Controlling Complex Networks: When Control Theory Meets Network Science

Satellite symposium of NetSci2024, Québec City, Canada

Date: June 18, 2024

Venue: Québec City Convention Centre

Registration: https://netsci2024.com/en/participate/registration

Organizers:
Shuang Gao
Erfan Nozari
Peter E. Caines
Aming Li
Yang-Yu Liu

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SYMPOSIUM

Controlling Complex Networks

When Control Theory Meets Network Science

June 18, 2024

Québec City, Canada

Speakers (in alphabetic order):

Mario di Bernado
Peter E. Caines
Xudong Chen
Alex Dunyak
Shuang Gao
Luca Claude Gino Lebon
Jr-Shin Li
Richard Naud
Erfan Nozari
Christoph Riedl
Emma Tegling
Yuan Zhang

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NetSci

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NetSci Satellite Symposium – ***Controlling Complex Networks***
June 18, 2024

Program

Time	**Presenter**	**Title**
8:50 - 9:00		Welcome and sign in
9:00 - 9:30	Mario di Bernado	Harnessing Complex Systems for Control: the multi-agent shepherding problem
9:30 - 10:00	Christoph Riedl	Collective Intelligence and Collective Problem Solving
10:00 - 10:30	Yuan Zhang	Bridge the Gap Between Weak Structural Controllability and Strong Structural Controllability
10:30 - 11:00		Coffee break
11:00 - 11:30	Jr-Shin Li	Control of Heterogeneous Large-Scale Networks using Dynamic Reduction
11:30 - 12:00	Alex Dunyak	Q-Noise Linear Stochastic Control Systems on Large Networks
12:00 - 14:30		Lunch break
14:30 - 15:00	Richard Naud	Current Theories for Learning in Neurobiological Networks
15:00 - 15:30	Shuang Gao	Network-Coupled Mean Field Games and Their Associated Network Centralities
15:30 - 16:00	Luca Claude Gino Lebon	On Controllability of Temporal Networks
16:00 - 16:30		Coffee break
16:30 - 17:00	Xudong Chen	Sparse Ensemble Systems and Structural Controllability
17:00 - 17:30	Erfan Nozari	Modeling Complex Dynamical Networks Across Scales
18:30 - 20:30		Dinner

Abstracts

Title: Harnessing Complex Systems for Control: the multi-agent shepherding problem

Speaker: Mario di Bernardo, Professor, University of Naples Federico II

Abstract: The emergence of coordinated action between groups of interacting individuals or agents is a common feature of multi-agent complex systems in Nature and Technology. Often different groups of agents need to interact to control and tame their behaviour. Among these types of behaviour, a notable case of study is that of herding where a group of “active agents” (the herders or controllers) is assigned the task of corralling and drive another set of agents (the herd) towards a desired goal region and maintain them therein, or to make the herd follow a desired path or trajectory. In Nature this is precisely what shepherd dogs do when controlling the motion of a group of flocking sheep. In Applied Science similar herding tasks have applications in robotic exploration, search and rescue operations, surveillance and containment and, more recently, in the study of human cooperation and interaction. Currently, this problem is studied often assuming some simplifying properties such as that the target agents have a tendency to aggregate or flock with each other. Moreover it is often assumed that one or two agents are tasked with the goal of corralling the target agents without an explicit need to cooperate and share information in order to solve efficiently the problem. In this talk I will present recent work carried out by my group to model and analyse herding behaviour in complex systems in order to solve the herding control problem in the absence of some often made simplifying assumptions. After presenting the mathematical control problem of interest, I will discuss some of the solutions we proposed and investigate applications in human-machine cooperation and the emergence of coordinated behaviour in multi-agent systems.

Biography: **Mario di Bernardo** (SMIEEE ’06, FIEEE 2012) is Professor of Automatic Control at the University of Naples Federico II, Italy and Visiting Professor of Nonlinear Systems and Control at the University of Bristol, U.K. He currently serves as Rector's Delegate for International Relations at the University of Naples Federico II and coordinates the research area on Modeling and Engineering Risk and Complexity of the Scuola Superiore Meridionale, the new School of Advanced Studies located in Naples. On 28th February 2007 he was bestowed the title of Cavaliere of the Order of Merit of the Italian Republic for scientific merits from the President of Italy. In January 2012 he was elevated to the grade of Fellow of the IEEE for his contributions to the analysis, control and applications of nonlinear systems and complex networks. His research interests include the analysis, synchronization and control of complex network systems; piecewise-smooth dynamical systems; nonlinear dynamics and nonlinear control with applications to engineering and computational biology. He authored or co-authored more than 220 international scientific publications including more than 110 papers in scientific journals, a research monograph and two edited books. According to the international database SCOPUS (June 2022), his h-index is 51 and his publications received over 11000 citations by other authors. In 2017, he received the IEEE George N. Saridis Best Transactions Paper Award for Outstanding Research.

