processing phase of the program available to all SMP's connected to the computer on an independent time-sharing basis.

In the processing phase of the program, called the "inner" program, the computer deals at any one time with data from a single SMP. The input coordinate information is transformed into X and Y coordinate pairs, and the desired measurement information is then abstracted, or, "filtered" from the set of X, Y coordinates. This filtered information is assembled as it is generated over a period of minutes, into a record to be written on magnetic tape for subsequent programs. To this record is added indicative information supplied by the SMP operator via the typewriter.

On the executive level, the computer deals with all the SMP's in a time-sharing fashion. The executive phase of the program acts as a superstructure for the inner program, providing access to the same inner program to every SMP, as requested individually. The resulting structure is not that of a typical

time-sharing system, in which control is passed among several independent programs. Rather, in the SMP system, all the operators share the same processing program, which is continuously in the computer memory, and which may service all the SMP's in a fraction of a millisecond.

To achieve this multiprogramming structure, the inner program is segmented into natural subunits, such as the transmission of a single typewriter character or the filtering of a single track. Each class of subunits is assigned to a priority level, with the shortest and most often repeated operations having the highest priority. As the SMP operators generate requests for processing operations, the requests are dealt with by a priority handling section of the executive phase. In this manner, the executive phase acts as a traffic controller, ensuring that the processing requests are handled in an efficient manner without interference.

The present SMP program, including the filter program occupies the CSX for about 15 seconds in processing a single event. This figure is for the typical event and is dependent upon event topology. For a typical event, about 15 seconds are required for the filter programs to filter five tracks, two vertices, and a fiducial, in all views. Unpacking the data coordinates and calculating X and Y for each point is done simultaneously with the operator's measuring and causes no apparent time loss. The figure of 15 seconds does not include

waiting time for the typewriter, the measurements, and the operator's reactions. During all such times, the multiprogramming structure frees the CSX to perform other operations.

B. THE SMP FILTER PROGRAMS

The SMP's method of digitization dictates the unique characteristics of the data generated. Specific individual points cannot be measured directly in the "normal measuring mode" as the SMP is more suited to measuring along figures composed of lines or curves. When a specific point, such as an interaction vertex, or fiducial mark is required, it is found in the normal measuring mode as the intersection of two straight lines or curves, or, by switching the SMP into Point Measuring Mode (Sec. VII). In this way, the data is usually generated on the SMP as the operator moves the measuring aperture along a line or curve to be measured.

In the following discussion, the object being digitized is taken to be a single smooth curved segment of a particle track image. Whether the bubbles on the track are distinguishable by eye, or merge to form a continuous line is immaterial, except that the digitization density will be different.

It is assumed that the information to be abstracted, or filtered, from a track measurement in one view, consists of a series of X, Y coordinate points accurately located along the track. The output points must be rather few in number, and in

order along the track. Such data are easily derived from the greater number of SMP digitizations along the track, by process of averaging, which also reduces the scatter of output points. Thus, the central task in preparing the output data is to select, from the set of point digitizations produced by the SMP, the subset of points actually lying on the track. This pattern recognition task falls into a portion of the SMP program called the track filter program. (There are corresponding specialized filter programs for fiducial marks and vertex points.)

The set of digitized points has the following characteristics. There is no guarantee that any given track point, or a point in any given small region, will be digitized. On the other hand, a point may be digitized more than once. Points on the track may be digitized out of order by a distance equal to the measuring aperture diameter, although the gross ordering of points will follow the aperture down the track. Any background of dark points on the path swept out by the aperture will be digitized along with the track points. Other objects in the digitizing path, such as crossing tracks, will be digitized as efficiently as the track itself. Finally, gross defects in the data can be produced by the operator straying off the track, reversing the direction of the measurement, or failing to keep the recording button down continuously. Each of these characteristics represents a handicap to the track filter program.

With reference to these problems, the filter program must select out those points which lie on the track, or return an error comment if it finds itself unable to perform the selection from the data presented. In the existing filter programs, the error comment provides information as to the probable cause of the deficiency in the data, as a guide to the operator in remeasuring the track.

The current method of selection incorporated into the track filter programs uses histograms of digitizations along coordinates in the image plane.

VII. THE MEASUREMENT OF SINGLE POINTS

As previously noted, the SMP in the normal measuring mode cannot directly measure a chosen point in the image; there are, however, various methods by which the location a point can be derived from measurements of other types.

