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TRIDENT: A Track and Vertex Identification Program
for the CERN Omega Particle Detector System

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I. INTRODUCTION

Since its very first configuration in 1971-1972 with a system of optical chambers operated inside a magnetic field and a read-out of two sets of plumbicon cameras, the CERN Omega Particle Detector System has continuously evolved and is now fully equipped with a system of drift and multi-wire proportional chambers⁽¹⁾. This evolution was done in very close contact between the hardware and software personnel so that the present system of chambers derives from the results of many studies to tackle at best both the hardware and software requirements. As Omega is conceived as a facility for many physicists to run different experiments the detector must be able to record events with various topologies characterized by primary and secondary vertices, high track multiplicity and an almost 4π angular coverage. This leads to a relatively high density of chambers arranged in such a way so as to satisfy the pattern recognition requirements as schematized in Fig.1.

Consequently a new computer program - TRIDENT - aiming at the full reconstruction of events, namely, track recognition, momentum evaluation and vertex fit has been implemented. Track recognition will be the subject of this paper. It is based on a three dimensional track following technique making use of the Principal Components Analysis.

II. CHOICE OF THE DETECTOR: The three dimensional approach

The experience gained with the optical chambers⁽²⁾ invoked the interest to work in space (three dimensions) rather than in projections (two dimensions), simply because a particle trajectory is a three dimensional object, which can be tackled much more efficiently if all the information is globally treated, rather than divided in several portions. This is particularly true for high track multiplicity events where the density of information is rather high in the target region. Consequently, an ideal detector would be a device delivering space points, or even better, space points and directions. Such detectors exist - at least as far as space points are concerned - but their performance is limited and their cost is prohibitive. Since this solution cannot be achieved other approaches were investigated in order to perform track recognition in space.

The first one is widely used in many detectors. It consists of grouping several planes with wires at different inclinations. Then the space points are found by combination of the coordinates in the different planes, keeping only those which are compatible. This process is not free from ambiguities so that wrong points are added to the correct ones. Conversely, correct points are missed if a plane (or more) is inefficient. Therefore, several planes are necessary, firstly, to increase the number of constraints in order to eliminate the wrong combinations, secondly, to tackle the possible chamber inefficiencies. This necessitates the construction of thick chambers giving only one set of information (point and direction) over a typical length of 15-20cm. This is unacceptable in the target region where the density of information must be as high as possible, but quite suitable in the lever arm region where a few accurate chambers are required to detect the high momentum particles. This led to the adoption of a lever arm outside the magnetic field of two drift chambers with 4 planes each, YUVY', where Y are the vertical wires, U and V the inclined wires at $\pm 10.14^\circ$ to the vertical and Y' the vertical wires staggered by half the wire spacing (5cm). The choice of 4 planes appeared to be quite adequate to compute an accurate line element (point and direction) and also sufficient to resolve the many combinations due to the right-left ambiguity⁽³⁾.

Instead of being represented by a collection of space points as illustrated in Fig. 2a a track can be defined as a collection of individual measurements in different planes as represented in Fig. 2b. This representation is well adapted to multi-dimensional analysis techniques as described further. The planes with wires at different angles are grouped in order to supply spatial information and, if possible, a constraint to remove the wrong collections. Thus the lever arm chambers can be regarded indifferently as a Y,Z object in a Cartesian system or as a Y, U, V, Y' object. Chambers with 3 planes each, say U, Y, V (Fig. 3), are still adequate. Such chambers were chosen in the forward region, but are still too thick in the target region where an alternating sequence of U, Y chambers and V, Y chambers was chosen. Such chambers are close enough together to provide a high density of information. In addition, a sequence of two consecutive chambers (U, Y), (V, Y) can be treated as a unique chamber (U, Y, V, Y) having the same properties as the two previous systems.

It should be noted that all these types of chambers have a Y-plane. This is because these planes measure the bending, and the momentum of a track is more accurately measured if the number of such planes is high. Also it is a requirement for the track finding algorithms that all the chambers be characterized by a common projection.

The complete today set-up of the detector is represented in Fig. 4. It consists of 20 C-chambers with 2 planes each (U, Y and V, Y) on both sides of the target, 6 B-chambers with 2 planes each (U, Y and V, Y) downstream of the target, followed by 6 A-chambers with 3 planes each (UYV). All these chambers are operated inside a magnetic field of around 18 Kgauss. Finally 2 drift chambers with 4 planes each (YUVY) constitute the lever arm of Omega in the fringe field region.

III. TRACK FINDING: The three dimensional approach

The track recognition is based on a three dimensional track following technique. Although well known, let us recall the principles of this method. Basically, it consists of two operations:

- i) research of small collections of points representative of pieces of tracks in space by investigation of a few chambers (usually three or four)
- ii) expansion of these "preliminary tracks" in a neighbouring chamber and addition of new points.

Repeat i) and ii) until all the chambers have been investigated.

Other characteristics of the method are:

- This is a spatial process. Ambiguities between tracks can be resolved much more efficiently in space than in projections.
- This is a parallel process. All the tracks are found simultaneously which allows the tracks which intersect in space or in projections to be dealt with.
- Because of ii) above and the choice of a parameterized model as discussed further on, the method is well adapted to the situation where a large number of chambers are traversed.

