A new automatic microscope for high-speed nuclear emulsion analysis of the OPERA experiment

M. Cozzi, L. S. Esposito and G. Sirri
(for the OPERA Collaboration)
Department of Physics, University of Bologna and INFN Bologna,
Viale Berti Pichat 6/2, I-40127 Bologna, Italy
E-mail: cozzi@bo.infn.it

Abstract. The large amount of emulsion plates to be analysed in the OPERA experiment requires the development of a new generation of automatic microscopes with an order of magnitude improvement in speed with respect to analogous past systems. We report on the large R&D effort in realizing automatic microscopes with a scanning speed of 20 cm$^2$/per hour, describing the progress in the mechanics, optics and in the technology of image acquisition and analysis. We also report on the features and performances of the scanning system (precisions, angular and position resolutions and efficiencies) evaluated exposing stacks of emulsions to high momentum pion beam at CERN.

1. Introduction
The features of nuclear emulsions as a detector have been known since a long time. One of the most fundamental contributions of the emulsion technique to particle physics has been the discovery of the pion in 1947 by observing the $\pi \rightarrow \mu^{-} \rightarrow e$ decay chain in nuclear emulsions exposed to cosmic rays [1]. During the 50’s and 60’s emulsions were used for cosmic ray experiments, energy measurements of electromagnetic showers, and several other particles were discovered. Nuclear emulsions were successfully used in neutrino experiments, like WA17 and WA75 at CERN [2, 3] and E531 at Fermilab [4]. Furthermore, the use of nuclear emulsions allowed the observation of $\tau$ neutrinos by the DONUT collaboration [5]. Nuclear emulsions still remain the detection technique with the best known three-dimensional spatial resolution, less than 1 $\mu$m, and zero intrinsic dead time.

For several decades since their appearance in physics research, their use was always connected with scanning and analysis by human eyes. In the last few years, the scanning of nuclear emulsions has considerably changed with the development of automatic scanning systems. The automation of emulsion scanning was pioneered by the group of Nagoya University (Japan); a first complete application of an automatic system, called Track Selector (TS), was used for the DONUT and CHORUS experiments [6, 7]. The TS was improved and the Ultra Track Selector reached the scanning speed of about 2 cm$^2$/h.

The OPERA experiment [8] will use a large amount of emulsions (a few thousands of m$^2$) to obtain an unambiguous signature of $\nu_\mu \rightarrow \nu_\tau$ oscillations in the parameter region indicated by atmospheric neutrino data [9, 10, 11, 12], using the CERN to Gran Sasso neutrino beam (CNGS [13]). The detector, located in the underground Gran Sasso National Labs., consists
of electronic trackers, iron spectrometers and a massive lead-emulsion target, segmented into bricks with size $12.7 \times 10.2 \times 7.5$ cm$^3$. Each brick is a sequence of lead plates and emulsion foils, made of two 43 $\mu$m thick films on either side of a 200 $\mu$m plastic base. Thanks to the excellent tracking resolution of nuclear emulsions, the short-lived $\tau$ particles produced in $\nu_\tau$ charged current interactions in lead can be directly observed and the appearance of $\nu_\tau$ neutrinos in an almost pure $\nu_\mu$ beam can be investigated.

The OPERA scanning load requires an automatic scanning system with a speed of about 20 cm$^2$/h (an improvement of about a factor ten in speed with respect to past systems). The European Scanning System (ESS) [14] have been specifically optimised for the scanning of thin emulsions, exposed to perpendicularly impinging particles, with high speed, sub-micron precision, high tracking efficiency and low instrumental background. In the following the performances of the ESS are presented, in terms of angular resolutions, efficiency and purity. The results were obtained from the track reconstruction in seven consecutive emulsion plates (with no lead interleaved) exposed at the CERN PS-T7 beam line to high energy pion beam.

2. Automatic scanning systems

A microscope for automatic emulsion scanning consists of a computer driven mechanical stage, an appropriate optical system, a photo detector (typically a CCD or CMOS camera) and its associated readout, as shown in figure 1. Since precision optical measurements depend on reliable position stability, the motor driven scanning table and a granite arm are positioned on a high quality table, which provides a virtually rigid and vibration-free working surface. The light system is located below the microscope table. Vertical displacements are obtained by a motor driven stage, which is fixed to the granite arm. The optics and the digital camera for image grabbing are mounted on the vertical stage. The emulsion support is provided with a vacuum system to keep the sheet steady during data taking.

During the acquisition, the emulsion is scanned view by view and the images are sent to the “frame grabber” hosted in a computer, which also controls the light intensity and the stage displacements. For each field of view, the readout is performed by moving the focus plane of the objective vertically ($z$-direction) inside the emulsion with constant speed and taking a series of successive vertical images by the camera.
The scanning system design had to take into account the requests of high scanning speed and of high position and angular accuracies. The system was thus conceived with the following features:

- high-performance mechanics with sub-micron position accuracy and short settling-time;
- optics with a large field of view, sub-micron resolution and suitable working distance (> 300 μm);
- camera with mega-pixel resolution and high frame rate;
- powerful image processors.

