In the future this information may be inserted in a vertex fitting program such as GUTS, which is used at Yale and Berkeley.

The work on the data handling equipment has been done by: R.I. Louttit, T.W. Morris, D.C. Rahm, R. R. Rau, R. P. Shutt, A. M. Thorndike, and W. J. Willis.

DISCUSSION

PAL: Would it be in order to ask what was the price of one of these 18 machines you are getting commercially?

RAU: The cost is 47 000 dollars for an instrument with automatic track following.

MACHINE ANALYSIS OF BUBBLE CHAMBER PICTURES

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1. AREA ELEMENTS VERSUS LINE SEGMENTS IN PICTURE ANALYSIS

Many people have suggested that a modern digital computer should be able to recognize a fairly complex pattern of tracks in a bubble chamber photograph such as that shown in Fig. 1a (*). Concrete schemes for such recognition generally assume that information is available about the presence or absence of bubbles in area elements covering the pictures and of a size appropriate to the resolution of the chamber. However, rough investigation of the time to read such information into a computer and to conduct a search for linear correlations among bubbles has so far led to computing times of hours or days for the recognition of tracks in a single picture.

The situation is changed if a computer can be provided with numbers describing the positions and slopes of line elements making up the tracks. For one reason, the quantity of information which must be handled by the computer is reduced by at least an order of magnitude. For a second and more important reason, the slope of each line segment provides the computer with a good prediction of the location of the adjoining line segment and so reduces enormously the search time in recognizing a track.

It will be shown below that the tracks in one picture may be recognized in a time of the order of 1-2 s, and therefore a stereo pair of pictures may be analyzed in less than 5 s. It seems that an analysis time of this order of magnitude is a reasonable goal since it matches the cycle time of large accelerators.

2. DIVISION OF A PICTURE INTO "FRAMELETS"

In our proposed analysis scheme, a picture such as that of Fig. 1a is subdivided into several hundred rectangular areas which we name "framelets".

The height of a framelet is chosen small enough so that the portions of tracks within each framelet

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(*) We are indebted to the hydrogen bubble chamber group at Berkeley for the provision of this print and the negatives mentioned in Sec. 6.

Fig. 1a A typical hydrogen bubble chamber photograph (Berkeley) with 1.1 BeV/c negative pions incident, showing an associated production.

