Dynamic Learning for Intelligent Autonomous Decision-Making Systems

I. Motivation and Research Foci

The phenomenal increase of interest in intelligent autonomous systems observed in the recent years is creating a paradigm shift in the way cyber-physical systems interact with humans in our society. It is, therefore, within the responsibilities of the new generation of scientists to determine new research directions towards automation augmented with actual machine intelligence. How can a robot reliably react to and operate within its environment? How is this connected to how humans dynamically process sensory information? The answer to these famous problems are not only linked to deeper understanding, but also to the decision-making potential of autonomous systems and their ability to interact with humans. Towards this direction, it is important to understand and formally analyze the fundamental properties of **learning, as a continuous, dynamic, and adaptive process** of acquiring new understanding, knowledge, or skills. My goal is to develop mathematical tools and computational algorithms to understand and utilize the dynamic process of learning in the context of autonomous decision-making systems, and beyond.

My research focus lies on the integration of three fields of mathematics: **control theory**, **optimization**, and **machine learning**. Control theory and optimization are closely related fields studying the properties of dynamical systems, and the algorithms and mathematics of optimal-decision making, respectively. Machine learning, on the other hand, studies computational algorithms that aim to recognize patterns and approximate numerical functions, and is a rapidly emerging field with recent experimental success. As a result, using the newly introduced learning algorithms to address traditionally difficult control problems has been a topic of increasing attention. However, I am mainly interested in the inverse problem: developing and utilizing rigorous mathematical concepts from control and optimization to overcome the fundamental limitations of current machine learning algorithms, especially towards their integration with autonomous systems, as well as with humans. In this direction, the interplay between machine learning, optimization, and control theory becomes a uniquely promising, yet, surprisingly unexplored, field.

II. Research Experience

In my research so far, I have focused on open learning and control problems with applications in image and sound identification, graph partitioning, reinforcement learning, control of multi-agent systems, identification of network influence graphs, intelligent transportation, safe robot navigation, and human-robot interaction.

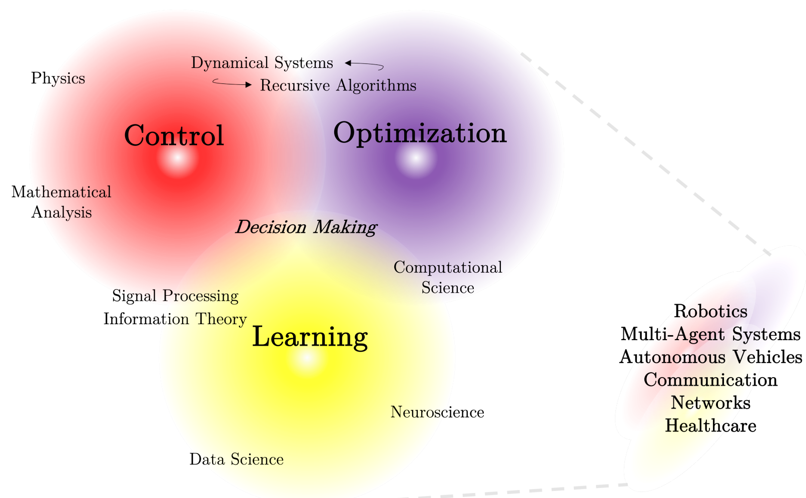

Figure 1: Research fields of interest. From theory to applications.

A. Learning with Progressively Growing Knowledge Representations.

Deep learning methods, the current state-of-the-art of machine learning algorithms, typically use overly complex black-box models that require enormous amounts of time, energy, data and computational resources to be trained, while lacking robustness with respect to input noise and adversarial attacks. To address these issues, I investigated the properties of learning with progressively growing knowledge representations, and proposed a novel and robust learning algorithm that progressively adjusts its complexity through an annealing optimization approach [1]. The proposed **Online Deterministic Annealing (ODA)** algorithm can be viewed as a progressively growing competitive-learning neural network with inherent regularization mechanisms, the learning rule of which is formulated as an online gradient-free stochastic approximation algorithm. ODA can be used in **supervised and unsupervised learning** [1], **memory-efficient reinforcement learning** [2, 3], and **graph partitioning** settings [4]. This is one of the first endeavors to construct such a progressive approach for machine learning applications, and can lead to new developments in the analysis and applicability of dynamic machine learning models that can augment autonomous systems in real time. The proposed architecture has been developed and shared with the community as an **open-source software package** [5].

B. A System-theoretic Approach Towards the "One Learning Algorithm" Hypothesis.

The existence of a universal learning architecture in human cognition is a widely spread conjecture supported by established experiments from neuroscience. I built upon the principles of the ODA algorithm to approach the design of a universal learning architecture based on system-theoretic concepts and well-established abstractions of the cognitive model of the visual and auditory cortex of humans, which involves: (a) **multi-resolution analysis**, (b) **invariant representations learning**, and (c) **hierarchical decision-making** based on a progressively-growing knowledge base. This architecture maps directly to current deep learning algorithms with one main difference: it is **robust**, **interpretable**, **hierarchical**, **progressive**, and **memory-based**, thus maintaining all the prevalent properties of human intelligence [6, 7].

C. Learning Interaction Laws of Networked Systems.

Networks of interacting agents are among the most fascinating systems to study. I focused on learning the coordination laws of complex collectives, such as bird flocks and artificial UAV swarms, which lies beyond the traditional boundaries of the field of machine learning and is related to multi-agent system identification. To discover their interaction dynamics, I used energy-based port-Hamiltonian modeling concepts and optimization techniques from control theory and machine learning in two different scales: the microscopic and the macroscopic. In the microscopic scale, I developed algorithms to **detect the leaders, the influence graphs, and the interaction laws of swarms by observing its agents**, with applications in defense mechanisms against adversarial drone attacks [8]. To study large animal flocks, I built upon mathematical principles from mean-field game theory and introduced new learning algorithms in the macroscopic scale, to **infer the coordination laws of large swarms by observing the evolution of their density** over time [9, 10, 11].

