Development of Machine Learning Based Triggering for ICEBERG Liquid Argon Time Projection Chamber

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Background & Motivation
Liquid Argon Time Projection Chambers (LArTPC)

- Detection of charged particles
  - Ionization Electrons
  - Scintillation Light
- Constructs 3D particle path using spatial (channel) information and timing information
- Components:
  - Liquid Argon
  - Electric Field
  - Induction Planes
  - Collection Plane
  - PMTs
LArTPC Event Displays

- Signals are read as ADC waveforms on the wires
- A 2D event display can be constructed to visualize the particle’s path:
  - Channel vs Time vs ADC count
Deep Underground Neutrino Experiment (DUNE)

- LArTPC deep underground to decrease background
- Major Objectives:
  - Neutrino Mass hierarchy
  - CP Violation in neutrinos
  - Observation of proton decay
  - Supernova neutrino detection
DUNE is very large and very expensive
Prototypes must be used to test the hardware/software
ICEBERG
  “Integrated Cryostat and Electronics Built for Experimental Research Goals”
Contains ~4.5 tons of liquid argon
  Dune will have a total of 70 kilotons
Not underground!
Michel Decay

- Cosmic rays
  - Atomic nuclei traversing space at relativistic speeds
- Upon entering Earth’s atmosphere, they decay into pions (mesons)
- Pions decay quickly into muons (heavy leptons)
- Muons most common mode of decay (Michel Decay) is:

\[ \mu \rightarrow \nu_{\mu} + \bar{\nu}_{e} + e \]
● Muons are unstable and decay within microseconds at rest
  ○ This is slower from our reference frame because they move at relativistic speeds
● DUNE will be strongly shielded from cosmic ray muons, but ICEBERG isn’t
  ○ Michel decay is well understood and can be used for electronics calibration and testing software
I am creating an algorithm for detecting Michel decay against background.

DUNE will generate several terabytes of data every second:
- Most of this cannot be stored.
- Must be reduced by an order of 10,000 to meet hardware limitations.

An algorithm that decides what data to store must be developed:

- **Must be fast**
  - DUNE will collect data in real time.

- **Must be accurate**
  - DUNE aims to observe very rare events; we can’t afford to miss them.
  - ~99.5% of noise signals must be discarded.

- **Must not be highly computationally complex**
  - Hardware resources are constrained.
Machine Learning has proven to be an effective method for event triggering.

- Two-Dimensional Convolutional Neural Networks (2D CNNs) perform excellently in image classification.
  - LArTPC event displays are simply images.
2D CNN

- **Input layer**
  - Tensor with dimensions: Length × Width × Color Channel

- **Zero Padding Layer**
  - Changes dimensions of tensor by adding entries with 0 value
  - May be necessary for operations in later layers

- **Pooling Layer**
  - Groups together nearby entries to reduce parameter count and computational load

- **Convolutional Layer**
  - Performs mathematical convolution between input tensor and a convolution matrix predetermined from training

- **Fully Connected Layer**
  - Every neuron applies a preset activation function to the input tensor
A neural network must be trained on a very large, labelled dataset
  - This can effectively be produced via simulation

Stopping muons can be simulated, but a data-driven noise model for ICEBERG does not yet exist
  - A method for generating noise must be generated using real noise data (because we can’t simulate from first principles) to ensure accuracy to real events
Data-Driven Noise Model
A Fast Fourier Transform (FFT) can be used to calculate the frequencies and associated amplitudes of a given waveform. This information is critical for generating a simulated waveform. Each channel experiences noise slightly different, with different lengths and positions within the detector. We must therefore analyze the frequencies associated with each channel independent of the others. Noise varies over time, with files containing data collected between 3/13/21 and 4/4/21 being analyzed to avoid overfitting to a single time. FFT’s for each day were compared to look for trends relating to time.
FFT spectrum for one channel, averaged over every analyzed event:

FFT of Channel 1000

Amplitude vs. Time
FFT spectra for all channels, averaged over every analyzed event:
Twenty-Two Days of ICEBERG Data:

Mean FFT for 3-13
- No trends were noticeable as time passes, but variance is still present
- The same channels tend to consistently be the noisiest
- Some days have different Data Acquisition (DAQ) configurations, causing them to have different dead channels
The average FFT is divided into three regions: low frequency, middle frequency, and high frequency.

A function is fitted to each region using polynomial interpolation:

- This function behaves as a probability density function.

One frequency is randomly selected from each region based on the probability density function.

An inverse FFT is performed to generate a waveform with these three frequencies.
Single Simulated Wave

Low: 70 kHz
Mid: 430 kHz
High: 700 kHz
Simulated Event Display (Collection Plane)
Convolutional Neural Network
- Two Dimensional Convolutional Neural Network (2D CNN)
- Based on a network previously developed to detect low energy neutrino events in DUNE
  - Low parameter count, and high accuracy
Training and Performance

- Training set contains simulated stopping muons and through-going muons
  - These simulations are only recently accessible, and further formatting is necessary to prepare them for training

- Network was tested on publicly accessible neural network datasets
  - Performance was poor because architecture was not optimized for this data
Summary & Conclusions
- A data-driven noise model has been developed for ICEBERG
  - A similar method will likely be used for DUNE
- A 2D CNN is promising for Michel Decay triggering, but it has not yet been trained and tested on the simulated data
Next Steps

- **Improve accuracy of noise simulation**
  - Truncate edge effects
  - Use larger dataset

- **Improve speed of noise simulation**
  - A simulated event display currently takes ~30 minutes to generate

- **Train/optimize the Neural Network**
  - Modify architecture to find ideal balance between complexity and performance
  - Compare if using all three detection planes improves performance

- **Use CNN for detection of other interactions**
  - Ar-39
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