Title: On Controllability of Temporal Networks

Speaker: Luca Claude Gino Lebon, PhD Candidate, Linkoping University

Abstract: Temporality has been recently identified as a useful feature to exploit when controlling a complex network. Empirical evidence has in fact shown that, with respect to their static counterparts, temporal networks may allow to reach larger reachable sets and may even require less control energy when steered towards an arbitrary target state. However, to date, we lack mathematical conditions guaranteeing that the dimension of the controllable subspace of a temporal network is larger than that of its static counterpart. In this presentation we consider the case in which a static network is input connected but not controllable. We show that when the structure of the graph underlying the temporal network remains the same throughout each temporal snapshot while the edge weights vary, then the temporal network will be completely controllable almost always, even when its static counterpart is not. An upper bound on the number of snapshots needed to achieve controllability is also provided.

Biography: Luca Claude Gino Lebon is a PhD candidate at the Department of Electrical Engineering, Division of Automatic Control, at Linkoping University, Sweden, working under the supervision of Claudio Altafini. He received the Master Degree (cum laude) in Electrical Engineering in 2022 from the University of Padua, Italy. His PhD project focuses on control problems for dynamical systems over networks.

Title: Bridge the gap between weak structural controllability and strong structural controllability

Speaker: Yuan Zhuang, Associate Professor, Beijing Institute of Technology

Abstract: Controlling complex networks is a fundamental challenge in various fields, where the concept of structural controllability offers a useful tool. A structured system is deemed (weakly) structurally controllable if a controllable realization exists, and strongly structurally controllable (SSC) if all realizations are controllable. Notably, it has been observed that as the number of nodes (n) in a network approaches infinity, the proportion of weakly controllable networks to the total number of networks tends to one (O'Rourke and Touri, 2016). By contrast, for SSC networks, this ratio converges to zero (Menara et al., 2017), presenting a significant disparity. To bridge the gap between weak structural controllability and SSC, we propose a novel controllability concept termed partial strong structural controllability (PSSC). By categorizing indeterminate entries into generic and unspecified, a system achieves PSSC if, for almost all values of the generic entries within the parameter space—excluding a set of measure zero—and any nonzero complex values of the unspecified entries, the system remains controllable. Notably, this notion extends the generic property inherent in conventional weak structural controllability. We provide algebraic and bipartite graph-based necessary and sufficient conditions for single-input systems to be PSSC, with the latter being polynomial-time verifiable. Furthermore, we outline conditions for multi-input systems in a specific case. We conjecture that by adjusting the ratio of generic entries, the ratio of PSSC networks to the total number of networks can be fine-tuned to any value between 0 and 1. Additionally, we introduce a related notion—perturbation-tolerant structural controllability—which relaxes the nonzero constraint on values of unspecified entries. This concept finds application in measuring the controllability resilience of networks against weight variants within any given subset of links.

Biography: Dr. Yuan Zhang received the B.S. degree in control science and engineering from Tongji University, Shanghai, China in 2014, and the Ph.D degree in control science and engineering from Tsinghua University, Beijing, China in 2019. Since then, he has worked in Beijing Institute of Technology, Beijing, China, first as a postdoctoral fellow, and currently an associate professor. He was a visiting research fellow at the University of Western Australia, Australia in 2024. He received the Excellent Doctoral Dissertation Award from Tsinghua University, and was selected in the China Postdoctoral Innovative Talent Support Program, both in 2020. His main research interests include control, analysis, and optimization of complex network systems, and data-driven analysis and control. He has published 10 papers in IEEE Transactions on Automatic Control and Automatica in the field of network science.