In one procedure, a point is found as the intersection of two curved or straight lines. To measure a vertex, or interaction point, the operator measures toward the vertex, portions of two tracks emanating from the vertex. The computer then finds coordinates on the two tracks measured and calculates their point of intersection. By this method, the vertex is found, although neither the vertex, nor any point very near it, may have been digitized.

It may occur that all tracks emanating from a vertex intersect so obliquely that no pair of tracks is satisfactory for the type of measurement described above. At the end of a stopping track, furthermore, there is no second track. In cases such as these, a device called a shadow wire may be used to simulate an adequate point of intersection. The wire is mounted on a horizontal swinging arm and is positioned by the operator just above the scanning surface. It casts a straight-line shadow whose appearance is that of a densely ionized track.

In the present SMP systems, there is an alternate method of single point measurement. This system uses a rigidly fixed

cross-hair mounted on the periscope cover, and is certainly simpler and at least as accurate as the shadow wire. The accuracy attainable with this method seems to approach $\pm 100\mu$ on the scanning surface.

The PMS (Point Measuring System) should not be used where natural measurements of tracks will do the job since it requires accurate settings by the operator and therefore consumes time and patience. The uses of the PMS are as follows:

- A. To replace the shadow wire in measuring the end points of tracks.
- B. To measure vertices in cases where the normal means (intersecting tracks) cannot be used.
- C. To measure tracks where normal tracking will not work.

Figure 9 is a diagram showing how the mask image rotates at radius $R = 2.406$ cm and crosses bench marks B_i . As drawn, the mask image is about to cross B_1 . As it does so, a "bucket" signal is produced at the output of the photomultiplier.

The electronics are altered so that a pulse L is produced in a circuit when the leading edge of the bucket signal occurs, and a second pulse T is produced at the time of the trailing edge. (Fig. 10)

If the L and T pulses replace the normal track-center pulses in the rest of the SMP logic circuits, the electronics will determine that there is a bubble at point P_{Li} at a distance of $R = 2.406$ cm from B_i on a line parallel to CM , where M

1. Relation between bucket signal from PMX (Photomultiplier Tube) and L and T pulses. The L and T pulses replace normal track-center pulses in SMP logic. Track-center pulses are discarded.

Fig. 10

is the instantaneous center of the mask image. As drawn in Fig. 11a, it is about a half-mask width to the left of C.

Similarly, when pulse T occurs, the electronics determines that there is a second point P_{Ti} to the right of C (Fig. 11b). (Note: Points do not actually exist where the electronics determine they exist. In a sense, the electronics "think" that they exist.)

If everything were perfectly constructed, the center of the periscope C would lie on the line through B_i that bisects the angle $P_{Li}B_iP_{Ti}$. This line will hereafter be called the bisector (Fig. 11c). The exact position of C along this line cannot be determined, since we do not know the actual radius at which the mask image crossed the bench mark B_i . It takes two lines to determine a point. However, about 6 to 8 bench marks are crossed in every periscope revolution. Therefore, there are 6 to 8 bisectors with which to determine the "best" coordinates of C.

At this time, the operator has positioned the crosshair precisely over the point to be measured; the relation (a translation by a known common vector) between the crosshair and the periscope aperture has been previously determined and incorporated into the CSX program.

A few other considerations have to be made in this procedure. The L and T pulses may need to be delayed in time by a different amount than the normal track center pulses. This correction has already been made electronically. Since the

- 1.) The L and T pulses enable the SMP logic and the CSX to find a bisector line that passes through the bench-mark B_1 . The center of the periscope C should be very close to this line. Several (at least two) such lines enable the CSX to solve for the "best" position of the point C.

cross-hairs on the periscope cover are at a different distance from the projector than the bench-mark plate is, a different known constant vector V will actually be a function of view number and of bench mark position. It will have to be programmed into the CSX.

MECHANICAL CHANGES

The only mechanical change is a minor one. The cross-hairs are scribed on the top of a post securely fastened to the carriage. This retains the relative positioning to an accuracy of better than 1 mil. The top of the post protrudes through a hole in the periscope cover, placing the cross-hairs flush with the top surface. The top plate may be removed without disturbing the calibration.

No new buttons or switches are required for the SMP operator. However, a foot operated record switch could be installed if the operator tended to move the stage when making a point measurement. The present system is set up such that when the SMP is in point mode the measurement comply is automatically sent upon releasing the record button. This types a "P" on the typewriter.

