# Convolutional Neural Network in Application to Slow Magnetic Monopole in the NOvA Experiment

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**Abstract**

The NOvA experiment, primarily focused on neutrino oscillation studies [1], provides an excellent platform for the search for slow-moving magnetic monopoles hypothetical particles predicted to carry magnetic charge. In this analysis, the focus is on detecting slow magnetic monopoles with velocities corresponding to a beta ( $\beta = \mathrm{v/c}$) in the range of $10^{-4}$ to $10^{-2}$. The existing analysis is based on a linear fit algorithm for the reconstruction and selection of slow magnetic monopole tracks [2, 3]. In this project, cross-checking and possibly improving the analysis within the convolutional neural network approach is suggested.

## Acknowledgments

I would like to thank to my supervisors Oleg Samoylov and Alexander Antoshkin for allowing me to participate in this interesting project and for their feedback and dedication. Thank you for this opportunity to work with you over the past 6 weeks and it would be a pleasure for me to continue this work in the future.

# Contents

# 1 Introduction

## 1.1 Magnetic Monopoles: Overview

A magnetic monopole is a hypothetical particle that possesses only one magnetic pole—either a north or a south pole—unlike traditional magnets that have both. The concept gained modern interest through theories such as grand unified and superstring theories, which suggest their existence. However, there is no experimental evidence confirming the existence of magnetic monopoles, and magnetism in typical materials is explained through electric currents and particle magnetic moments.

The Dirac monopole is a theoretical construct proposed by Paul Alain Maurice Dirac in 1931 [4], representing a magnetic monopole analogous to an electric point charge. To date, no magnetic monopoles have been observed in nature, leaving them as purely speculative entities. However, their theoretical framework holds significant importance in both physics and mathematics.

The potential existence of a single magnetic monopole would lead to a remarkable symmetry in Maxwell's equations, which would enhance their aesthetic appeal. More importantly, Dirac demonstrated that such a monopole would necessitate the quantization of electric charge, which presents a compelling physical implication.

Of particular interest in this analysis are slow magnetic monopoles, with velocities much smaller than the speed of light ($\beta = 10^{-4} - 10^{-2}$). These slow monopoles would lose energy primarily through ionization as they pass through matter, leaving highly ionizing tracks that can be distinguished from the signals produced by other particles in the NOvA (far) detector.

## 1.2 NOvA Far Detector

The NOvA experiment [5] is a particle physics experiment designed to detect neutrinos in Fermilab's NuMI (Neutrinos at the Main Injector) beam, that consists of two detectors, one at Fermilab (the near detector), and one in northern Minnesota (the far detector).

The far detector consists of about 344,000 cells, each 4 cm $\times$ 6 cm $\times$ 16 m, filled with liquid scintillator. Each cell contains a loop of bare fiber optic cable to collect the scintillation light, both ends of which lead to an avalanche photodiode for readout.

This experiment was designed to measure the oscillation of muon neutrinos but provides an excellent platform for the search for slow-moving magnetic monopoles-hypothetical particles.

