SySal: System of Salerno*

S. Amendola, E. Barbuto, C. Bozza, C. D’Apolito, A. Di Bartolomeo, M. Funaro, G. Grella, G. Iovane, P. Pelosi and G. Romano.

University of Salerno and INFN, Salerno, Italy

March 25, 2022

Abstract

SySal (SYstem of SALerno) is the automatic scanning system developed in the emulsion laboratory of Salerno to take part in the emulsion scanning phase of the CHORUS experiment at CERN. In the following chapters we will present features, results and further developments of this automatic multi-tracking system.

1 Introduction

Since the early stages of high-energy physics, the detection of sub-atomic particles and the study of their trajectories were often based on visual techniques. The "nuclear emulsion technique" is a typical example: charged particles crossing emulsion pellicles form a latent image as a trail of sensitised silver bromide microcrystals. After development a three dimensional "track" can be studied under high magnification by means of an optical microscope.

Initially, human observers operated manually the microscope by moving the stage, adjusting the focal plane of the objective, and examining a magnified image through eyepieces. Later, the stage was motorised and the image

*Presented in The First International Workshop of Nuclear Emulsion Techniques (12-14 June 1998, Nagoya, Japan), http://flab.phys.nagoya-u.ac.jp/workshop.
made available also on a TV screen; often the stage control and the image analysis performed by the operator were assisted by a host computer, thus configuring the so-called semi-automatic systems.

Ideally, the last step in this chain is to let the computer do the image analysis usually performed by the operator to implement the instruments into fully automatic systems.

SySal (SYstem of SALerno) \[1\] is the automatic scanning system developed in the emulsion laboratory of Salerno to take part in the emulsion scanning phase of the CHORUS experiment at CERN. In the following chapters we will present features, results and further developments of this automatic multi-tracking system.

2 SySal: A Multi-Tracking Scanning System

2.1 Hardware

The hardware configuration of the system currently at work in Salerno includes:

- Nikon microscope with 40 × 40 cm² stage, with 37 cm stroke on both horizontal directions, motor driven axes, 1 μm horizontal position accuracy, 0.5 μm vertical position accuracy;

- High-resolution (1024×1024 pixels) custom made CCD camera, capable of 30 frames per second at full resolution, and 60 frames per second in 512 × 1024 mode (not used), with a minimum gate time of 0.9 ms;

- Custom made stage controller with 3 PID filters for the 3 axes;

- Custom made lamp controller;

- Matrox Pulsar frame grabber card, with 4 Mb on-board;

- PC Pentium MMX 233 MHz with 64 Mb RAM on-board, 4 Gb HDD;

- Auxiliary monitor to see the image coming from the camera to the frame grabber.
2.2 The SYSAL Multi-Tracking Method

The inspiring idea of SySal is very simple at first glance: basically, the computer is asked to reproduce the human process of track recognition presented in the introduction. The aim is recognizing tracks studying the alignment of their grains through the emulsion layer.

Bearing this in mind one can use a computer to look at the emulsion at different depths (usually 50 levels for 350 $\mu$m thick emulsions) and get tomographic images of all the tracks. These images must then be assembled together for the real pattern recognition to take place. Once all the tracks are reconstructed all the measurements are then easily obtained.

The figure 1 fixes the main steps of the analysis process.

![Figure 1: Analysis Process](image)

It is clear that, at the end of this process, the multi-tracking system allows to get the whole physical information available (tracks, kinks and vertices).

The scanning process must be smart enough to deal with ambiguous situations and damaged information (this could come from zones with scratches or dirt on the emulsion surfaces, and from inhomogeneous physical characteristics of the plates); the main aim of an automatic system is, however, to do fast its task, and this has not been forgotten. Most code has thus been
written in C++. When required, Assembler has also been used.

2.2.1 Image Handling

The starting point is, of course, the image coming from the camera. The analog signal is digitized by the Pulsar, and converted to a gray scale of 256 levels (0 = black, 255 = white). The Pulsar stores the data while they come into a 1 Mb internal linear buffer; however, this cannot be accessed while it’s receiving data. The double-buffering technique helps for the need to have maximum speed: one 1 Mb buffer holds an image, making it available to the CPU for analysis, while another buffer grabs the new image.

