Global Transformations in Pattern Recognition of Bubble Chamber Photographs

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Abstract—In this paper we present some new ideas on pattern recognition of bubble chamber photographs. We have found global transformations that reduce circular tracks to a point in a two-dimensional angle-curvature space. The performance of this tracking method on a sample of bubble chamber events is presented and planned improvements are discussed.

Index Terms—Angle-curvature space, bubble chamber photographs, clustering techniques, global tracking, image processing, orthogonal transformations, pattern recognition.

I. INTRODUCTION

BUBBLE chambers have been used since 1954 to study high-energy collisions. Millions of bubble chamber photographs are being produced and analyzed through various systems each year. Many systems are now performing well; however, one would like to further improve the speed and especially the efficiency with which bubble chamber events can be extracted from film. The ultimate goal is to implement a practical, full pattern recognition system.

We present some new ideas on pattern recognition of bubble chamber photographs. Global transformations are used on the raw data obtained by scanning the pictures with a CRT device. These transformations allow the extraction
of entire tracks at once from all the digitizations. This type of global approach was originally suggested a few years ago [1], [9]. We have found that there exist two “orthogonal” transformations that can be conjunctively applied to the raw data. This new approach is considerably more powerful and has been successfully tried on bubble chamber film.

This paper is divided into four sections: 1) a limited description of the hardware that is used to gather the data, a CRT scanner called PEPR; 2) the global transformations; 3) preliminary results obtained with our system; and 4) discussion of the improvements which are currently being contemplated.

II. PEPR Hardware

The PEPR hardware was proposed by Pless and Rosen- son at M.I.T. [2] and developed by Pless, Wadsworth, and others. It is a CRT scanner that uses a flying line segment to locate track elements. This hardware has been described in several publications and only the relevant details are reviewed in this paper. The reader is referred to other publications on this subject for a more complete description [3].

A schematic drawing of the PEPR system is shown in Fig. 1. A computer is attached on line to the hardware: in our case, a PDP-10 with a 48K memory. A 20-μ spot can be produced on the CRT at any one of 4096 x 4096 points. We define these as scan points. The distance between each scan point is 25 μ on the CRT (also called a main deflection count, MDC). Besides the spot, a line segment of various lengths (2, 1, 1/2, 1/4 mm) can be generated by means of a diquadrupole. The line segment can be oriented at any angle and swept either in the x or y direction from any one of the 4096 x 4096 scan points for a distance of either 200 μ or 2 mm.

The flying line segment is projected onto the film plane by means of a high-resolution lens with a 1:1 magnification. The light transmitted through the film is amplified by a photomultiplier. If a track happens to be on the film at the correct angle on a sweep, it will produce a characteristic pulse which is recognized by the track element detecting (TED) circuits. The output of the TED circuits gives position(s) of the track element(s) in a sweep. These data or “hits” are sent back to the computer that then decides where to scan next. There are two sweep speeds: a slow sweep that covers 200 μ and gives a 2-μ accuracy on the center of the track, and a fast sweep that covers 10 times as much distance (2 mm) and gives an accuracy of 20 μ.

Let us look in detail at the sweeping of a line segment of width D and length L across a slit of width W. The theoretical light output for various angles between the line segment and the slit are shown in Fig. 2(a). In actual practice what is seen by the photomultiplier of the PEPR hardware when scanning a bubble chamber track is shown in Fig. 2(b). In this figure, seven slow sweeps are shown and the angle of the line segment is being increased by 1° on each sweep; the sharpest pulse occurs when the line segment is tangent to the track.

The track element detector circuits operate as follows. If
at some time \( t \) the photomultiplier signal \( V(t) \) satisfies the following conditions,

\[
V(t - \Delta t) = V(t + \Delta t) \\
V(t) \geq 2V(t - \Delta t) \\
V(t) > V_{\text{threshold}}
\]

the pulse is taken as a hit. The time \( t \) gives the position of the center of the pulse. The parameter \( \Delta t \) is adjustable by means of delay lines and controls the maximum width of the pulse.

It should be obvious from Fig. 2(b) that the TED circuits will in general fire at several angles around the tangent angle and that some angle-averaging procedure is necessary. This is done by software and is fairly involved. It turns out that the angle is known with an accuracy of roughly 2°. Details on this part of the software and on the complex calibrations which have to be made will be found in [4].

