Towards Real-Time UCN Detection and Super Resolution using Chip Based Optical Neural Network

S. Lin,[1,2] H. Zhu,[2] S. Clayton,[1] C. L. Morris,[1] Z. Tang, [1] Z. Wang,[1,*] and R. T. Chen[2,3,4,*]

[1] *Los Alamos National Laboratory, Los Alamos, NM 87545, USA*
[2] *Department of Electrical and Computer Engineering, The University of Texas at Austin, Austin , TX 78705, USA*
[3] *Microelectronics Research Center, The University of Texas at Austin, Austin , TX 78758, USA*
[4] *Omega Optics, Inc., Austin , TX 78757, USA*
[*] *Z. W. (zwang@lanl.gov), R. T. C. (chenrt@austin.utexas.edu)*

Abstract: Real-time super position resolution of ultracold neutron (UCN) hit position is highly desired for position-sensitive neutron experiments. Chip based optical neural networks offer a radiation-hard and energy efficient computing platform in high radiation environments. (LA-UR-24-31949)

1. Introduction

Ultracold neutrons (UCNs) have a kinetic energy less than 400 neV, giving them unique properties that enables them to be a powerful tool in studying the fundamental forces in nature. UCNs are utilized in many experiments including but not limited to measuring the neutron lifetime, determining the properties of neutron beta decay, and searching for the neutron dipole moment. Some UCN experiments and applications require position-sensitive measurements, with resolution of 1 μm or less, of UCNs such as studying the UCN quantum gravitational states. These experiments motivate real-time detection and super position resolution of UCNs. Our previous work [1] demonstrated an *offline* super position resolution neural network framework for extracted singular UCN hits. Specifically, we demonstrated that a chip based optical subspace neural network (OSNN) [2] can achieve sub-micron position resolution with 3-bit weight resolution. In this work, we aim to combine the UCN detection and super position resolution process into a real-time two-shot UCN detection framework.

While we motivate the use of OSNNs for UCN detection and super resolution, silicon photonics in general has recently started to become of interest in the area of high energy physics as *radiation-hard* alternative technologies for traditional electrical systems [3]. Compared with their electrical counter parts, optics offers very high bandwidths, lower power consumption, and higher radiation tolerance. One recent work [4] showed that a ring modulator designed following a radiation hardening by design method can withstand up to a total ionizing dose of 11 MGy with no degradation in performance. These studies motivate the research and applications of optical neural networks (ONNs) as radiation-hard, high-speed, and energy efficient computing platforms in high radiation environments.

2. Deep Learning for Real-time UCN Detection and Super Resolution

Experimental UCNs hit images are generated using the direct detection method using solid state detectors such as CMOS imaging cameras. The number of UCN hits varies per image, and thus having a neural network directly output the bounding box and hit position coordinates is not possible as the number of output neurons will vary with the number of UCN hits. To address this issue, we propose to utilize the You Only Look Once v3 (YOLOv3) network [5] as an efficient region proposal network to detect and extract UCN hits. The extracted patches are then fed into a second neural network for super position resolution resulting in a two-shot detection framework.

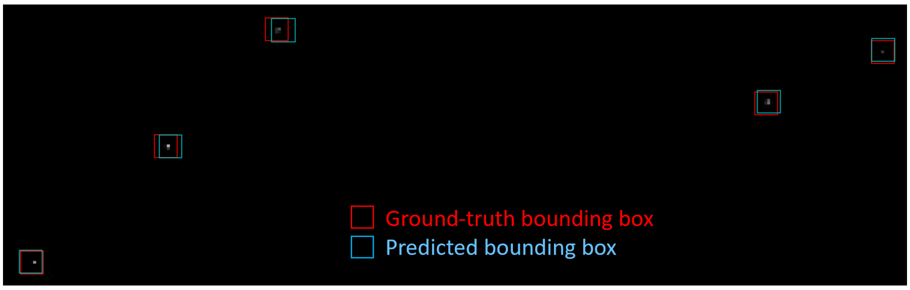

Fig. 1: An example of a cropped synthetic UCN hit image consisting of 5 hits with the ground-truth bounding box (red) and the predicted (blue) by the trained YOLOv3 network.

3. Results and Future Work

We generate a large synthetic dataset of 6,500 UCN images of size 416×416 pixels and their corresponding ground-truth labels. The dataset is split approximately into 75% for training, 5% for validation, and 20% for testing. Each image is generated by randomly placing individual UCN hits generated by Allpix Squared in a blank 416×416 image. The total number of UCN hits per image is randomly chosen. An example of a cropped synthetic image is shown in Figure 1. We note that the results shown here will only be for the network accuracy for UCN *detection*. Further work is needed to incorporate the super position resolution task.

The network is trained for 50 epochs and the performance of the trained model is evaluated using the test dataset consisting of 5558 true UCN hits. The model performance is summarized in Table 1. From the 5557 predicted hits by the trained model, almost all predicted hits are true positive (TP), where the predicted bounding box captures an UCN hit. The remaining predicted hits are split between false negative (FN), where the model did not predict a bounding box for a true UCN hit, and false positive (FP), where a bounding box was predicted but did not capture a UCN hit. Figure 1 shows an example of the predicted bounding box (blue) and the ground-truth (red). Overall, the model can detect UCNs with very high accuracy.

Table 1: Summary of UCN detection performance on the test dataset.

# Ground Truth Hits	# Predicted Hits	TP	FP	FN	Precision	Recall	F1 Score
5558	5557	5530	13	14	99.77%	99.75%	99.76%

Currently, we have demonstrated the performance of the UCN detection portion of our real-time algorithm. Further work is being done to implement the hit position prediction into the algorithm for real-time super position resolution. In addition, work is being done in parallel to implement and test the network performance using an OSNN. In summary, the goal of this work is to develop and demonstrate a two-shot network that simultaneously performs real-time UCN detection and super resolution on a chip based ONN.

References

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