The new camera, the MC1310 model from the Mikrotron company, is used in order to reach the desired scanning speed. It is a high-speed mega-pixel CMOS camera with Full Camera Link interface. Unlike high resolution CCDs, modern CMOS sensors offer high resolution and extremely high data rates. The CMOS sensor has 1280 × 1024 pixels, each pixel size is 12 μm (giving a sensor area of 1.5 × 1.2 cm²). The camera is able to work up to a rate of 500 frames per second (fps) at full resolution, which implies a maximum data rate of 660 MB/s. The ESS uses a camera configuration at 376 fps, which is satisfactory for the requested scanning speed. The images are grabbed in a 256 level gray scale (the light acquired by one pixel is converted in a 8-bit digital signal) and sent to the frame grabber in the host PC.

3. The on-line acquisition software

The on-line DAQ software for the emulsion automatic scanning and track segments reconstruction was developed using the object-oriented C++ language. It is based on a modular structure where each “object” (module) carries out a well defined task. Each object has a corresponding parameter window for configuration setting. The scanning output is a collection of raw data files (in binary format) which are saved in the file server.

3.1. Image processing and clustering

The images are digitized and converted to a gray scale of 256 levels (where 0 is black and 255 is white). Digital images are analyzed for clusters recognition. Some clusters are due to grains associated to physical tracks, some others are due to fog grains.

The first step is the “flat field subtraction”. It is an on-line image process studied to remove clusters due to the presence of dust on the camera sensor and inhomogeneities in the illumination system. The operation consists in the subtraction of one image grabbed outside the emulsion from all the images grabbed inside.

The second step is the image convolution with a filter, aiming at the enhancement of the contrast between focused and unfocused grains. The convolution extends the original 255-value gray level scale to a wider one, which flattens the shape of the background.

Finally, the third step is the “binarization”. A well-chosen threshold is applied to the data and pixels with values exceeding the threshold are classified as black; the remaining ones are white. The chosen kernel and threshold define the vertical resolution of the apparatus.

The last step of image processing is the clustering. The image is scanned row by row and the algorithm looks for black sequences inside each row. After a row has been scanned, the sequences are compared with all the sequence in the previous row and adjacent sequences are merged into a cluster. If two or more clusters come in contact, they are also merged. A cut on the cluster area helps to discard background due to the noise in the camera signal. The cluster center of gravity is calculated and position, area and shape are stored in the output file.

3.2. Micro-track reconstruction

The tracking on a single emulsion sheet consists of two main algorithms: micro-track recognition and micro-track fitting. In the first step, the algorithm recognizes an array of grains as a track
Figure 2. Two micro-tracks connected through the base. The base-track is defined by joining the two micro-track points closest to the plastic base.

with geometrical alignments. In the second step, the algorithm performs a linear fit of the position of the clusters and evaluates track slopes. Intercepts are given on the surface between emulsion and base.

The track recognition algorithm is the most important part of the tracking because it is the main source of inefficiency in tracks measurements. The first operation is the search for a track start-up on some trigger layers. In order to reduce the CPU time, the field of view is divided in cells, whose linear dimension is about 25 μm, and the start-up is searched for only inside the same cells. The sequence of layers defined as a “trigger” is formed by two distant layers and a list of central layers (up to eight). For a given cell and a given sequence, all the clusters in the first two layers are connected with a line and other aligned clusters are searched for in one of the inner layers within some tolerances. If at least one other cluster is found, a trigger is produced.

When a start-up is found, the tracks are followed in all the other layers. Also the neighboring cells are considered for track following, in order to increase the angular acceptance.

Once all clusters have been found, a linear fit is performed and spurious clusters are removed from the tracks. If the number of clusters that form the track is larger than a minimum number (e.g. six), the micro-track is saved in the output file.

4. The off-line reconstruction software

The on-line program provides the positions and angles of the detected micro-tracks for each emulsion layer. The full track reconstruction is performed by an off-line analysis tool in several steps:

- 2 micro-track linking (or base-track reconstruction);
- emulsion plate intercalibration;
- volume-track reconstruction.

where a micro-track is a chain of aligned clusters in one emulsion layer, a base-track is built by connecting the two micro-track points closest to the plastic base and a volume-track is constructed from two or more base-tracks, each one in a different emulsion plate.

The base-track reconstruction is performed by projecting micro-track pairs across the plastic base and searching for an agreement within given slope and position tolerances. The base-track
Figure 3. The angular resolution of micro-tracks measured in the top side and connected on the bottom side of the emulsion film. It is evaluated by comparing with base-track angles (figure 2). Left: micro-track resolution at 0 mrad. Right: micro-track resolution at 400 mrad.

is defined by joining the micro-track points closest to the plastic base (figure 2). Since these points lie in regions unaffected by distortion effects, the base-track has an angular resolution approximately one order of magnitude better than the micro-tracks. Thus the angular difference between micro-tracks and base-track provides an estimate of the micro-track angular resolution. Figure 3 shows the micro-track resolutions for incident angles $\theta = 0$ and $\theta = 0.4 \text{ rad}$. The micro-track angular resolutions are 8 mrad and 18 mrad, respectively. The average number of clusters for each base-track as a function of the reconstructed angle is shown in figure 4. There is a minimum between 200 and 300 mrad. Vertical base-tracks ($\theta = 0$) have a larger number of clusters since each grain is reinforced by its shadow; also the 400 mrad base-tracks have on average a larger number of clusters because of their longer path in emulsion.