In summary, we can determine both the \( x, y \) coordinate and the angle \( \phi \) of the track element. A triple \( x, y, \phi \) is called an element. The final accuracy on \( x, y \) is approximately 5 \( \mu \) and \( \phi \) is known to 2°.

III. GLOBAL TRANSFORMATIONS

Our approach to the software is called "vertex guidance" in high-energy physics: the film is prescanned for interesting events and the vertex point is measured and given as input to the program. These operations take place on a device called image plane digitizer (IPD).

As an example, look at the picture shown in Fig. 9. There are two six-prong events on the picture and the positions of both vertices will be given to the program. We assume for the purposes of discussion that the accuracy with which the vertex point is measured on the IPD machine is much better than a track width. This is not actually the case and we shall discuss in Section VI how we handle the real-life situation.

We define a cell scan: From any one of the 4096 \( \times \) 4096 scan points we scan at all angles, as shown on Fig. 3. Between -45° and 44° the line segment is swept along \( y \), and between 45° and 135° it is swept along \( x \). The cell scan will in general yield a certain number of track elements \( (x, y, \phi) \).

An area scan is a set of cell scans that cover the entire picture. The scan points of an area scan are in general separated by \( \sim 0.5 \) mm, implying an overlap of 50 percent.

To each element \( (x, y, \phi) \) found in the area scan, two transformations are applied. For each element one computes the potential curvature \( (\equiv \rho) \) and an angle \( (\equiv \psi) \), based on the vertex point and the \( (x, y, \phi) \) coordinate of the element. When the \( (\rho, \psi) \) values corresponding to each element are plotted on a two-dimensional scatter plot, circular tracks emanating from the vertex are reduced to a point cluster. Tracks that do not go through the vertex are spread as background over the scatter plot.

A. \( \psi \) transformations

The geometry of the \( \psi \) transformation is shown in Fig. 4. It is easy to see that, for all the elements (subscript \( n \)) belonging to a circular track (superscript \( i \)) emanating from the vertex \( V \) (and ignoring errors), the following relation holds:

\[
\psi_n = \delta_n + \phi_A = \psi^i_n, \tag{1}
\]

\( \delta_n \) is the difference between the angle of the chord from the vertex point to \( (x_n, y_n) \) and \( \phi_A \). \( \phi_A \) is the angle between the \( x \) axis and the chord, and \( \psi^i_n \) is the angle between the tangent to track \( i \) at the vertex point and the \( x \) axis.

The error on \( \psi_n \) is constant over the whole PEPR scope, except very near the vertex, and is approximately equal to 2°:

\[
\Delta\psi_n \approx \Delta\phi_n \approx \pm 2°. \tag{2}
\]

If we histogram all \( \psi_n \)'s for the area scan, circular tracks emanating from the vertex will show as pulses of width 2°, independent of the curvature of the track.

B. \( \rho \) transformations

In Fig. 5 we show a configuration where both tracks have the same tangent at the vertex point, and therefore will fall in a single \( \psi \) pulse. It is possible to separate them by taking
the elements belonging to the $\psi$ pulse and making a histogram of the curvature ($\rho_n$) for those elements. The curvature is computed by the following relation:

$$\rho_n = \frac{2 \sin \delta_n}{d_n}.$$  \hspace{1cm} (3)

The error on $\rho$ is not nearly as well behaved as the error on $\psi$:

$$\Delta \rho_n = \frac{2}{d_n} \cos \delta_n \Delta \delta_n.$$ \hspace{1cm} (4)

However, one notices that

$$\frac{d \rho}{d \psi} \approx \frac{2}{d} \frac{d}{d \psi} \sin (\psi - \phi_n) \approx \frac{2}{d}.$$ \hspace{1cm} (5)

Therefore, the errors on $\rho$ and $\psi$ are very strongly correlated, even though $\rho$ and $\psi$ themselves are "orthogonal" quantities. Consequently, it is better to histogram the quantity $\rho^*$

$$\rho_n^* = \rho_n + \frac{2}{d} (\bar{\psi} - \psi_n),$$ \hspace{1cm} (6)

where $\bar{\psi}$ is the average value of a $\psi$ pulse.

