SSM
Scuola Superiore Meridionale

MERC PhD Project Proposal 2023/2024

Title of the research project:

Towards Trustable Biologically Plausible Neural Learning, Optimization and Control

Keywords (up to five)

Biologically Plausible Neural Networks, Neuroscience, Nonlinear Dynamics, Optimization

Supervisors (at least two from two different areas):

Supervisor 1: *Francesco Bullo (bullo@ucsb.edu)*
Center for Control, Dynamical Systems, and Computation, UC Santa Barbara, CA 93106 USA
https://fbullo.github.io
Complex Systems, Contraction Theory, Nonlinear Dynamics, Stability

Supervisor 2: *Giovanni Russo (giovarusso@unisa.it)*
Dept. of Information and Electrical Engineering & Applied Mathematics (DIEM) at University of Salerno
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Reinforcement Learning, Data-Driven Control, Control Theory, Complex Systems, Optimization

Project description (max 5000 characters)

The vision and the context of the project. Over the past few years, the theory and application of artificial neural networks (NNs) have seen tremendous progress and impact in numerous fields. Yet, despite the remarkable achievements of this technology, we do not know how to design artificial NNs that can learn from few data and generalize their outputs to handle new situations. In contrast, the consensus among neuroscientists and cognitive scientists is that these features are essential for human-level *intelligence* and are intrinsic to biological NNs. Given this analysis, the **overarching goal** of this project is to design trustable, biologically plausible architectures to tackle learning, optimization and control tasks. We aim to: (i) guarantee resilient stable behavior in any operating condition, despite disturbances; and (ii) allow autonomous self-rewiring, adapting their synaptic topology and weights to handle new situations. Unifying concepts from neuroscience and machine learning, our technical approach is threefold:

(i) propose general normative approaches to translate learning, control and optimization problems into continuous-time recurrent dynamics implementing firing-rate NNs with synaptic dynamics implementing learning rules;

(ii) characterize key dynamical properties of the resulting NN architecture, in terms of functionality, efficiency, contractivity, and more. We also plan to devise dynamical mechanisms enabling the network to autonomously re-wire and re-tune its weights to adapt to different operating conditions;

(iii) applying the results to one or more applications areas, selected depending upon opportunity and time, among (a) data dimensionality reduction problems in neuroscience and engineering, (b) modern optimization-based feedback control design such as model predictive control, NN-based system safety verification.

The results of this highly interdisciplinary project will be transversal to several communities, such as neuroscience and cognitive sciences, systems and control engineering, machine learning.

Project objectives and methodology. The detailed research program will be shaped based on the **interests of students**. A preliminary list of concrete research objectives is given below.

O1 – *From Learning, Control and Optimization problems to NNs***.** With this objective we aim at obtaining a normative framework to systematically translate learning, control and optimization problems into NNs that are guaranteed to converge, despite disturbances, to equilibria corresponding to the optimal solution to the problem. We will consider possibly non-convex, constrained, problems and, leveraging the prior work by the proponents, we might exploit tools from monotone operators, proximal gradients and contraction theory to devise NNs exhibiting both neural and synaptic dynamics with the desired properties.

O2 – Dynamic Synapses Re-wiring. Given the framework from O1, we will distil dynamic rules enabling the network to re-wire and tune its weights in order to adapt to new tasks and streams of data. These dynamic processes will be embedded into the synaptic dynamics of the network and we aim at characterizing both the corresponding dynamic properties and how the NN topology changes in response to external stimuli. A particular emphasis will be given in investigating if known features of biological NNs, such as plasticity, emerge from this re-wiring mechanism. As a by-product, we also aim at investigating is our biologically plausible NNs would exhibit the ability, elusive for artificial NNs, to *forget* information that becomes irrelevant.

