**Research Plan**

**Brendon Matusch**

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This intent of this plan is to define the general research areas that I will undertake in the next several months. The general goal of this research is to develop robust techniques to assist the PICO project team in the classification of particle interactions detected by the PICO-60 detector, providing techniques based on neural networks to, foremost, accurately discriminate between neutrons and alpha particles, and secondly, to handle additional classification and regression tasks for data analysis including chirp detection and discrimination between wall events and non-wall events.

While the techniques utilized will predominantly be based on machine learning, they will be compared and contrasted to other techniques previously applied.

**Research Area #1: Audio Classification**

Research Goal: The goal of this research is to develop techniques be which to discriminate various types of events strictly from audio data drawn from the PICO piezometers. The intent is focus on the application of machine learning technologies, although other techniques will be considered.

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| Application | Technique to Be Tested | Comments |
| Neutron / Alpha Discrimination | Banded FFT | * Train a multi-layer perceptron on the temperature-, pressure-, and position-corrected frequency domain audio information which was used to train a similar network in the original PICO-60 paper. |
|  | Raw Waveform Analysis | * Train a neural network on the audio waveform recorded at the time of the event. This includes multiple architectures; a few convolutional layers followed by a dense network, as well as a fully convolutional architecture with only a single small dense layer at the end. * The goal is to discriminate between low background data and neutron calibration runs (starting with AmBe and later including other sources). * Modify the number of layers and the hyperparameters of the individual layers to improve the performance of the network. |
| Chirp Detection | Raw Waveform Analysis | * Unknown audio events known as “chirps” are present in parts of the training data. Discover a meaningful predictor of these events in the available data, and use it to train a neural network (potentially using semi-supervised learning) to predict their presence. Analyze their characteristics and ideally determine their source. |
| Event Localization | Raw Waveform Analysis | * The acoustics of events located near walls and events located in the middle of the vessel are notably different. Analyze their waveforms and Fourier transforms to determine how they differ, and potentially train a neural network to distinguish between them or predict their distance from the wall in a continuous way. |

**Research Area #2: Visual Classification**

Research Goal: The goal of this research is to develop techniques for analysis of bubble event data based on the images recorded during and after an event is detected. This will focus on use of 2-dimensional convolutional neural networks for image processing.

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| Neutron / Alpha Discrimination | Convolutional Neural Network | * Train a 2D convolutional neural network to distinguish between alpha particles and neutrons based on small windows cut out at the approximate locations of the bubbles in the images. * The idea is to cue on the shape of the bubble and the visible shockwaves around the bubbles, which may be correlated with certain aspects of the audio and potentially the identity of the source. * Initial testing was notably unsuccessful; the network was able to obtain high training accuracy, but had a validation accuracy of 50% (the same as would be expected from random choice). |

**Research Area #3: Semi-Supervised Learning**

Research Goal: The goal of this research is to develop techniques, ideally independent of the specific data format used, to produce an effective discriminator between categories of bubbles at the same time as providing more confident labels for questionably categorized training examples. This will be based on a modified neural network training process, either through an iterative clustering process or a system for altered gradient generation.

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| Neutron / Alpha Discrimination | Iterative Cluster Nucleation | * Start with a small set of training examples for each category that we are very sure about. Train a neural network on this data (preferably a small one including lots of regularization so it won't overfit). * Then, run inference on the remainder of the dataset which is presently unclassified. Take the ones which the network is most confident about and add them to the corresponding training datasets. * Train another network (possibly with less regularization or a more complex architecture because the dataset is larger and provides more information) on the new labeled dataset. * Run inference again, and repeat until the entire dataset has been classified. |
| Neutron / Alpha Discrimination | Gravitational and Distribution-Biased Gradients, and Probabilistic Ground Truths | * Start by training a conventional model with a very low learning rate. However, modify the learning rate for each example depending on how confident we are that its label is correct. This means the most-confident ones result in large steps to the weights, while the most questionable examples result in very small changes. * Later on in the training process, introduce a "gravity" term to the gradient calculations which pulls examples towards either 0 or 1, whichever they are closest to, and with the strength of this pull depending on how close they are. * In addition, it is practical to add a new term which slightly offsets the gradient for the output layer such that it will push all examples to equalize the overall distribution to the expected distribution. |