To make absolutely clear what is meant by these two transformations, we choose to show the results of the program on the $\gamma$ ray of Fig. 6. By $\gamma$-ray event we mean materialization of a photon into an electron and a positron in the field of a nucleus. The point is that the photon has no mass, and therefore the opening angle between the electron and the positron is zero. So in effect this event is analogous to Fig. 5. A coarse mesh area scan of the $\gamma$ ray is shown in Fig. 7(a) (scan points separated by 2 mm). The program is given the position of the $\gamma$-ray vertex and computes the $\rho$ and $\psi$ values for each element. A plot of these is shown in Fig. 7(b). The two concentrations of points correspond to the electron and the positron. One also notes the strong correlation between $\rho$ and $\psi$. A simple program can easily isolate these two concentrations and obtain whole tracks at once. The resulting tracks are shown in Fig. 7(c).

To isolate the concentrations, we project the scatter plot on the $\psi$ axis and obtain the histogram shown in Fig. 8(a).

The program recognizes the $\psi$ pulse and projects the elements in that pulse on the $\rho$ axis [Fig. 8(b)]. The pulse recognition algorithm is now applied to the $\rho$ histogram.

Finally, the elements in a $\rho$ pulse are processed through a circle-fitting routine that is capable of eliminating elements with large residuals.
IV. PERFORMANCE OF THE PROGRAM ON 91 EVENTS

We have applied this preliminary program to 91 randomly selected events in all three views. On 75 events either all tracks are found in all three views or possibly one track in a single one of the views is missing. Five events are classified as unrecoverable failures. Eleven events fail a track in more than one view, usually because the track is either very curved or very short, and we obtain no data. These events are classified as “recoverable” failures since these problems will be solved in the next version of the system, as we shall see in Section VI (see Table I).

The conclusion is that on this particular film, despite the above handicaps, an 82 percent operating level is attained. Including 50 percent of the recoverable failures raises the operating level for this type of film to 90 percent.

It is instructive to look in some detail at one of the recoverable failures. Let us look at the two six-prong events in Fig. 9. Applying our system to these two events yields the results shown in Fig. 10. Fig. 10(a) is a fine mesh area scan of the picture. Fig. 10(b) shows the tracks found on the right-hand event: all the tracks have been found plus the vertical arm of a fiducial that happens to point directly to the vertex. Fig. 10(c) shows the left-hand event that has two tracks missing: the very curved track has not registered, since we used the 2-mm line segment exclusively for these scans, and one of the five tracks going in the forward direction is incorrect. Looking at Fig. 9, one sees that a track belonging to the second vertex is exactly lined up with the first. Finally, most of the missing forward track has not been digitized.

The conclusion is that if the hardware digitizes properly, we see all the tracks, even on difficult events. Occasionally, extra tracks appear but not in all three views, and hence can be removed by the powerful three-view matching programs now in existence [5].

V. PLANNED IMPROVEMENTS

Improvements are being made in two areas. First, the angle resolution can be improved by a factor of 8 on 90 percent of the elements and by a factor of 4 on 100 percent of the elements. Second, a new approach to track segment and vertex location has been devised; even though the $\psi$ and $\rho$ transformations are still used, the new approach is radically different from what has been described up to now. The vertex position measured on the IPD machines is not accurate to better than three track widths; the new approach will work even if the vertex position is not known to better than 20 track widths. It is somewhat similar to the POLLY programs [6].

A. Angle Resolution Improvement

Having obtained an element $(\vec{A}, \vec{B}, \phi)$ with the standard cell scan routine, we sweep at equidistant points along a line passing through $\vec{A}, \vec{B}$, and making an angle $\phi$ with the x axis (see Fig. 11). The scan points $\{a_i, b_i\}$ are spaced a distance $\Delta$ along the line; $\Delta$ depends on the line segment used to sweep (see Fig. 11). We obtain data at points $\{a_i b_i\}$. A straight line is fitted through $\{a_i b_i\}$ and a better angle is
obtained. The number of extra angle resolution improvement steps is two, excluding
the point $A$, $B$.

If a single one of the sweeps does not register, we do not use the element since it is most likely that something is
wrong, i.e., crossing track, gap, etc.

A $\psi \rho$ scatter plot for a three-prong event with this new
cell scan routine is shown in Fig. 12(b) and with the old cell
scan in Fig. 12(a). The improvement is considerable and we
remind the reader that our results on the 91 events were
obtained with the old cell scan.