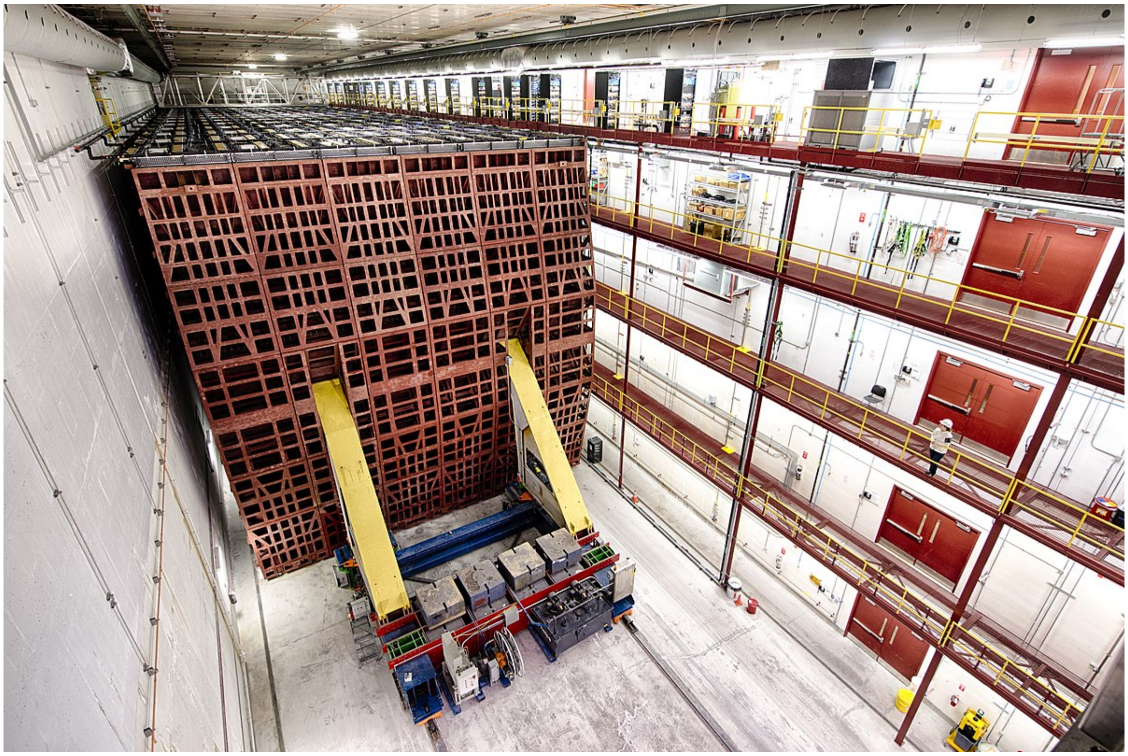

Figure 1: NOvA Far Detector in Minessotta [5].

# 2 Events selection

## 2.1 Track Reconstruction Process

The initial stage of offline event selection involved track reconstruction, first focusing on speed-of-light tracks (primarily cosmic-ray muons) and then on slower tracks of interest. Speed-of-light tracks, taking about 50 ns for height or width and 200 ns for length, could be distinguished from slow tracks due to their clear timing resolution of 20 ns and numerous hits.

Clustering was employed to identify and combine hits into straight tracks, with overlapping speed-of-light tracks removed to avoid contamination of monopole track reconstruction. They require candidates to have at least 20 hits, cross 10 planes, and have a reconstructed length of at least 10 m [1].

## 2.2 Selection Criteria for Monopole Tracks

Once candidate tracks were identified, their speed, linear correlation coefficient, and time gap fraction were calculated. Any candidate track with a speed above $\beta > 0.01$ is rejected, as the analysis focused on slow monopoles. The minimum linear correlation coefficient ($r^2_{min}$) was computed to assess track straightness, with values close to unity indicating true monopole tracks.

Background tracks caused by misidentified cosmic rays can be filtered based on the maximum time gap between hits, defined as $f_{max}$, with high-quality tracks expected to have f values near zero. The final selection criteria established for identifying monopole events included $\beta < 10^{-2}$, $r^2_{min} \geq 0.95$, and $f_{max} \leq 0.2$, ensuring effective separation between signal and background.

### 2.3 Datasets

The data that we process represents a simulated and calibrated event recorded by the NOvA Far Detector and contains the following variables:

. Time of the hit (as XZ-coordinate projection)

. Time of the hit (as YZ-coordinate projection)

. Charge of the hit (as XZ-coordinate projection)

. Charge of the hit (as YZ-coordinate projection)

This is a preselected event that has undergone some quality cuts. The project involves fitting these tracks using a linear regression algorithm to determine the fit parameters. We apply specific requirements to ensure the linearity and temporal continuity of monopole tracks.

## 3 Results

First, it obtains the plots from the tracks corresponding to two events as shown in Figure 2 for $\beta = 10^{-2}$ where it can see two separate tracks corresponding to the event numbers 2 and 3, and the hits formed a straight line. The plots show the relation between the cell hit position in X- and Y-projections vs. the position on Z/2 corresponding to the detector planes.

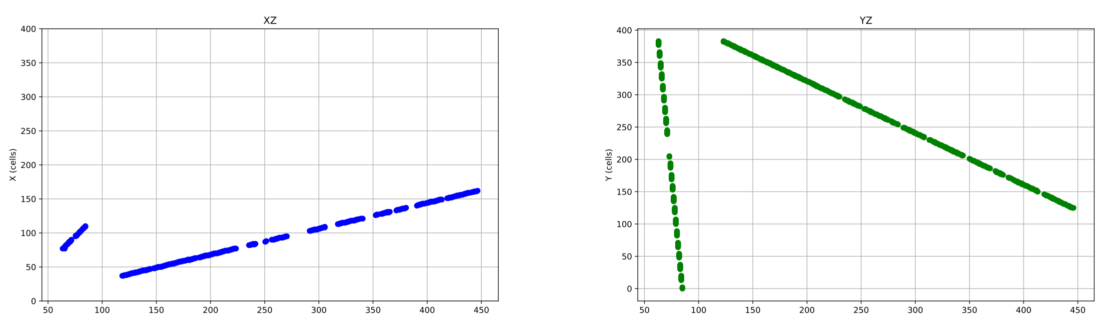


Figure 2: Tracks reconstruction corresponding to slow magnetic monopoles with $\beta = 10^{-2}$.