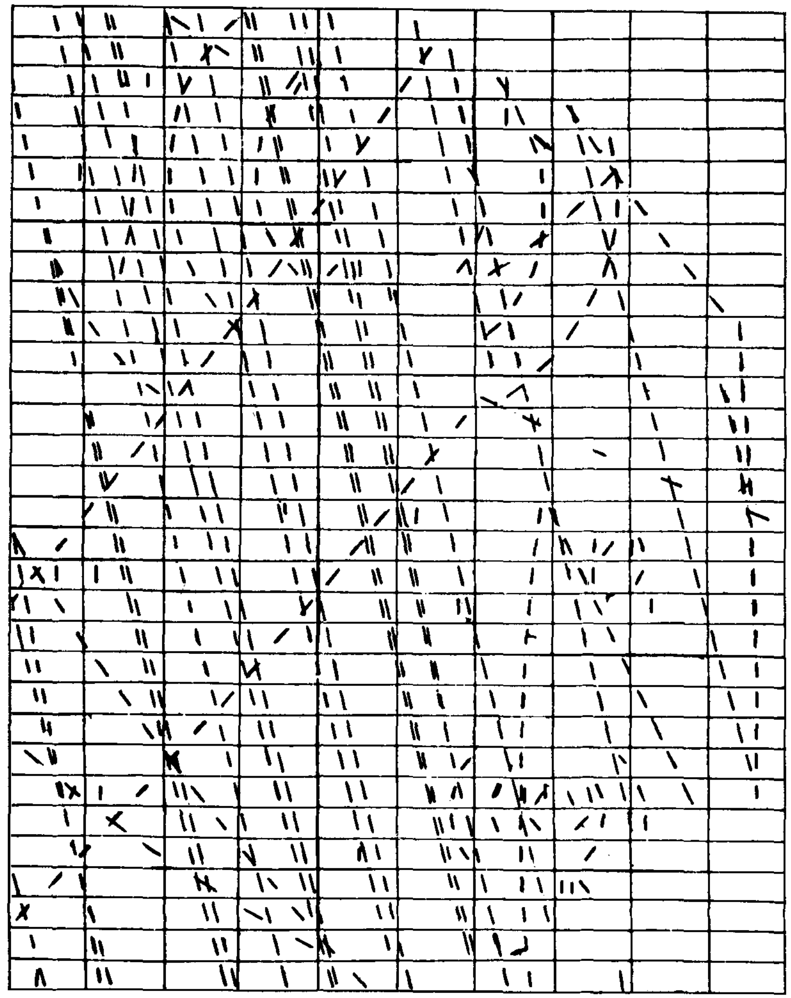

Fig. 1b A subdivision of the photograph of Fig. 1a into " framelets " for machine analysis.

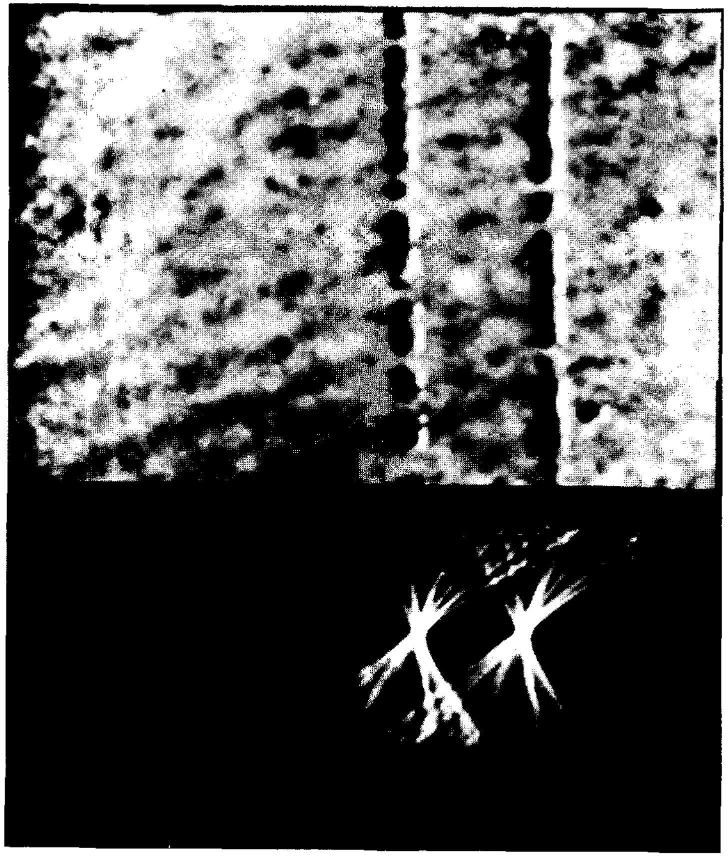

Fig. 2 A framelet giving a simple bubble pattern. The white pattern shows the portion of the bubble pattern detected by the electronics. The transform of the white pattern, drawn electronically, appears at the bottom.