O3 – Embodying the Architecture. With this objective, we aim at embodying the neural-synaptic dynamics from O1 and O2 into an architecture that is suitable for real-time computations. We will investigate if the architecture from the above objectives can be effectively implemented into a computational platform with limited power/computational abilities. We also aim at investigating if the architectures from O1 and O2 would resemble those of known connectomes (such as the C. Elegans connectome that has been fully mapped) from simple organisms. We expect that this analysis will help us to both map the functionalities arising from the NNs of this project into specific biological circuits and, if needed, to simply our NNs making it possible to embody them into real hardware.

O4 – *Validating the Architecture*. We will validate the results onto challenging and exciting applications, selected depending upon opportunity and time (see item (iii) above). We expect an iterative process between theory and applications, where application aspects inform the development of the methodological tools.

Workplan. The project will be developed in incremental tasks and periodic meetings will be scheduled with the supervisors. First, the student will start with becoming familiar with the existing literature in the areas related to the project. The output of this first step will be the definition of a preliminary methodology that has the potential to tackle the above objectives. Then, in the second phase, the student will develop the methodology and deploy/test the theory on small-scale problems. The final part of the project will see the student applying the methods and tools developed to a selection of real-world applications (see above) that are relevant to MERC.

See the list of references for further details on the different aspects of the project.

Relevance to the MERC PhD Program (max 2000 characters)

The project is, by its very definition, highly interdisciplinary. The ambition of the project is to disrupt the way NNs are designed and analysed. Our aims are clearly related to modern intelligent complex systems. The project also has a link with risk, not only through the application, but also through the fact that the embodied networks will need to safely operate in environments that are noisy.

See the list of references for further details on the different aspects of the project.

Key references

B. Lake, T. Ullman, J. Tenenbaum and S. Gershman, "Building machines that learn and think like people," Behavioral and brain sciences, vol. E253, pp. 1-72, 2017

C. Hoffmann, "Is AI intelligent? An assessment of artificial intelligence, 70 years after Turing," Technology in Society, vol. in press, pp. 1-38, 2022.

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D. Hall and Z. Altun, C. Elegans Atlas, Cold Spring Harbor Laboratory Press, 2008.

N. Bhattasali, A. Zador and E. Engel, “Neural circuit architectural priors for embodied control,” 2022. [Online]. Available: https://arxiv.org/abs/2201.05242 [Accessed 2022].

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V. Centorrino, F. Bullo, G. Russo, "Modelling and Contractivity of Neural-Synaptic Networks with Hebbian Learning", Automatica, in press, 2024

V. Centorrino, A. Gokhale, A. Davydov, G. Russo, F. Bullo, "Positive Competitive Networks for Sparse Reconstruction", Neural Computation, in press, 2024

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V. Centorrino, F. Bullo, G. Russo, "Contraction Analysis of Hopfield Neural Networks with Hebbian Learning", 2022 IEEE 61st Conference on Decision and Control, Cancun, Mexico, 2022, pp. 622-627

V. Centorrino, A. Gokhale, A. Davydov, G. Russo, F. Bullo, "Contracting Dynamics for Time-Varying Convex Optimization", IEEE Transactions on Automatic Control, 2023, Submitted.

A. Davydov, S. Jafarpour, A. V. Proskurnikov, and F. Bullo. Non-Euclidean Monotone Operator Theory and Applications. Journal of Machine Learning Research, June 2023. Submitted.

A. Davydov, A. V. Proskurnikov, and F. Bullo. Non-Euclidean Contraction Analysis of Continuous-Time Neural Networks. IEEE Transactions on Automatic Control, August 2023

Joint supervision arrangements

Meetings will be scheduled on an as-needed basis, in order to ensure the effective development of the project. As a minimum, supervisor(s) will meet students at least once a week.

Location and length of the study period abroad (min 12 months)

The candidate will be able to spend a research period (or research periods) at Prof. Bullo's lab at the University of California, Santa Barbara.

Any other useful information

The project is best suited for students with a preference towards mathematical (proof-oriented) mindset, and with a background in nonlinear dynamical systems. For further details on the background students can contact their potential supervisors.

Please return this form via email by no later than 9th February 2024 to merc@ssmeridionale.it