Now, we can analyze the tracks separately, applying specific requirements to ensure the linearity and temporal continuity of monopole tracks. To evaluate this, we fit a line to the hits associated with each monopole track and calculate the squared correlation coefficient $r^2$ for the xt and yt projections for each one, using standard linear regression techniques.

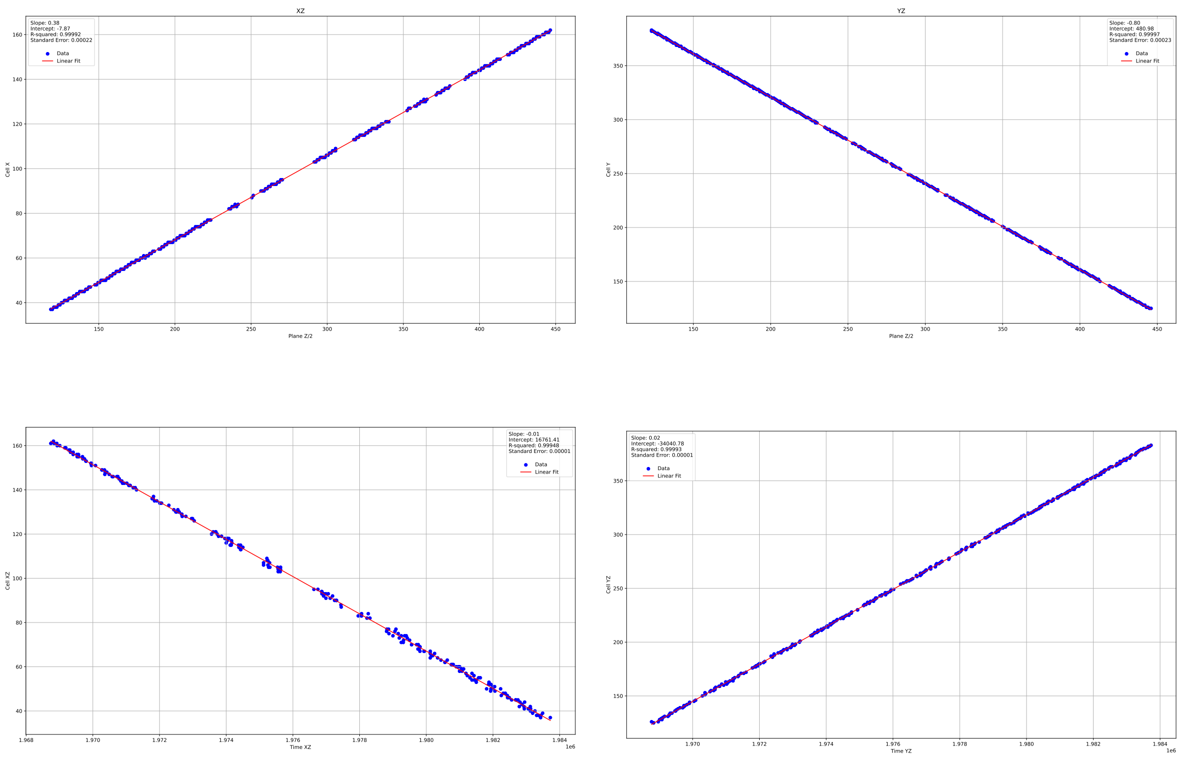


Figure 3: Track reconstruction for the event 3 and $\beta = 10^{-2}$ in the XZ,YZ planes (top) and YZ, XZ time projections (bottom). The dots represent the hits and the red line, the linear fit with the parameters calculated as slope, intercept, standard error, and the squared correlation coefficient.

As a next step, we calculate the squared correlation coefficients $r^2_{xt}, r^2_{yt}, r^2_{XZ}, r^2_{YZ}$ for the whole dataset (around 100 events) for several monopole beta points ($\beta = 10^{-3}, \beta = 5 \cdot 10^{-3}, \beta = 5 \cdot 10^{-4}$) using Python.

For that, calculate $r^2_{min}$ between xt and yt, and XZ and YZ for each beta point monopole and compare them with the results obtained from the Novasoft approach.