The emulsion plate intercalibration is done by subdividing the scanned emulsion plates in several cells and applying some relative displacements. The translation which will align the plates will maximize the number of track coincidences. Once all plates are aligned, the track reconstruction algorithm follows all the measured base-tracks of an emulsion film to the upstream and downstream ones. A number of connected base-tracks, not necessarily adjacent, forms a volume-track. In the experiment the emulsion plate intercalibration will be done first with x-ray mark and finally with cosmic ray muons [15].

By considering only volume-tracks with base-tracks measured in all the emulsion plates, base-tracks angular and position residuals have been calculated with respect to the angle $\theta$ of the fitted volume tracks. The base-track resolutions are defined analogously to the micro-track resolutions.

These resolutions are dependent on measured angles and range from 1.6 to 7 mrad (figure 5). The corresponding position resolution ranges from 0.9 to 2.5 $\mu$m (figure 6). Note that position residuals is composed of both measurement and alignment errors unlike the angular residuals. Considering that the distance between two consecutive plates is 300 $\mu$m, the position residuals...
Figure 4. Average number of clusters in a base-track as a function of the measured angle. The errors are only statistical and are within the point size.

from the angular errors is $\sigma_{\text{pos}} = \sigma_{\text{angle}} \times 300$. In this way it is possible to evaluate the alignment precision, which is about 0.4 $\mu$m.

Figure 5. Angular resolution of base-tracks as a function of the reconstructed angle $\theta$. It is evaluated by comparing base-track angles with respect to the volume-track angles. The errors (that are inside the dimensions of each black points) are only statistical.

4.1. Efficiency and background estimate
For each emulsion plate, the efficiency $\varepsilon_{bt}$ is defined as the number of passing through volume-tracks that “hit” that sheet with respect to the total number of passing through tracks:

$$\varepsilon_{bt} = \frac{\text{Number of measured base-tracks}}{\text{Number of base-tracks searched for}}$$
Figure 6. Position resolution of base-tracks. Note that position residuals are composed of both measurement and alignment errors unlike the angular residuals. The alignment error is at the level of 0.4 μm. The plotted errors are only statistical.

Figure 7. Base-track finding efficiency as a function of the reconstructed volume angle. Error bars are only statistical.

$\varepsilon_{bt}$ is independent of the number of used emulsion plates, provided that this number is large enough to avoid that the volume-track sample includes tracks due to random coincidences or to tracks that are not minimum ionizing particles (mip).

In order to minimize the number of base-tracks not related to the pion beam, the efficiencies have been evaluated taking into account volume-tracks with at least six (not necessary adjacent) base-tracks and with a reconstructed angle within 3 sigma of the beam directions.

The base-track tracking efficiency have been calculated separately for each beam direction with respect to the optical axis; the result is shown in figure 7. The mean efficiency is larger than 90% and corresponds to a micro-track finding efficiency of about 95%. The shape of this curve is due to the number of clusters associated to the base-tracks (figure 4).
The background measurement was made using a non exposed emulsion plate from the same batch production as the others, refreshed and developed at the same time. The scanning was done with the same on-line parameters, and the same quality cuts were applied. The number of base-tracks not related to the beam is \(\sim 400/\text{cm}^2\) with the angle \(\theta < 0.4\) rad.

While most of them are cosmic ray tracks, some tracks can be random coincidences of two micro-tracks generated by aligned fog grains. In order to separate cosmic ray background from instrumental background, we manually inspected 405 base-tracks (measured in 1 cm\(^2\) with \(|\theta| < 0.4\) rad). Defining fake track, a base-track with one of the two micro-tracks generated by aligned fog, only 2 base-tracks have been classified as fake. The instrumental background is then of the order of 1 base-track/cm\(^2\) within \(|\theta| < 0.4\) rad.

5. Conclusions
The goal of 20 cm\(^2\)/h scanning speed was achieved. The analysis of the data of emulsions exposed to an high momentum pion beam gives a base-track reconstruction efficiency of \(\sim 90\%\) for mip with \(\theta \leq 500\) mrad. The corresponding micro-track reconstruction efficiency is \(\sim 95\%\). The measured base-track angle resolution is \(\sim 1.5\) mrad for vertical tracks. The instrumental background, evaluated by visual inspection, is about 2 base-tracks/cm\(^2\) within \(|\theta| < 0.4\) rad. These results fulfill the requests of the experiment for the emulsion general scan. However, this is not the ultimate performance. The intrinsic resolution limit for OPERA emulsions is 0.06 \(\mu\)m. High accuracy measurements, aiming to measure special events or to perform the final selection of \(\tau\) decays, can be performed by means of dedicated microscope stages [16].

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