The CPU is in charge of recognizing black spots (called ”clusters”) in the image: some of these are track grains in the emulsion; most clusters are spurious grains, carrying no information, but physically existing in the emulsion (they are called ”fog” grains), due to the developing process; some clusters come from noise in the electronic signal. Often the image of the emulsion is not very clear due to shadows caused by grains that are not in the focus plane or to scratches and dirt. Solving this problem is possible using a simple FIR (Finite Impulse Response) filter. The result is shown in figure 2.

![Image of the emulsion before and after the FIR filter application](image.png)

Figure 2: On the left the image coming from the camera, on the right the FIR filter is applied: wide black spots coming from electrons are resolved.
Basically, a well chosen threshold is used to look at the image, so to divide the pixels in two classes: the ones with gray level above the threshold (they are "white" pixels), and the ones with gray level below the threshold (they are "black" pixels). The image stored in the buffer, however, is not actually modified. The classification phase scans the image row by row, from left to right. Each sequence of black pixels found is called a "segment" and stored in memory. The segment finding process is the most time-consuming, because it has to deal with a huge amount of data. This led to write it in Assembler. After a row has been scanned, the new segments are compared with the segments in the previous row; adjacent segments are merged into a "cluster", an entity that has essentially an area and a center. If two or more clusters come into contact, they are merged.

Figure 3: The image is turned into black segments that are then assembled into clusters.

### 2.2.2 Track Recognition

After all clusters have been formed, they are divided in three classes. Small clusters are discarded (they mostly come from noise in the camera signal); large clusters (sometimes called "blobs") are discarded too: they are usually surface defects of the emulsion, or grains of heavy nuclear fragments, usually with little energy, not so interesting for the kinematical reconstruction of the interactions. Medium size grains survive, and are used to recognize tracks left from high energy particles. These should be straight; indeed, they are quite
The tracking method is designed to reduce the computing time: to quote a relevant number to understand the kind of work the CPU has to do, it can just be said that, typically, for each of the 50 layers, one can find 500 grains out of 900 clusters, and all of them are, in principle, grains that may belong to a track.

Figure 4: The tracking procedure.

Each layer is divided in "cells", about $10 \times 10 \, \mu m^2$ wide; then, one looks for alignment of grains in 3 adjacent layers, within cells stacked one on top of the other. This phase is called "track startup": when such an alignment is found, the computer looks for more aligned grains in the next layers, up and down the startup point. During this "track following" phase, the tracking algorithm is also allowed to change the cell stack. After a new grain is
appended, the current slope of the track is recomputed; this makes it harder to miss next grains, because track distortion is automatically accounted for. It may happen that, for some reason, on one layer no grain is found belonging to the track being followed. If this repeats for 5 adjacent layers, the track following phase ends.

While a track is being built, it may cross some already existing track. In this case, if the tracks share three consecutive grains, they are joined together in a single entity.

When a track stops both in the upward and downward directions, the number of points collected is compared with a minimum threshold (usually 12 points), required to store the track in the final array.

**Figure 5: Track corrections.**

### 2.2.3 Track Postprocessing

After all the tracks in a field have been recognized (that’s why we refer to SySal as a multi-tracking system), the next step is to assign each of them some global parameters, such as a slope and an intercept, obtained from a linear fit. Of course, this cannot be done with distorted tracks. So, the tracks that pass the whole thickness of the emulsion layer are used to estimate the distortion vector, which is then used to correct the positions of the grains of all the tracks in the current field. This correction relies on the assumption
that the slope at the exit point is the original one. Sometimes this is not exactly true, and gives rise to some systematic deviation of the computed slopes from the real values. However, this kind of measurement error is not unrecoverable, and also an off-line correction is possible.

Emulsions shrink during the developing process. So, when they are scanned, the thickness is only 50% of the original one. The reconstructed tracks are thus finally "expanded".

The process described above is repeated for each of the two sides of the emulsion. Then, for each track on the upper side, a pairing track on the bottom side is searched, with the same angle and position (within proper tolerances, typically 5 µm and 20 mrad). When this process is finished all the tracks in the scanning field are reconstructed without any selection in slope so that the whole information present in the emulsion is stored and available for the analysis.