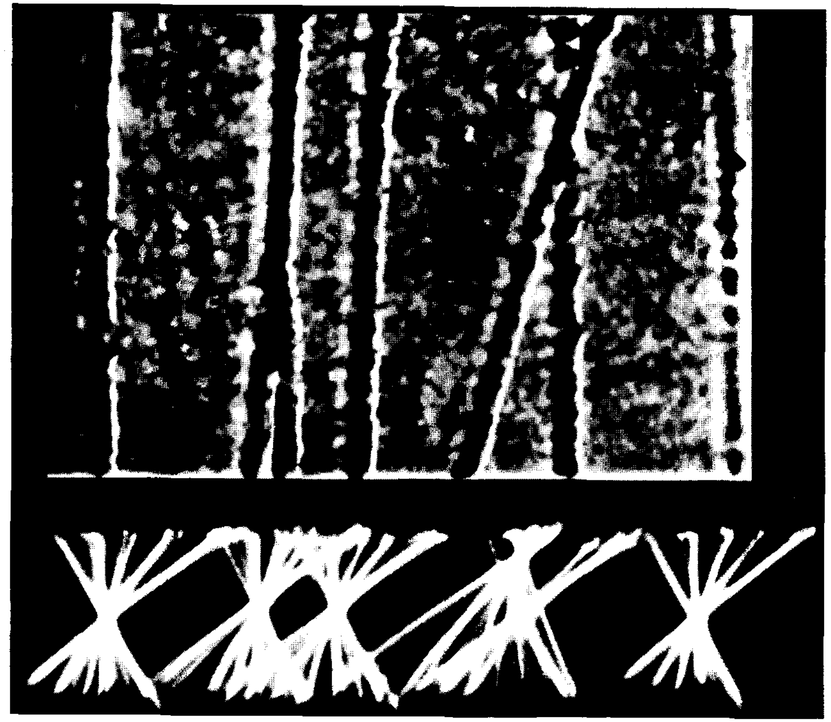

Fig. 3 A framelet giving a reasonably complex bubble pattern. The electronically-drawn transform appears at the bottom.

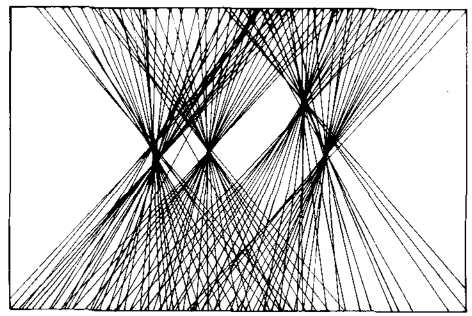

Fig. 4 A hand-drawn transform of the white pattern of Fig. 3. (The extreme right and extreme left tracks are not transformed.)

are essentially straight lines and large enough so that line segments can be distinguished reliably from the random bubble background.

A reasonable framelet subdivision of the picture of Fig. 1a is shown in Fig. 1b.

The width of a framelet is selected according to the accuracy needed in the measurement of the lateral position of the segments in the framelet. If the lateral position of the television scanning beam can be known via calibration to within 1% of its total span, then the framelet subdivision of Fig. 1b leads to an accuracy of lateral position determination of 0.1% of the width of the bubble chamber. A chamber of 20 cm lateral extent would therefore have track segment positions determined to within about 1/5 mm (in the chamber).

3. THE " PLANE TRANSFORM "

Framelets are presented successively to a television camera, probably in blocks of 4 each 1/60th s. Examples of framelets are shown in the upper parts of Fig. 2 and Fig. 3, as photographed from a television receiver connected to the television camera. The bubble pattern observed is in black; the accompanying pattern in white shows the portions of the bubble pattern detected by the electronics.

A " transform " of the white pattern of Fig. 3 appears in Fig. 4; it has been constructed by hand according to the following rules: for each white pulse in the framelet a line is drawn in the transform. (To avoid undue labour, the extreme right and extreme left tracks are not transformed.) The line is made to have an *intercept* with the horizontal midline in Fig. 4 equal to the horizontal co-ordinate of the white pulse in the framelet. The line is drawn with a *slope* relative to the vertical which is proportional to the vertical displacement of the white pulse from a horizontal midline in the framelet.

Now it is an exact theorem, easy to prove, that if a set of white pulses in a framelet lie on a straight line, the corresponding lines in the transform intersect in a point. This intersection point we call a " knot ".

The rectangular co-ordinates of a knot in the transform plane turn out to have this significance: the horizontal co-ordinate equals the horizontal co-ordinate in the framelet plane at which the line of white pulses intercepts the horizontal midline of the framelet. The vertical co-ordinate of the knot (relative to a horizontal midline) is proportional to the slope of the line of white pulses relative to the vertical. So the positions of knots in the transform plane give the slopes and intercepts of line segments in the original framelet.