D. Human-Robot Interaction, Safe Robot Navigation, and Intelligent Transportation.

The applications of the fusion of control, optimization, and learning in robotics and autonomous driving are tremendous. Regarding safe navigation, I designed a real-time control scheme to solve the challenging problem of **safe robot navigation, under spatial and temporal constraints** [12]. Regarding human-robot interaction, I worked on both **physical human-robot collaboration** [13], and the development of a **novel brain-robot interface** [14]. In both cases, I gave emphasis on human intention estimation using adaptive control techniques and subspace system identification methods. The proposed methodology was validated through extensive experimentation, teleoperating a redundant, anthropomorphic robotic arm in real time. Finally, with the advent of autonomous vehicles on public roads imminent in the near future, I worked on the focal problems of **safe overtaking and highway merging in both autonomous and mixed-traffic settings**. I focused on optimal and model predictive control policies and adaptive estimation techniques to solve the traffic control problems in real time, while guaranteeing safety [15].

III. Future Research Goals

In the immediate future, I will be working on developing new mathematical tools and algorithms for intelligent autonomous systems, based on my own work and both new and established results from mathematics, control theory and machine learning. In particular, I plan to:

(i) **Study new methods for constructing invariant data representations**, based on mathematical tools for symmetry group representation. This is considered to be the "holy grail" of machine learning research, and can also greatly enhance the design of dynamical models, including multi-agent cyber-physical systems. In this direction, I have already started to explore the role of symmetries in enhancing the expressive power of data representations through principles of mathematical physics, similar to these of the celebrated theorems of Emmy Noether (1882-1935), that connect symmetries to conservation laws.

(ii) **Investigate new analytics for the study of "deep learning" algorithms** including recursive neural networks and reservoir computing in control applications, based on properties of dynamical systems and accelerated optimization.

(iii) **Develop risk-sensitive reinforcement learning methods** for single- and multi-agent systems. I am studying extensions of established principles of robust control, with special focus on the approximation of the so-called "information state", and the development of temporal-difference learning algorithms based on adaptive and progressively growing learning representations.

(iv) **Augment human decision makers with machine intelligence**. Interpretable knowledge representations, such as the ones constructed by the Online Deterministic Annealing approach I developed, can be used to augment human decision makers with machine intelligence, providing situational awareness, e.g., in assistive robotics or battlefield situations.

(v) **Explore Human-Robot Interaction and Human-Centered Machine Learning**. Developing dynamic learning algorithms with adaptive representations can be critically important to ensure safety and success in human-machine collaboration. Truly autonomous systems that can safely interact with humans need to be able to be trained in real-time, using human demonstration instead of programming commands written by experts in the field.

(vi) **Analyze network dynamics and structure**, and develop new network control schemes, with emphasis on social networks and the importance of "leaders" and self-organization.

Longer term, I want to push the boundaries of machine learning theory by bringing the unification of control theory, optimization, and machine learning to the mainstream. Among other things, I plan to:

(i) **Bridge the gap between control theorists, engineers, and computer scientists.** While the intersection of control and learning is an extremely promising field, there is a discrepancy between the interests, background, and research approach of the two communities. As a scientist and an engineer, equipped with solid background in the fields of control theory, computer science, and engineering, I want to bring these research communities together through my research work and interdisciplinary collaborations. I believe that these research fields can make huge leaps forward by close collaboration.

(ii) **Develop automatic theorem proving for control theory.** In the field of Programming Languages, automatic verification and testing has been shown to accelerate the productivity of the community and increase its confidence on new and surprising claims. In control and systems theory, new theorems are typically difficult to understand and check without deep knowledge of the field. As a result, the introduction of a semi-automatic theorem proving framework will not only help and accelerate the research endeavors on the field, but also the understanding and adoption of important control-theoretic results by other communities, including computer science and artificial intelligence. I plan to start a long-term large-scale project, involving multiple collaborations with computer scientists and engineers, to build a theorem dictionary database as well as new formal verification methods for control-related theorems.

(iii) **Explore alternative methods of computation.** The continuously increasing demand for computational power has already caused the emergence of new computational approaches, from analog computing via electronic circuits, to chemical and biological substances used to simulate the evolution of partial differential equations. What is there beyond Turing machines and discrete computations? How can we design input-output maps to quantify the results of analog computations, including neuromorphic architectures? What is the role of quantum computing in the fields of control and learning? New insights regarding these problems will be pivotal in a plethora of scientific fields.

(iv) **Study autoimmune diseases.** When I was diagnosed with a severe autoimmune disease located in the large intestine, the solution turned out to be unique and simple: remove the entire organ. The causes of such diseases are still unknown to scientists today. Since then, I have set a personal life-long goal to help, through my research in learning algorithms, identify the causes of autoimmune diseases, with emphasis on the effect of the different populations of gut bacteria on the onset and severity of inflammatory bowel diseases. I believe that machine learning research can lead to breakthroughs in health sciences, and can trigger real-life changes, improving our quality of life.

IV. Conclusion

I envision a future where machine intelligence is based on autonomous, continuously adaptive algorithms that can be reliably used in real-life applications and induce larger societal changes. I am actively working towards this long-term ambition, pushing the boundaries of machine learning and autonomous systems theory by developing mathematical tools from control and optimization to study and overcome the current limitations.

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