2.3 Brief outlook of SySal measurements in the CHORUS experiment

![Figure 6: Side view of the CHORUS detector.](image)

Chorus (Cern Hybrid Oscillation Research apparatus) is a short base-
line neutrino experiment. Its detector is installed in the West Area of the CERN. It is composed of a bulk emulsion target (four stacks of 36 sheets of emulsion) interfaced through some emulsion sheets (called special and changeable sheets) to the electronic tracking part of the detector (scintillating fibers). After these devices a magnetic spectrometer, a calorimeter and a muonic detector follow (fig. 6).

Scintillating fibers provide a prediction for every event that is therefore followed back in the interface emulsion sheets. Then, using measurements in these emulsion sheets as a new prediction, the tracks are followed back in the target stack.

In the following some distributions of differences between predicted and found coordinates (fig. 7, 8 and 9) and predicted and found slopes (fig. 10, 11 and 12) are presented for every kind of emulsion sheet used in the CHORUS experiment.

Figure 7: Differences of predicted and found y (left) and z (right) coordinates in changeable sheet.
Figure 8: Differences of predicted and found y (left) and z (right) coordinates in special sheet.

Figure 9: Differences of predicted and found y (left) and z (right) coordinates in bulk sheet.
Figure 10: Differences of predicted and found y (left) and z (right) slopes in changeable sheet.

Figure 11: Differences of predicted and found y (left) and z (right) slopes in special sheet.
3 Features and benefits of a Multi-Tracking System

3.1 The Multi-Tracking System

As it turns out from the latter discussion, SySal is a multi-tracking system. This means that during the scanning the system pays attention to all the tracks in the field. Because of this, some important features are stressed.

Reconstructing all the tracks rather than the single scanback track allows the complete identification of an interaction vertex and of decay topologies. Of course the physically interesting phenomenon is contained in the interactions. If the particle momentum and energy are known, from the geometrical parameters of a track before and after a kink one can get information on the decaying particle. Using the kinematical data of the daughter particles, and geometrical/topological knowledge of a vertex, the complete kinematical reconstruction and the whole on-line study of an interaction is therefore possible. The SySal approach is indeed the first automatic scanning method that has been specifically designed for the task of recognizing and reconstructing complete topologies.

Moreover, the local mapping of tracks near the scanback track can help for
the identification of the latter in another sheet of emulsion and can provide information to improve the precision of angle measurement.

This is not all: mapping of wide zones of the emulsion is possible without any further complication and can be successfully used for the intercalibration of two sheets of emulsion. It follows that flux measurements are very easy to perform. All these benefits are strictly connected with the choice of a multi-tracking system.

Figure 14: Benefits of a Multi-Tracking System.

1. Reconstruction of Interaction Vertex
2. Complete on line Study of Event
3. Recognition of decay topologies
4. Mapping for intercalibration
5. Flux of particles
3.1.1 Study of two interesting events

As a sample of the features of a multi-tracking system, two interesting events of the CHORUS experiment are presented. The good ability of SySal in detecting kinks and in following back the tracks are stressed. Together with this two requirements SySal satisfies the need for an on-line complete study of the event.

The first interaction (Fig.15; Event 1339/380) was produced in the 1994 run of the CHORUS experiment at CERN.

![Diagram of Event 1339/380]

Figure 15: Neutrino interaction shown in a 3D reconstruction by computer.

In this case, the interaction point was in the plastic base, 80 μm upstream of the nearest ends of the tracks in the emulsion; so the tracks were extrapolated, and their extrapolations were found to cross.

In the following table we show the comparison between the prediction and the real event, as found in the emulsion; angles are measured with respect to the detector axis (X) at the vertex; the direction of a particle is defined by the angles (YX, ZX).
Track 4 was not predicted, but was found at the vertex, while another track was predicted and not found.

Track 3 was found in two pieces, with different slopes: this sudden variation, after 380 µm, of a high-momentum particle cannot be due to scattering; so, one can conclude that there was a decay. One can compute the transverse momentum of the daughter particle with respect to the mother one, by knowledge of the particle direction before the decay. The angles were (−43 mrad, −41 mrad). The variation of the particle direction is (34 mrad, 59 mrad); the angle between the initial direction and the final one is 68 mrad.