VIII. SMP SYSTEM CONSIDERATIONS

A. TIME-SHARING STRUCTURE

The central arithmetical and logical processing units of digital computers currently operate much faster than do many of the input-output units and external systems with which such computers deal. The time-sharing system of the SMP is an example of this. However, a present day large scale solid state digital computer is still faster than is needed to service the SMP. Even if the computer were perfectly matched to the peak data load from the SMP's, it would still be idle much of the time as a result of the difference in measuring rates among the SMP operators. This "idle computer time" is quite costly; it is therefore necessary to consider systems in which the SMP's time-share the computer with other programs as well as with each other.

In the Illinois system, the SMP shares the CSX with a restricted class of other programs rather than a general run of programs. The advantage of this is that the programs sharing the CSX with the SMP program are specifically compatible. The programs might be simple ones to perform "clerical" tasks, such as listing of tapes and card to tape conversion.

B. FAST FEEDBACK AND AUTOMATIC BOOKKEEPING

Measured bubble chamber events that fail in the various later analysis programs constitute a problem as the number of events typically measured in an experiment increases with time.

The CSX can eliminate failing events by recognizing each failure and immediately requesting that the operator remedy the cause of the failure, while the data in question are still in front of the operator. Presently, however, this fast feedback and error correction is applied at only two levels: in governing the sequence of the measurement dialogue, and in filtering measurements. If a message typed by the SMP operator is not compatible with the request of the CSX, then the CSX will not accept it. For example, if the operator is asked the frame number, and the operator replies with alphabetic rather than numeric characters, the CSX will then signal an error and request the information again. Similarly, if a measurement of a track, vertex, or fiducial does not pass through the filter programs, the CSX will request that the erroneous measurement be remade, and will not proceed until the measurement is satisfactory to the filter programs. (Note: In order for a measurement to be accepted, it must pass through the filter programs. This is not to say, however, that the measurement is an entirely correct one.) An end point measured out of correspondence with its track, or different events measured in

different views may pass through the filter programs. Even beyond all measurement errors, moreover, there remain events that fail because the interactions actually recorded on the film are not provided for in the analysis. Such events are in a sense perfectly good physics, but because they fall into unwanted categories in the experiment, they are classed as rejects. This class of events includes interactions of particles contaminating the incident beam track, event configurations that simulate other topologies and are misidentified, and all interactions not included in the list of hypotheses to be attempted in the analysis programs.

Thus, the checking of events and the correction of measurement errors through referral to the SMP operator need to be extended down through the chain of event analysis. A brute force method would be to "patch" the existing format checking, geometrical reconstruction, and kinematics programs onto the SMP program. The existing error branches of the programs would be modified to request corrective actions by the operator; but problems of time-sharing and computer utilization arise. The analysis programs are too bulky and generally too time consuming to coexist with the SMP program in today's computers. Furthermore since the SMP operator is, in general, not a trained physicist, there is no point in transmitting to him reject information which requires the interpretation of a physicist.

APPENDICES

A. THE BENCH MARK COVERING PROBLEM

As previously described, the circles of radius R about each bench mark are the loci of the digitization of points in the SMP image plane. The pattern of circles corresponds to the raster on a flying-spot device, which determines where information can be gathered. It is important that the "raster" of circles on the SMP cover the image plane as uniformly as possible.

If we assume a square grid of bench marks, the SMP raster pattern is a function of only one variable, namely:

$$\frac{\text{Radius of Circles}}{\text{Distance Between Bench Marks}} = \frac{R \text{ cm}}{1 \text{ cm}} = R$$

The patterns for different values of R are shown in Figure 12. The most obvious indications of poor values for R are the dense clusters of circles and large blank regions, or gaps, as in the pattern for $R = 2.10$.

A computer program has been written to investigate the uniformity of bench mark covering.^{1/} This program examines the rasters for different values of R, and searches for large gaps in which line segments fall without intersecting the raster pattern.

^{1/}Program written by Dr. W. Humphrey of L.R.L.

$R = 2.10$ cm.

$R = 2.406$ cm.

By using this program, for a bench mark spacing of 1 cm, values for R giving maximum uniformity of coverage were found to be 2.406, 3.48, and 4.39 cm. The value of $R = 2.406$ cm was then incorporated into the SMP periscopes. Although arbitrarily large values of R are theoretically possible, and would lead to a greater density of covering of the image plane, problems of periscope drum design and diverging light paths within the periscope limit the size of R . The value $R = 2.406$ produces a pattern of circles with an average of nine digitizing intersections per cm with a randomly oriented straight line.