Title: Q-Noise Linear Stochastic Control Systems on Large Networks

Speaker: Alex Dunyak and Peter E. Caines, McGill University

Abstract
The control of linear dynamical systems on networks of arbitrary scale and complexity is inherently intractable. However, subject to conditions, sequences of such networks can be approximated by their graphon limits which are convergence objects for dense graphs as the number of nodes and edges tends to infinity. Analytically, graphons constitute the space of bounded measurable symmetric functions on the unit square. This paper builds on recent developments in games and optimal control for linear stochastic systems on graph limits (Dunyak and Caines, CDC (2022, 2023)); in that work, input disturbance processes which enter at all nodes are modelled by Q-Wiener noise processes across the graph. Following classical work (Curtain (1975), Bensoussan (1971,2007), Ishikawa (1979)), explicit solutions are given for the LQG optimal control problem for systems distributed over graphons. The natural solution to this problem is given via operator-valued differential Riccati equations which do not typically have analytic closed form solutions. However, it is shown that for undirected network systems with (necessarily) symmetric graphon A, and with identical input matrices, an explicit solution S(A, Q) to the infinite dimensional Riccati equation exists. When A is low rank, S(A, Q) may be further analyzed (following Gao et al (2019, 2021)) via finite dimensional operator invariant subspaces. In particular, for systems on network limits, the discounted infinite horizon LQG problem has an explicit value function V(S, Q) = V(S(A, Q), Q) which depends upon the relation between the eigenfunctions of the underlying graph limit A and the noise covariance Q. Finally, the relationship of the value function V(S(A, Q), Q) to features of networks studied in network science (Watts(1999)) is explored. These results are illustrated on explicitly solved low rank examples.

Biography (Alex Dunyak)
Alex Dunyak is a PhD student at McGill University studying the application of control theory to large networks. He received a master's degree from the New York University Tandon School of Engineering in 2019, working with Professor Quanyan Zhu, and a bachelor's degree in computer systems engineering and mathematics from the University of Massachusetts, Amherst in 2017.

Biography (Peter E. Caines)
Peter E. Caines received the BA in mathematics from Oxford University in 1967 and the PhD in systems and control theory in 1970 from Imperial College, University of London, supervised by David Q. Mayne, FRS. Following PDF and visiting positions he joined McGill University in 1980, where he is Distinguished James McGill Professor and Macdonald Chair in the Department of Electrical and Computer Engineering. He received the IEEE Control Systems Society Bode Lecture Prize (2009), is a Fellow of IFAC, CIFAR, SIAM, IEEE, the IMA (UK) and the Royal Society of Canada (2003), and a member of Professional Engineers Ontario. His monograph, Linear Stochastic Systems (Wiley, 1988), is now a SIAM Classic and his research interests include stochastic and hybrid systems, and mean field (games and control) systems on complex networks.

Title: Network-Coupled Mean Field Games and Their Associated Network Centralities

Speaker: Shuang Gao, Assistant Professor, Polytechnique Montreal

Abstract: This talk will present models and solutions to mean field games with large network couplings and the decomposition method for identifying low-complexity solutions for such problems. More specifically, we will investigate approximate solutions to large-scale linear quadratic stochastic games with heterogeneous network couplings following the graphon mean field game framework. A graphon time-varying dynamical system model is first formulated to study the finite and then limit problems of linear quadratic graphon mean field games. The Nash equilibrium of the limit problem is then characterized by two coupled graphon time-varying dynamical systems. For the computation of solutions, two methods are employed where one is based on fixed point iterations and the other on a decoupling operator Riccati equation; furthermore, two corresponding sets of low-complexity solutions are established based on graphon spectral decompositions. The equilibrium Nash values of such dynamic games lead to the introduction of fixed-point centralities for large networks for identifying important and influential nodes on networks, and the connections with existing network centralities will be illustrated.

Based on joint work with Peter E. Caines, Minyi Huang and Rinel Foguen Tchuendom.

Biography: Shuang Gao is an assistant professor in the Department of Electrical Engineering at Polytechnique Montreal (the affiliated engineering school of University of Montreal). Before joining Polytechnique Montreal, he was a postdoctoral researcher at McGill University and a research fellow at the Simons Institute at University of California, Berkeley. He received his PhD degree in Electrical Engineering from McGill University with specialization in systems and control in 2019. His research aims to discover fundamental properties of dynamics and control of systems that involve large populations of network-coupled decision makers, and achieve intelligent decision-making for such systems. Broadly, his research interests include control, game and learning theories for large networks, and their applications in social networks, epidemic networks, smart renewable energy grids and neuronal networks.