The transverse momentum is
\[ p_{\perp} = p \sin \Delta \vartheta = 5.4 \text{ GeV/c} \times 0.068 = 367 \text{ MeV/c} \]

Information on the transverse momentum \( p_{\perp} \) is useful to understand what kind of decay we are analyzing. A \( K^+ \) decay into a \( \pi^+ \) has a maximum transverse momentum of 205 MeV/c so, taking into account our \( p_{\perp} = 367 \text{ MeV/c} \), we must give up the hypothesis of such a decay. But a \( D^+ \) decay into \( \pi^+ \) has a maximum transverse momentum of 925 MeV/c and is therefore allowed.

This second hypothesis is in good agreement with the lifetime of the particle that can be calculated from the length of its track in emulsion.

From the Lorentz transformation relating the momentum in the center of mass with the momentum in the laboratory we yield:

\[ \langle \Delta \alpha \rangle \approx \frac{1}{\gamma} \implies \gamma \approx 15 \]

Now the life time (\( t^* \)) of the decaying particle can be derived using the relation:

\[ L = \beta \gamma c t^* \]
Considering once again $\beta \approx 1$, we have:

$$t^* \approx 10^{-13} \text{s}$$

that is in good agreement with the charmed particle decay hypothesis. Concluding we can give the following interpretation of the event:

$$\nu_\mu N \rightarrow \mu^- D^+ X$$

$$D^+ \rightarrow \pi^+ Y$$

This study was very quick using the properties of the multi-tracking system that gave us all the topological information related to the event during its scanning. Then same basic relations of the high energy physics allowed us to store and classify the event as a charm decay.

Let’s analyze the second interesting interaction (Fig.16; Event 1495/371).

![Figure 16: The Interaction is shown in the xz plane.](image)

This is a $0 \mu$ event with the primary interaction vertex in the 35$^{th}$ bulk sheet and a secondary interaction in 33$^{rd}$ bulk sheet. The latter vertex had five tracks, three of them matching with the prediction with a primary charged track. The scanning was updated and the old scanback track
(\(Sy = 38\) mrad, \(Sz = 13\) mrad) found at the secondary vertex was changed into the primary charged track (24 mrad, \(-36\) mrad) and followed back in the previous sheet. In the 35th sheet this track led to the primary interaction vertex and so the topological reconstruction was complete.

Unfortunately the kinematics of the event was not completely reconstructed by the CHORUS detector. At the secondary vertex two of the five reconstructed tracks were not detected by the spectrometer and therefore their charge and momentum are unknown. This makes impossible any analysis on the primary charged track.

For the sake of completeness we must say that the secondary vertex could signal a 5-prong decay of a \(\tau\) that is however a very rare event. The same can be said for a charmed particle, but identifying it as the interaction of a secondary particle is more reasonable. The reconstruction of this event was not problematic since the updating of the scanback track is an automatic feature of the system.

### 3.1.2 Intercalibration of two emulsion sheets

A second sample of the ability of the multi-tracking system turns out in the intercalibration procedure. In the CHORUS experiment, each one of the four stacks is composed of 36 bulk sheets and so, in order to reach the interaction vertex, the problem of getting all these sheets in the same frame of reference has to be faced. One of the needs to get a successful intercalibration between two bulk sheets is being able to match two maps of tracks belonging to different sheets. For example tracks belonging to X7 beam (a muon beam passing through the detector, useful to calibrate it) can be followed. The procedure becomes harder taking into account that as a first step the special sheet must be matched with the first bulk of the stack. Due to the different time of exposure (1 year for the special sheet, 2 for the bulk sheet) about 50% of the tracks in the bulk sheet are not present in the special sheet. Matching tracks must be followed for 36 bulk sheets, widening the scanning area because of the natural spread of the X7 beam.

The Multi-tracking system turns out to be very useful to build map of tracks and to compare them, getting the transformation necessary to switch coordinates of one map to the coordinates of the other.

Fig.17 shows two maps of tracks belonging to special and bulk (target) sheets, in fig.18 these two maps are matched.
Figure 17: On the left a special sheet map, on the right a bulk sheet map (in the latter the number of tracks is almost double).

Figure 18: Matching of the two previous maps of tracks.
4 SySal approach to Vertex Detection: An "Intelligent Scanning"

4.1 On-line vertex recognition and study in CHORUS experiment

Vertex recognition and study using SySal is based on two important features. The former is, of course, multi-tracking strategy and the latter is the choice of following more than one track for every event.