- The method is not influenced very much by the background and the chamber inefficiencies.

We now describe in more detail the two fundamental operations.

The first operation is dominated by the combinatorial aspect which in a multi-chamber, multi-track environment is of the highest importance. It is advisable to initiate this process at the far end of the detector where the tracks are usually well separated by the magnetic bending. In this manner the high momentum tracks are found first. Then the process is dynamically applied to the other chambers to find the other tracks.

The second operation involves the choice of a model to expand a track in a neighbouring chamber. Such a model is also necessary to recognise the genuine combinations of coordinates from the wrong ones.

Since in Omega the main component of the magnetic field is perpendicular to the direction of the incoming particles, then the trajectories have a helical shape represented by an arc of circle in the x, y plane (normal to the main component of the magnetic field) and an arc of sinusoid in the x, z plane (parallel to the field). In most of the cases this latter curve can be replaced by a straight line for not too low momentum particles emitted at a small angle. In reality this representation is exact as long as the magnetic field is uniform. This is true at the centre of the magnet but on the edges of the forward chambers and in the chambers surrounding the target the magnetic field varies from 18 Kgauss to 14 Kgauss introducing a large variation in the curvature of a track.

The helical model although locally exact is difficult and computer time consuming and has led to the study of a simple model to compute the predictions.

Let a track be defined by N measurements at different projections. We can consider each measurement as a coordinate in a N -dimensional space so that a track is represented by a point in this space. Since a particle trajectory is completely defined by five parameters there exists a five-dimensional subspace in which all tracks have to lie. Feature selection techniques based

on the method of principal components analysis⁽⁵⁾ are a suitable tool to re-express by a linear transformation the original set of coordinates into a set of 5 significant variables and n-5 non-significant variables.

Expanding the new variables - w_j - as functions of the original ones - v_j - we have:

$$w_j = \sum_{i=1}^n a_{ij} \cdot v_i \quad j = 1, n$$

For the non-significant variables we can write:

$$w_j = \sum_{i=1}^n a_{ij} \cdot v_i = 0$$

and for a given j:

$$a_1 \cdot v_1 + a_2 \cdot v_2 + \dots + a_n \cdot v_n = 0$$

Thus any coordinate can be regarded as a linear function of the n - 1 other ones as for example:

$$v_n = -\frac{1}{a_n} (a_1 \cdot v_1 + a_2 \cdot v_2 + \dots + a_{n-1} \cdot v_{n-1})$$

This means that if we know n - 1 measurements on a track we can predict with a linear model where this track should be on any other chamber. In practice the coefficients are computed by a least-squares method on a sample of tracks.

Fig. 5 illustrates the effectiveness of this method. A track defined by nine measurements in three chambers spread over 90cm has been extrapolated to a fourth chamber at 30cm. The r.m.s. of the distribution is 0.1mm compared to 0.2mm for the wire spacing.

4. TRACK FINDING: implementation

The track finding in Omega consists of the following operations:

- 1) Track finding in the two lever arm chambers
- 2) Extrapolation of these tracks in the last three or four forward chambers
- 3) Track following in the forward chambers.

The lever arm tracks are treated exactly as the forward tracks.

- 4) Track following in the target chambers.

4.1 Track finding in the lever arm chambers

4.1.1 Space points approach

The digitizings in the four planes of each chamber are combined so as to construct track elements (positions and directions). They must satisfy prescribed slopes in x, y and x, z and also the constraint relation:

$$2y \cos \alpha - u - v = 0.$$

Then the track elements are linked. Each straight line must have a slope in agreement with the local slopes. In addition the tracks must point to the target in the x, z projection.

This method may fail as the space point reconstruction does not tolerate any chamber inefficiency.

4.1.2 Global approach

The second technique deals with both chambers at a time, i.e. eight planes. First the 'Y' planes are combined to make strings of 4 or 3 measurements. Then using the constraint relation between u, y and v the u and v coordinates are investigated so as to construct with the y coordinates a straight line in space. Allowance is made for at most two missing coordinates out of eight. About 30% of the tracks are found in this way.

4.2 Extrapolation of the lever arm tracks in the forward chambers

The tracks found in the lever arm chambers are then extrapolated in the last three or four forward chambers. In fact it would be more correct to say 'interpolated' as the centre of the target is used with the lever arm to define a cubic spline in the x, y projection and a straight line in the x, z projection. This simple model was found quite adequate although the tracks travel from a no field region to a full field region. The next operation consists of assigning the digitizings to the predictions within the errors. This operation is quite similar to the creation of 'preliminary tracks' as described below. Once assigned, the digitizings are marked in order not to be re-used on other tracks.

4.3 Track following in the forward chambers

As already said the track following process consists in finding pieces of tracks - called preliminary tracks - by combination of a few chambers. Then the positions of where these tracks should be in the next chamber are computed and the digitizings assigned accordingly. In practice the two steps of this process are performed at each chamber in this order:

- extrapolation of tracks, association of digitizings which are then marked. This process is activated as soon as preliminary tracks are found.
- creation of new tracks with the non-associated digitizings if any.