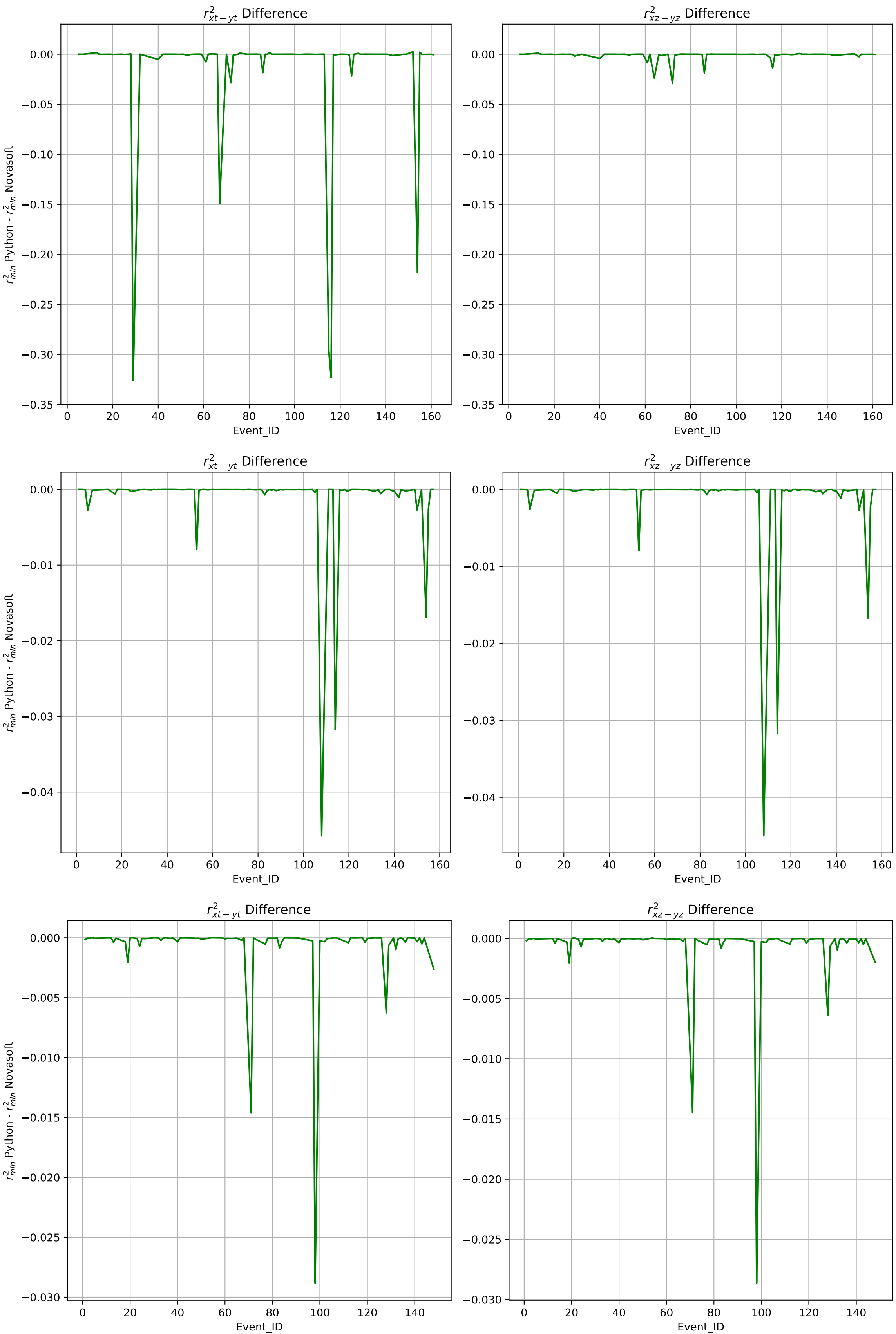


Figure 4: Differences between the fit from Python vs. Novasoft approaches for $\beta = 5 \cdot 10^{-3}, 10^{-3}, 5 \cdot 10^{-4}$ respectively, comparing the values among $r^2_{min}$ xt,yt (left) and $r^2_{min}$ XZ,YZ (right) of both methods.

It finds that there are no big differences between the approaches, from the plots of monopole's beta points $10^{-3}$ and $5 \cdot 10^{-4}$ in Figure 4. It can investigate if there are events where the Python linear regression algorithm gives the positive decision (when $r^2_{min} \geq 0.95$) but the "Standard" one fails and it seems from the results that we obtained that there are no positive falses for the Standard approach, indeed just a few values are under 0.95 for the Standard but so are the Python results.

# 4 Summary and Outlook

It reproduced the results of the linear fits applied to particle trajectories (tracks) in the NOvA detector, particularly focusing on the distinction between slow monopole tracks and backgrounds like muons. Using Python, it implemented algorithms to fit the straight-line trajectories of highly ionizing particles such as magnetic monopoles. This involved working with data sets that represent particle tracks in the detector, applying linear regression techniques, and comparing their results with established benchmarks.

As prospects could be great, to continue the analysis with the Convolutional Neural Network and image segmentation and check if it is possible to "find or isolate" monopoles from the simulated monopoles and NOvA far detector activity mix images using the network model.

# References


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