During the scanning three vertex alarm are set:

- Intersection of a scanback track in its scanning field with one or more tracks matching with the event prediction;
- Disappearance of the scanback track;
- Closest approach of two scanback tracks belonging to the same event (pre-location of the event).

Now we are going to discuss these three opportunities.

4.1.1 Intersection of a scanback track in its scanning field with one or more tracks matching with the event prediction

Tracks matching with the scanback prediction are recognized in both side of the emulsion. Intersections between these matching tracks and all the other tracks in the scanning field are calculated; then a vertex alarm is given if at least one of the other intersecting tracks matches with a track belonging to the event prediction.

This alarm is able to recognize not only vertices in the current sheet of emulsion but even in the following one (fig.19)

Vertex reconstruction and detection is somehow related to the local depth of a vertex in the emulsion sheet. Therefore we can roughly divide the plate thickness into three zones (fig.20).

Vertices located in the second zone of the emulsion sheet shown in fig.20 are usually well reconstructed in both sheets of emulsion (the vertex plate and the previous one). Reconstruction of vertices in the first zone is better in the previous bulk because in the vertex plate there are few grains per track while vertices in the third zone are usually well reconstructed in the
Figure 19: Detection of the event is possible even from the sheet before the vertex plate.

Figure 20: Reconstruction of the event in the three zones of the vertex plate.
vertex plate. For these vertices the other tracks belonging to the event are often outside the scanning field of the previous bulk so that an intersection is seldom possible.

Following (fig.21) there is an example of vertex found in bulk 9 but already detected in bulk 8.

![Figure 21: An event in bulk 9 already detected in bulk 8.](image)

In bulk 8 the scanback track is intersecting with a track matching with the prediction. In the next bulk these two tracks are still intersecting and the whole vertex is completely reconstructed.

### 4.1.2 Disappearance of the scanback track

Intersecting the scanback track with other tracks in the scanning field won’t be useful to detect quasi-elastic events. These events consist of only one track predicted by the tracking system and so every intersection is useless.

Therefore disappearing of the scanback track can be the winning strategy to detect a kink of this track or the interaction vertex itself. Sometimes it can happen that ”missing” a linked track in a bulk sheet goes together with the presence of a one side track matching with the prediction and intersecting a wide angle track: this can be a further hint of the presence of a vertex.

In general ”missing” a track for two following bulk sheets can be used as a vertex hint.

### 4.1.3 Intersection of two scanback tracks: pre-location of the event

This is an important matter because it can provide the chance of conceiving a new scanning strategy. About this opportunity some ideas will be presented
in the next section.

Of course, following more than one track per event can be useful to locate the event before reaching it, by calculating the intersection of two tracks reconstructed in the same bulk sheet. To avoid any misleading information coming from kinks it could be wise to follow even three tracks per event.

Let’s now introduce the basics of such a study.

**Introducing the ”closest approach”**

Let’s consider two points belonging to two different tracks in the space:

\[
P_1 = (x_1; \ a_1^y x_1 + b_1^y; \ a_1^z x_1 + b_1^z) \\
P_2 = (x_2; \ a_2^y x_2 + b_2^y; \ a_2^z x_2 + b_2^z).
\]

The distance between them is:

\[
d = \sqrt{(x_1 - x_2)^2 + (a_1^y x_1 + b_1^y - a_2^y x_2 - b_2^y)^2 + (a_1^z x_1 + b_1^z - a_2^z x_2 - b_2^z)^2}.
\]

If we now consider only distances of points with the same x coordinate this distance becomes:

\[
d = \sqrt{((a_1^y - a_2^y)x + b_1^y - b_2^y)^2 + ((a_1^z - a_2^z)x + b_1^z - b_2^z)^2}.
\]

Choosing the condition \(\frac{\partial d}{\partial x} = 0\), we yield the depth of the minimum distance (extrapolation depth):

\[
x_{\text{min}} = \frac{[(a_1^y - a_2^y)(b_1^y - b_2^y) + (a_1^z - a_2^z)(b_1^z - b_2^z)]}{[(a_1^y - a_2^y)^2 + (a_1^z - a_2^z)^2]}
\]

and so the minimum distance itself:

\[
d_{\text{min}} = \sqrt{((a_1^y - a_2^y)x_{\text{min}} + b_1^y - b_2^y)^2 + ((a_1^z - a_2^z)x_{\text{min}} + b_1^z - b_2^z)^2},
\]

that is called ”closest approach”.