Title: Collective Intelligence and Collective Problem Solving

Speaker: Christoph Riedl, Professor, Northeastern University

Abstract: How do collectives solve difficult problems? Solving complex tasks requires striking a balance between exploiting known best solutions, and exploring new ones. Here, network structure plays a crucial part, as it influences how quickly information diffuses through the collective. Some theoretical work suggests dense networks lead to premature convergence on sub-optimal solutions, reducing collective problem solving performance. Empirical studies with human subjects, on the other hand, sometimes failed to reproduce such findings showing instead that efficient networks produce superior collective outcomes. One possible explanation for these conflicting findings may lie in behavioral differences between simulated agents and humans, namely (a) how agents explore (i.e., their search strategy) and (b) how they learn from the solutions of others (i.e., the specific mechanism of social influence). In this talk I introduce a new framework treats searchers as predictive agents that explore and exploit the solution space based on internal "mental" models built from their own past experience and experience of others. A perception-action loop controls how each agent integrates information from other searchers and controls its own exploration of the solution landscape. These predictive agents readily integrate well-established concepts including memory (bounded rationality), absorptive capacity, curiosity, search costs, and trust.

Biography: Christoph Riedl is professor for Information Systems and Network Science at the D'Amore-McKim School of Business at Northeastern University. He holds a joint appointment with the Khoury College of Computer Sciences and is a core faculty member at the Network Science Institute. He is a fellow at the Institute for Quantitative Social Science (IQSS) at Harvard and the Center for Collective Intelligence at MIT. His work has been published in leading journals including Science, PNAS, Nature Communications, Organization Science, Management Science, Information Systems Research, Academy of Management Discoveries, practitioner journals like Harvard Business Review and Sloan Management Review, as well as top computer science venues such as AAAI and CHI. His research has been featured, among others, in the New York Times, Financial Times, Wall Street Journal, and Forbes. He currently serves as a member of the editorial board of Organization Science. He is known for his scholarship on collective intelligence, human-AI collaboration, and crowdsourcing.

Title: Modeling Complex Dynamical Networks Across Scales

Speaker: Erfan Nozari, Assistant Professor, University of California, Riverside

Abstract: One of the greatest challenges in controlling complex networks is their span across multiple scales. The human brain, e.g., is commonly modelled as a network but with nodes that may be entire regions, neuronal populations, neurons, or even sub-cellular chemical reactions. A similar span across multiple scales is present in nearly all complex systems, and often drastically different dynamics are observed at each scale. Nevertheless, how the dynamics at one scale relate to those at another is poorly understood. In this talk, I focus on one key process that connects dynamics across spatial and temporal scales: averaging. I present empirical, numerical, and analytical evidence demonstrating how stationary averaging leads to linear dynamics on macroscopic variables. This is a nearly universal effect and applicable to nearly all forms of autonomous networked dynamical systems. Adding control inputs, however, can prevent averaging from completely linearizing dynamics and preserve some nonlinearity, as can any other source of nonstationarity. I will describe the theoretical limits of each scenario as well as the implications of macroscopic linearity for modeling and understanding complex network dynamical systems.

Biography: Erfan Nozari is an Assistant Professor at the University of Riverside, California Department of Mechanical Engineering. He received his B.Sc. degree in Electrical Engineering-Control in 2013 from Isfahan University of Technology, Iran, and his Ph.D. in Mechanical Engineering and Cognitive Science in 2019 from University of California San Diego. He was subsequently a postdoctoral researcher at the University of Pennsylvania Department of Electrical and Systems Engineering. His main research interests lie at the intersection of computational neuroscience, dynamical systems, and machine learning and his lab's recent focus has been on understanding the neural code and its generative mechanisms across spatial and temporal scales using the unique perspective of dynamical systems and controls. He is a Hellman Fellow and has been the recipient of the NSF CAREER Award, the IEEE Transactions on Control of Network Systems Outstanding Paper Award, and Best Student Paper Awards from the IEEE Conference on Decision and Control and the American Control Conference.

Title: Control of Heterogeneous Large-Scale Networks using Dynamic Reduction

Speaker: Jr-Shin Li, Professor, Washington University in St. Louis

Abstract: Control of complex dynamic networks is an essential yet difficult task in numerous applications across disciplines from biology and medicine to robotics. The major challenge not only lies in the large-scale nature of the networks, but also arises from the heterogeneity in the network dynamics, including node and coupling dynamics. The underactuated characteristic of the control operation adds an additional dimension to challenge the solution of controlling such networks. This in turn drives the demand for developing novel control strategies beyond conventional approaches. In this talk, we will present a dynamic reduction framework to overcome the obstacle of controlling large-scale networks. We will illustrate the main idea of our approach with diverse control problems involving large-scale networks of heterogeneous oscillators described by phase models. We will introduce a new formulation and reduction translating phase control problems into a quadratic program using Fourier decomposition. We will show the applicability and efficiency of this approach by considering diverse phase control tasks in oscillator networks, including robust phase assignment and synchronization pattern formation. We will further present a dynamic kernel method transforming a generic network system into a dynamically-equivalent system defined on a reproducing kernel Hilbert space induced by a well-defined moment kernel. We will show that the proposed kernel method can be directly adopted in a data-driven setting to facilitate system identification and learning for network systems and control.

