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Oscillatory Neural Networks Implemented on FPGA for Edge Computing Applications

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***Abstract*—This PhD work focuses on Oscillatory Neural Network (ONN) computing paradigm for edge artificial intelligence applications. In particular, it uses a digital ONN design implemented on FPGA to explore novel ONN architectures, learning algorithms, and applications. First, using a fully-connected ONN architecture, ONN can perform pattern recognition, applied in this work for various edge applications, like image processing and robotics. Then, this work introduces layered ONN architectures for classification tasks applied to image edge detection.**

***Index Terms*—Oscillatory neural networks, Edge AI, Pattern Recognition, Image edge detection, Robot obstacle avoidance**

I. Introduction

In recent years, neuromorphic computing has emerged as a promising hardware for edge artificial intelligence implementation. In particular, Oscillatory Neural Network (ONN) [1], [2] emerges as a suitable solution for edge computing [3]. ONNs are artificial neural networks where each neuron is an oscillator coupled with synaptic elements. ONN phase computing, with information represented in phases between oscillators, allows to limit voltage amplitude and reduce power consumption [4]. This PhD work explores novel ONN architectures, learning algorithms, and applications with a digital implementation on FPGA [5]. In state-of-the-art, ONN is used with a fully-connected architecture to solve auto-associative memory tasks. This work showcases ONN auto-associative memory properties for edge applications using ONN for real-time image recognition and obstacle avoidance on mobile robots. Additionally, other architectures are investigated to perform beyond auto-associative memory tasks. Two-layer ONN architectures are introduced with bidirectional or feedforward connections to solve hetero-associative memory or classification tasks. The two-layer ONN architectures are applied for image edge detection applications.

II. ONN Computing Paradigm

ONN is a neuromorphic paradigm inspired by brain oscillations. ONNs are networks of coupled oscillators, where each neuron is an oscillator coupled by analog or digital synaptic elements. ONN uses phase computing, where information is represented in the phase difference between oscillators. ONN inference starts by initializing oscillators' phases. Then, phases evolve depending on coupling elements until phase stabilization to a stable point representing the output. The inference is associated with the minimization of an intrinsic energy parameter. Coupling elements define the energy landscape, which allows associating the correct output given an input. Coupling elements are configured during learning to solve specific tasks efficiently.

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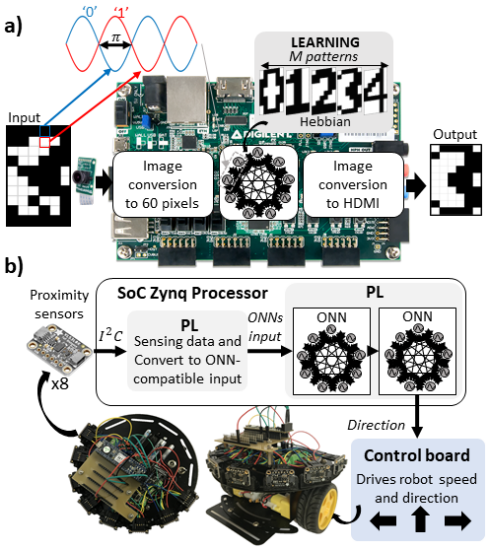

Fig. 1. a) Fully-connected ONN applied to real-time digits recognition from camera stream. b) ONN-based SoC to read, condition, and treat sensory data.

III. ONN Digital Design

This work focuses on a specific ONN implementation with a digital ONN design on FPGA [5]. In this design, each oscillator is a 16-stage digital oscillator. It can represent 16 phases between 0° and 360°, oscillating between 0 and 1. Synapses are 5-bits signed registers allowing integer synaptic weight amplitude between $[-15; +15]$.

IV. Fully-Connected ONN for Pattern Recognition

ONNs with fully-connected architecture can perform auto-associative memory tasks. It can learn patterns and retrieve them from corrupted information, executing pattern recognition. Learned patterns are memorized in the synaptic couplings

between oscillators. Synaptic weights are commonly computed from unsupervised learning rules and normalized to fit weights amplitude from implementation. ONN for pattern recognition can be used for various edge applications. For example, in this PhD work, ONN is used to perform real-time digits recognition from a camera stream [5], see Fig. 1.a). The ONN learns five 10x6 images representing digits (0 to 4) and can retrieve them from input images with flipped pixels. At first, learning is computed offline, but more recently, the digital ONN architecture has been modified to allow on-chip learning [6]. In this case, a 5x3 ONN is trained on-chip with up to 3 digits (0 to 2).

Additionally, a second robotic application is developed with ONN configured for pattern recognition to perform obstacle avoidance. Two cascaded-ONNs are included in robots equipped with proximity sensors. Proximity values are encoded to become inputs of the first ONN. The first ONN detects obstacles, and the second ONN defines a novel direction to avoid detected obstacles. A first version is tested on the industrial robot E4 [7] and shows efficient performances to avoid obstacles and hollows in real-time (Video). Then, an all-in-one architecture is developed to have an ONN-based System-on-Chip (SoC) capable of reading, conditioning, and treating sensory data based on ONN [8]. The system is tested on an Arduino robot equipped with 8 proximity sensors, see Fig. 1.b).

V. Layered ONN for Classification

The latest research focuses on ONN layered architectures to enlarge the scope of applications. First, a bidirectional two-layer architecture is introduced to perform hetero-associative memory by associating data with different dimensions. Using an adapted Hebbian rule with learning patterns from state-of-the-art Sobel filters, this novel architecture can replace convolutional filters to perform image edge detection [9], see Fig. 2. However, some edges are still incorrectly retrieved. Additionally, the main limitation is the latency of the computation. Using parallel ONNs can partially solve the problem, but for large images, resource utilization limits the number of parallel ONNs, increasing latency. Thus, an alternative architecture is introduced with the digital ONN to solve latency limitations and edge detection precision. Using a two-layer feedforward ONN requires only a 'one-shot' computation and less weighted sum computation, thus computing faster with fewer resources. The feedforward ONN is introduced in [10] and applied to image edge detection by customizing weights from bidirectional two-layer ONN, see Fig. 2. The feedforward ONN shows better precision, resource utilization, and latency on the image edge detection task than the bidirectional ONN [10].

VI. Conclusion

This PhD work explored various ONN architectures and learning algorithms to enlarge the scope of ONN applications for artificial intelligence at the edge. In particular, the ONN with fully-connected architecture was used to perform pattern recognition for image processing and robotic applications. Additionally, a solution was proposed to achieve learning on-chip

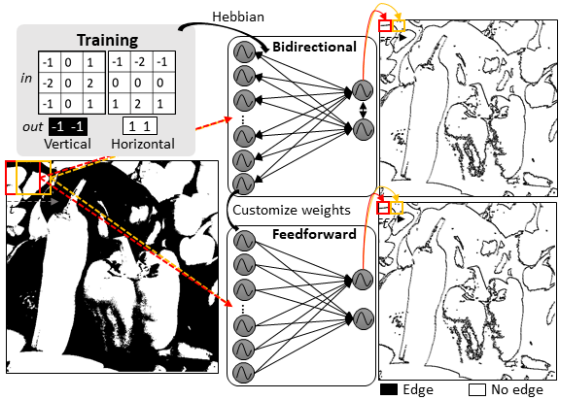

Fig. 2. Two-layer ONN architectures applied to image edge detection.

for pattern recognition. Then, this work introduced layered-ONN architectures which showed efficient performances to solve the image edge detection application.

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