In the recognition machine, transforms are drawn by a simple circuit on an oscilloscope screen while the television camera scans the framelet. The electronically-drawn transforms corresponding to the framelets of Figs. 2 and 3 appear at the bottom of these figures. Note that the hand transform of Fig. 4 uses the same information about which bubbles are detected as the electronic transform—i.e. both are transforms of the white pattern of Fig. 3. Therefore the imperfections in the electronic transform are only electronic " drafting errors " and it is believed they can be largely eliminated.

A much more important question is whether the knots of a good transform such as Fig. 4 can be reliably detected. A second image orthicon camera has been used in rather preliminary experiments which make it seem unlikely that the complex knot structure at the left of Fig. 4 can be detected instrumentally as two and only two knots.

4. AN ALTERNATIVE METHOD FOR LINE SEGMENT RECOGNITION

Although more prosaic than the plane transform, a rotating mirror, multiple slit, and photocell method for detection of the line segments may still be more useful. In initial trials track segments have been detected reliably but with insufficient angular accuracy.

In order to prevent classification of a track segment in more than one angular channel, it appears worthwhile to prepare multiple images of the framelet and present these images to the set of slits defining the various angular channels *simultaneously*. About 30 slits and 30 images are required to cover with sufficient resolution the band of angles from $-45°$ to $+45°$ relative to the vertical.

In this method, as well as in the plane transform method, each picture must be scanned twice at right angles.

Although the multiple slit method is mechanical, the scanning time for a picture is reduced over the plane-transform scanning time so that the computing operation of the next section constitutes the entire limitation in speed of analysis.

5. " ZIPPERING "—THE LINKING OF LINE SEGMENTS INTO TRACKS

We now suppose that by one of the methods of the two preceding sections the line segments in a picture are detected, and that numbers representing slope and intercept for the segments are recorded on magnetic tape. The time required for taping the whole picture is about 1 s by the plane transform method, and less than ½ s by the multiple slit method. An equal time is required for a second scan of the same picture at right angles to the first, leading to a total taping time of 1-2 s for each stereo view.

A small buffer storage is to be provided to group together on the magnetic tape the numbers from each framelet (or row of framelets). It has been found then (by actually writing a code) that an IBM-704 computer can be made to " zipper " together the track segments into tracks and provide at specified locations in its memory tables of track co-ordinates. The search operations which accomplish the zippering are carried out while the input magnetic tape is running, between transmissions into memory of the groups of numbers which specify the track segment information.

One feature of the code should perhaps be mentioned. Track segment numbers are stored in the machine at *addresses* in the fast memory which have one-to-one correspondence with *geometrical position* in the original bubble chamber photographs. An instruction to search for a continuation of a track is then easily given as an instruction to examine the contents of the fast memory in the neighbourhood of a certain address.

6. CURRENT EXPERIMENTAL PROGRAMME

Attempts to realize the instrument described above are proceeding at the beginning and end of the data-handling chain.

For the work at the end of the chain, slope and intercept numbers are measured by hand from a picture such as that of Fig. 1a. The zipper code can then be checked out using these numbers, and this checkout is in process. If the 704 zippers correctly and provides correct tables of track co-ordinates, the code will be extended in an effort to obtain recognition of complex events (such as the associated production event of Fig. 1a) as well as to measure particle momenta and production or scattering angles.

For the work at the beginning of the data chain, individual framelets from hydrogen bubble chamber negatives are being projected onto a television camera tube, the corresponding plane transforms are being constructed electronically, and the knot detection problem is under study. In a parallel operation, the detection of line segments by a multiple slit system is under investigation.

Acknowledgements

The zipper code has been constructed with skill and ingenuity by M.J. Smit. The co-operation of IBM and the General Motors Corporation in the computer work is gratefully acknowledged. D. E. Damouth and J. A. Koenig have found solutions to many problems of electronic, optical and mechanical design. The Michigan Memorial Phœnix Project and the U. S. Atomic Energy Commission have provided essential support.