B. THE SMP TRACK FILTER PROGRAM

In the SMP track filter program, an approximate fit to the track is made with a parabola. Each coordinate pair (X,Y) is transformed into new coordinates, which are the distance along the parabola Z and perpendicular to it ZZ . The transformation to new coordinates eliminates the problem of dealing with tracks of arbitrary orientation. At the same time, the parabola is "straightened out" in the new coordinates, so that the track lies nearly along the Z axis. Thus, a histogram in ZZ corresponds to a servo-centering slit aligned nearly along the track.

The points (Z,ZZ) are next ordered with respect to Z since Z represents the distance along the track. Each point receives a "tally" telling how well it corresponds to the coordinate

with its ten nearest points in Z. The tally is in the form of a histogram described above and is analogous to the strength of the signal received from the servo-centering slit as it passes over the point in question. The higher the tally, the greater the indication that the point is part of a curve in the Z direction.

The filter program then progresses along the track, starting either at a previously measured vertex or at the point with the highest tally. In a region of the track ahead, the program examines each point with a criterion involving both the tally for the point, and how well the point lines up with the projection of the track. The point best satisfying this criterion is selected as a stepping stone point, and the program essentially "looks" beyond it into the next region. When such stepping stone points have been found up and down the length of the track, they are all considered to be points exactly on the track.

The program then constructs a narrow band from each stepping stone to the next, and all the digitized points lying in these bands are taken as being on the track. The selected points are averaged in groups of ten in order to increase the accuracy and to produce the lesser number of output points. The points are averaged in the (Z,ZZ) coordinates, in which the track is nearly straight. Thus, there is no veritable error in finding the centroid, as there would be in finding

the centroid of the coordinates (X,Y). The (Z,ZZ) coordinates of the averaged points are then transformed back to (X,Y) for output.

In various stages of the calculations described above, tests are made to see whether the data exhibits certain standards of expected measurements. If the data falls into one of these tests, the track filter program returns to the SMP program (then to the operator) an error comment indicating the nature of the deficiency of the data.

GLOSSARY

APERTURE	An opening to the periscope through which the image portion passes in order to be swept over the bench-mark plate.
BENCH-MARK PLATE	A plate of glass coated with a photographic emulsion. There are accurately placed reference marks on the plate, over which the image portion passes in order to be digitized.
CARRIAGE	A set of runners on which the detecting head glides. (See DRUM below.)
COARSE COORDINATES	Pulses resulting from a movement of the X and/or Y curtain(s) are counted in the reversible X and Y scalers giving the approximate location of the detecting head. The readings from the scalers are the coordinates of the above location. (e.g. 06.320, 07.140)
CSX	An experimental digital computer built by the Coordinated Science Lab and used in the SMP systems at the University of Illinois.
CURTAINS	Mylar sheets that cover the scanning and measuring surface of the SMP.
DIGITIZATION	The process by which a point on the image plane is recorded.
DRUM	A rotating cylinder within the DETECTING HEAD with magnetic recordings. (Note: The words drum, periscope, and detecting head are sometimes used interchangeably.)
ECLIPSE	The crossing of a bench mark by a projected portion of the image.
IMAGE	<ol style="list-style-type: none">1) A projection of the filmed event onto the scanning surface of the SMP.2) A translation of a portion of this event through the aperture, through the periscope, and onto the bench-mark plate.

GLOSSARY (Cont.)

PICKET FENCE

A row of rectangular slits in both the X and Y curtains. There are two photodiodes and two bulbs mounted on either surface of the X and Y curtains; in this manner, a pulse is transmitted each time a slit in the picket fence passes over the photodiode.

ACKNOWLEDGEMENTS

Recognition should be given John H. Munson whose doctoral thesis provided the basis for this text. Since the time of publication of Dr. Munson's thesis, however, the Scanning, Measuring, and Projecting machines have undergone developmental changes. The primary function of this manual is to present these developmental changes as well as those aspects which are peculiar to the SMP system at the University of Illinois. With these factors in mind, the following paper should be regarded as an updating and an adaptation, rather than a complete revision of Dr. Munson's thesis.

C. Schaad

The University of Illinois SMP Setup

SMP Setup Showing the Operator's Position

Overall Layout of the Berkeley SMP

Close Up of the Berkeley Projector and Film Transport

Close Up of Argonne Projector and Film Transport

Brookhaven Projector and Film Transport