Bio-inspired Artificial Vision with Complex-Valued Neural Networks

Master 2 Internship

Laboratory: SONDRA, Supélec ONERA NUS DSO Research Alliance, France & IPAL, CNRS IRL 2955, Singapore

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Complex-valued Neural Networks (CVNNs) are a variant of traditional Real-Valued Neural Networks (RVNNs) in which at least some components of the model are extended to the complex domain [Hir]. These models have been extensively studied over the last years [BQL21, LHG22], notably for classification, segmentation, and reconstruction tasks in the domain of signal processing and radar imaging [BRV+22]. The aim of this master internship is to design innovative CVNN architectures in the context of artificial vision and bio-inspired AI. We are notably seeking innovative mechanisms to enhance their performance and representational capabilities. One prominent source of inspiration is given by the neural computations performed in biological systems and notably by the temporal synchronization of neural assemblies. According to prevailing theories, neural synchrony is a crucial element in sensory processing and the degree of synchronization among neural populations influences the outputs of downstream neurons, thereby gating information transmission. Moreover, the timing of neuronal spikes is believed to carry complementary information to that conveyed by firing rates. A significant example is the dynamic formation of neuronal sub-populations to bind distributed representations, such as visual objects within a scene. It was suggested that the importance of neural synchrony can be modeled using complex values, wherein a firing rate and a phase variable describe each neuron's output [RS13]. The proposed method demonstrates that CVNNs can robustly approximate bio-inspired neural networks such as Spiking Neural Networks (SNNs) [TGK+19]. More precisely, biological neurons communicate through two sort of messages: they encode feature presence via discharge frequency, known as rate coding, and represent information binding through the synchrony of their firing patterns.

The internship aims to build on previous studies that used CVNNs for com-

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puter vision and computational neuroscience applications. We notably wish to continue the work of Sindy Löwe et al., presented in their article "Complex-Valued Autoencoders for Object Discovery" [LLRW22]. This method applied the bio-inspired CVNNs theory to the well-known Auto-Encoder (AE) architecture for object discovery. More precisely, an artificial phase of zero is added to each pixel of the input to obtain a complex-valued input: $\mathbf{x} = \mathbf{x}' \odot e^{i\theta}$. The complex-valued AE is then trained to reconstruct the amplitude of the image: during the training, neuronal sub-populations emerge as a result of the neuronal synchrony. As such, phase information can be extracted from the complex-valued output of the model: this article demonstrates that such information represents a learned spatial segmentation of objects in the image. We want to apply bio-inspired CVNNs to computer vision problems, whether artificial, for object discovery, or biological, to understand how biological neural networks function when dealing with similar tasks. We aim to explore how these models can outperform existing architectures while also being an explainable tool for neuroscience. Finally, we want to implement a new architecture for complex-valued RNNs [She20] to test the capabilities of the bio-inspired CVNN theory on spatio-temporal data.

The internship will start in the first semester of 2025, and will be hosted at SONDRA, a CentraleSupélec laboratory, in cooperation with IPAL, an international CNRS laboratory based in Singapore. The intern will be supervised by Benoit Cottereau (DR CNRS at IPAL), Chengfang Ren (Associate Professor CentraleSupélec), Joana Frontera-Pons (CR ONERA), Jérémy Fix (Associate Professor CentraleSupélec), Quentin Gabot (Ph.D Student SONDRA/ONERA/IPAL), and Jean-Philippe Ovarlez (DR ONERA & CentraleSupélec). Missions to Singapore during the internship are foreseen. The internship could lead to a Ph.D thesis.

The candidate should be willing to work in an international environment that involves Singapore and France, have a good level of AI, signal processing, and English, have excellent programming skills, and be interested in neurosciences. Some knowledge of computer vision would be a plus.

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