B. Track Segment and Vertex Location

We now discuss our strategy for events where the vertex
is poorly known. The error on the input vertex position is
assumed to be a maximum of 20 MDC (250 $\mu$ on film). The
first step is the data gathering. Using the input vertex as
center, an area scan is performed in the circular area of
radius 600 MDC (7.5 mm on film). The 1/4-mm line segment
is used to a radius of 250 MDC and the 1-mm line segment
is used in the annulus from about 300 to 600 MDC radius. It is
not necessary to perform the scan at all angles since the segment
length needed to determine curvature and center coordinates for road scanning of the track is inversely propor-
tional to the curvature. The angular range used at a given
position may be approximated in the following way (see
Fig. 13):

\[
(\phi_1, \phi_2) = (\phi_0 - \theta(d), \phi_0 + \theta(d)),
\]

\[
\phi_0 = \arctan \frac{x - x_v}{y - y_v},
\]

where $d$ is the distance between $(x_v, y_v)$ and $(x, y),

\[
\theta(d) = \theta_0 + \frac{k_1}{k_2 + d^2}.
\]

Suitable values for $(\theta_0, k_1, k_2)$ are $(10, 1.0 \times 10^6, 1.2 \times 10^4)$.

The 1/4-mm line segment is used in the area where high-
curvature tracks would be seen. The data gathering is per-
formed in a sequence that orders the located elements by
decreasing (or increasing) distance from the given vertex
position. Local inversions of that order can occur, but are
irrelevant since local order is rapidly achieved for elements
on the same track. This is important for later processing.

The next step is to group the elements into track segments.

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Fig. 11. Sweep positions for angle resolution improvement.

Fig. 12. Effect of the angle resolution improvement
on the $\psi \rho$ scatter plot.

Fig. 13. Limits on the scan angle range.
This is accomplished by taking the most distant element from the vertex and using its position and angle to perform the $\psi$-$\rho$-circle fit sequence on the remaining elements in the bank. This will either unambiguously yield a track segment or cause a removal of that element from further consideration. Then take the next most distant unused element from the bank and perform the same transformations. Do this until the element bank is exhausted.

Any segment outside of the expected error range of the vertex position is removed from further consideration. The removal of elements that fail to yield an unambiguous segment can occur only for elements whose angle is incorrect. These elements usually result from an occasional false element at small angle crossings. To be recognized, a segment should have a minimum of four elements within the expected dispersion on $\psi$, $\rho$ and circle-fit transformations. With the angle accuracy now obtainable with the cell scan routine, the only reason for missing a track should be the lack of digitizations that result for very short tracks and stubs and for tracks not resolvable by the detection circuits because they lie close to and parallel to another track.

Following segment location, the position and tangent angle of each fitted segment at the point of the arc closest to the given vertex position are calculated. These are used pairwise to obtain intersection points when the tangent angles differ by 10° or more. A point cluster will occur at the real vertex position and can be easily distinguished from background intersections. Only rarely, less than 1 percent of the time, can a background and event topology yield a second point cluster that will cause an incorrect determination of the vertex position. The real vertex position is calculated as an average of the coordinates in the cluster. Since the error range of the vertex is now considerably reduced, remaining background can now be removed except when it passes close enough to nearly overlay the vertex. Some of the overlaying background can be removed since the number of tracks for the event is known; hence an excess can be detected. The existence of an overlaying track is part of the input data; hence it is known when to expect such a case.

Failure to determine the vertex position occurs on less than 5 percent of the events and its occurrence is almost always an indication that the event is not digitizing well enough to determine track segments. This usually means that the film plane is out of focus or the operational level of the scanner is marginal or the film contrast is very poor. The only other reason for failure would be an input vertex position outside of the expected range of a detected cluster and is easily distinguishable from a lack of digitizations. The discussion on vertex determination applies to events with more than two outgoing tracks, since frequently, for two prongs, a cluster does not result or is not unambiguously distinguishable from background. The maximum number of intersections expected in the cluster is given by

$$\frac{n(n - 1)}{2}$$

where $n$ is the number of tracks emanating from the vertex.

VI. CONCLUSIONS

Some work remains to be done in order to bring this system to its full capability. We feel that this approach has great potential because of its global character. When following tracks locally, one is always plagued with gaps caused either by poor contrast on some area of the frame or by crossing tracks at narrow angles that confuse the hardware. The global approach essentially eliminates this problem provided the tracks are circles. This is an excellent approximation to real life, especially at very high energies where most of the research in the field is currently being done.

Another interesting development in bubble chamber physics is the new trend towards hybrid systems [7], [8]. Counters are used to ensure that interesting interactions have occurred in the chamber before a picture is taken. One is therefore guaranteed an event on every picture and full pattern recognition becomes economically feasible by following beam tracks until they interact. Our software is very easily adaptable to this sort of film and we are planning to analyze some in the near future.

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