This process is initiated in the last forward chambers; then the chambers are investigated one at a time in the direction of the target.

Let us now examine the mechanism of these operations.

4.3.1 Creation of tracks

This three dimensional process decomposes itself into two operations.

First the digitizings in the Y-planes of three or four chambers are combined so as to define arcs of circle. Cuts on slope of segments and curvature are applied. Allowance is made for one missing coordinate in a combination of four chambers. The target can be used as a constraint, but this is not a requirement. Then the candidates in the Y-planes are completed in space. For each chamber and a given y the u, v combinations compatible with y ($2y \cos \alpha - u - v = 0$) are looked for, allowing z and z' ($2z \sin \alpha = v - u$) to be derived. Only the u, v combinations giving rise to z 's on a straight line are kept. Here also allowance is made for missing coordinates. In a general way any missing coordinate is derived from the found ones by a helical or a parametrized prediction so that a track is always represented by a continuous string of u, y, v measurements.

On completion of this operation, it happens that some tracks have the same digitizings in common; these ambiguities will be resolved in the course of track following.

4.3.2 Extrapolation

This process consists of the following operations:

- a) Extrapolation in the planes of the next chambers with the parametrized models already described. The coordinates in the last three or four chambers only are used. In certain circumstances a helical model is used instead.
- b) Detection of track overlaps. Tracks at a distance less than the two track resolution of the chambers require a special treatment.
- c) Digitizings are then assigned and marked in order not to be re-used. Multiple associations are resolved in space and missing coordinate(s), if any, replaced by prediction(s).
- d) Ambiguous "preliminary tracks" are resolved here.
- d) Track parameters are updated. Tracks which do not acquire digitizings over a few consecutive chambers are no longer followed. This is the case for the branches of a V - zero.

This process is then repeated until all the chambers have been treated. As can be seen very little combinatorial operations are required and simple arithmetic is involved.

4.4 Target Chambers

The track finding in these chambers is exactly as in the forward chambers; only the cuts relevant to low momentum tracks are different. For the program there is no discontinuity between target and forward regions with tracks simply going to the right or to the left of the target so that a track is found as a unique collection of measurements.

5. RESULTS

TRIDENT has now been used by several experimental groups with different set-ups and various event topologies. (Experiments WA49, WA56, WA57, WA58, WA60⁽⁷⁾). Fig. 6 represents an event which is by no means a "typical event",

but a good example of the versatility of both the detector and the program to deal with low and high momentum tracks. The track finding results - efficiency and computer execution time - depend on experimental conditions like beam intensity, track multiplicity, chamber inefficiencies, background, etc. etc... On the basis of the data so far processed we can say the following: the track finding efficiency does not depend very much on the above conditions as long as the detector efficiency is not below 90%. The efficiency ranges between 100% and 98% for events with 4-5 prongs and decreases very slowly as the multiplicity increases. On the contrary, the execution time is more sensitive to these conditions. The higher the background and chamber inefficiencies the more the program must cope with difficulties and spend time to resolve them. Figs. 7a and 7b show the dependency of the computer time on the number of digitizings and tracks respectively. While the time varies almost linearly with the number of tracks it varies more rapidly with the number of digitizings. Let us note that these results could be very much improved by tuning the cuts for each individual experiment which is not the case at the present time.

Although devised for the Omega detector TRIDENT is much more general in its principle and its implementation. A reduced version has been used as a fast off-line analysis program by the Omega WA4 collaboration with a set up of two drift chambers, one proportional chamber with three planes, and three proportional chambers with two planes. Presently it is being used by the CERN WA1 collaboration with a set up of MWPCs operated within the Goliath magnet. It will be used soon by the CERN NA14 collaboration on a set up of MWPCs operated inside and outside two magnets.

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Figure Captions

- Fig. 1: Requirements for the Omega Particle Detector: detection of low and high momentum particles.
- Fig. 2a: Representation of a track as a collection of space points.
- Fig. 2b: Representation of a track as a collection of individual measurements
- Fig. 3: Schematic layout of a UYV chamber.
- Fig. 4: Full set-up of MWPCs.
- Fig. 5: Distribution of the quantity: true position-predicted position of a track in a chamber.
- Fig. 6: Event reconstructed by TRIDENT.
- Fig. 7a: Plot of execution time versus no. of digitizings.
- Fig. 7b: Plot of execution time versus no. of tracks.

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Fig. 1: Requirement for the Omega Particle detector:
detection of low momentum and high momentum particles

Fig. 2a: Representation of a track as a collection of space points

Fig. 2b: Representation of a track as a collection of individual measurements

Fig. 3: Schematic lay-out of a UYV chamber. Relations between the projections.

Fig. 4: Full set-up of MWPC. Y-planes: vertical wires
u/v-planes inclined wired ($\pm 10.14^\circ$)

TRUE TRACK POSITION - PREDICTED POSITION

Fig. 5

EVENT 27176 RUN 1069
DIGITISINGS + TRACKS AFTER TRACK FINDING

Fig. 6