**A study of d_{\text{min}}**

This study was performed on about 50 closest approaches calculated during the scanning of the stack 3 module 3 top part of the year 1994. These closest approaches were derived from pairs of not kinking tracks that led to interaction vertices. The aim is to check the precision of the measurements of the vertex coordinates and the validity of the closest approach in connection with the extrapolation depth.
As expected $d_{\text{min}}$ is strictly connected with the extrapolation depth that is negative because the extrapolation is done backward (fig.22).

Fig.23 shows the differences between the predicted (using $d_{\text{min}}$) and the found transverse coordinates of the vertex. The mean point of the segment representing the closest approach is chosen as the predicted vertex. According to this, scanning of only one field of view is necessary to locate the vertex using a 50× magnification.

From the distribution of the differences of the longitudinal coordinate (fig.24) it is easy to deduce that the interaction bulk pellicle is well predicted.

We performed this study using tracks that led to vertices. Therefore this study gives no suggestions about fake closest approaches, generated by pairs of tracks in which there is a fake candidate. As it turns out from fig.22 $d_{\text{min}}$ increases with the extrapolation depth. So at long extrapolation depths it is easy to mistake a good closest approach for a fake one and vice versa.

### 4.2 A further step: an "intelligent" scanning

Time consumption is an important matter when dealing with huge amounts of tracks to scan. That’s why an "intelligent" scanning is required to skip:
Figure 23: Accuracy of the transverse coordinates of the vertex.

Figure 24: Accuracy of the longitudinal coordinate of the vertex.
- all the fields that cannot be useful for the reconstruction of the scanback track;
- all the sheets that would not give any important information about interesting kink and vertex reconstruction.

### 4.2.1 Skipping scanning fields

The new version of SySal is considering the opportunity of skipping several fields during the scanning of a track. This is performed using on-line "intelligent" choices.

Figure 25: When something interesting is found in the upper side a scanning is performed in the lower side.

Whether in the upper side there is no track in good agreement with the prediction then the lower side of the emulsion can be skipped; otherwise, centering the interesting track and following down along its direction, a scanning in the lower side of the emulsion can be performed.

Furthermore, scanning can be stopped if a good candidate (say within 5 mrad) is found and the remnant part of the scanning area can be skipped.

### 4.2.2 Skipping emulsion sheets

The study of intersections of two tracks belonging to the same event together with the information of the event prediction is leading to the elaboration of a new scanning strategy. The goal is to provide as soon as possible, with the minimum scanning effort, a pair of tracks to locate the interaction
vertex. This scanning strategy is possible for those events with at least three "safe" tracks (well reconstructed by the detector, with angles < 400 mrad) otherwise a "classical" scanback scanning must be used.

![Figure 26: Strategy to locate the second track.](image)

Once the first track is located, using the predicted longitudinal coordinate and the assumption that the vertex is along the direction of this track, it is possible to locate the position of a second track. The second track must be scanned in an area whose dimensions along the two directions in fig. 26 are related with the uncertainty on the longitudinal vertex coordinate ($\sigma \simeq 1700 \mu m$) and on the predicted slopes of the tracks ($\sigma \simeq 3 \text{ mrad}$).

When the second track is found and reconstructed it is possible to calculate the closest approach otherwise the scanning of a third track can start.

Once two tracks are available their closest approach can be calculated. If the extrapolation depth is too long it could be wise following the tracks for the number of bulk sheets necessary to get a safe closest approach. Otherwise one can jump directly to the bulk sheet necessary to begin the analysis of the event (say a few sheets before the vertex plate).

References

[1] G.Rosa et al, Automatic Scan and Analysis of Digitized TV Images by a Computer Driven Optical Microscope, NIM A 394 (1997) 357-367.

[2] The CHORUS collaboration, The CHORUS experiment to search $\nu_\mu \rightarrow \nu_\tau$ oscillation, CERN-PPE/97-33 March 14, 1997.