Biography: Dr. Jr-Shin Li is Newton R. and Sarah Louisa Glasgow Wilson Professor in the Department of Electrical and Systems Engineering at Washington University in St. Louis, where he also holds a joint appointment in the Division of Computational & Data Sciences (DCDS) and the Division of Biology & Biomedical Sciences (DBBS). Dr. Li received his B.S. and M.S. from National Taiwan University, and his Ph.D. in Applied Mathematics from Harvard University in 2006. His research interests lie in the areas and at the intersection of systems, computational, and data sciences, and their applications to biology, neuroscience, quantum physics, brain medicine, public health, and control engineering. He is a recipient of the NSF Career Award in 2008 and the AFOSR Young Investigator Award in 2010. He is currently Associate Editor of the SIAM Journal on Control and Optimization (SICON) and Editorial Member of Nature Scientific Reports. He is also a co-chair of the IEEE Technical Committee on Quantum Computing, Systems and Control.

Title: Sparse Ensemble Systems and Structural Controllability

Speaker: Xudong Chen, Associate Professor, Washington University in St. Louis

Abstract: Many large-scale systems, such as biological networks and social networks, comprise relatively small networks with recurring patterns, which are commonly referred to as motifs. The importance of motifs is in the belief that their structures are essential for certain functions to be achieved. The function of our interest in this talk is a fundamental one in control theory, namely, system controllability. Specifically, we introduce and solve a structural controllability problem for continuum ensembles of linear time-invariant systems. The individual systems of the ensemble have sparse (A, B) pairs, all of which are governed by the same sparsity pattern. Controllability of an ensemble system is, by convention, the capability of using a common control input to simultaneously steer every individual systems in it. A sparsity pattern is said to be structurally controllable if it admits a controllable linear ensemble system. We provide a graphical condition that is necessary and sufficient for a sparsity pattern to be structurally controllable.

Biography: Xudong Chen is an Associate Professor in the Department of Electrical and Systems Engineering at Washington University in St. Louis. He obtained the B.S. degree in Electronic Engineering from Tsinghua University, Beijing, China, in 2009, and the Ph.D. degree in Electrical Engineering from Harvard University, Cambridge, Massachusetts, in 2014. He is an awardee of the 2020 Air Force Young Investigator Program, a recipient of the 2021 NSF Career Award, the recipient of the 2021 Donald P. Eckman Award, and the recipient of the 2023 A.V. Balakrishnan Early Career Award. His current research interests are in the area of control theory, stochastic processes, optimization, network science, and their applications.

Title: Current theories for learning in neurobiological networks

Speaker: Richard Naud, Professor, University of Ottawa

Abstract: Synaptic plasticity is believed to be a key physiological mechanism for learning. It is well established that it depends on pre- and postsynaptic activity. However, models that rely solely on pre- and postsynaptic activity for synaptic changes have, so far, not been able to account for learning complex tasks that demand credit assignment in hierarchical networks. Here we show that if synaptic plasticity is regulated by high-frequency bursts of spikes, then pyramidal neurons higher in a hierarchical circuit can coordinate the plasticity of lower-level connections. Using simulations and mathematical analyses, we demonstrate that, when paired with short-term synaptic dynamics, regenerative activity in the apical dendrites and synaptic plasticity in feedback pathways, a burst-dependent learning rule can solve challenging tasks that require deep network architectures. Our results demonstrate that well-known properties of dendrites, synapses and synaptic plasticity are sufficient to enable sophisticated learning in hierarchical circuits.

Biography: Richard is originally from Montreal where he studied Physics at McGill University. He became a computational neuroscientist through his graduate studies in Switzerland (EPFL), followed by postdocs at the University of Cambridge (UK) and TU Berlin. After a number of research discoveries in neural coding, he started his lab at the University of Ottawa (2016). He is the co-author of the textbook *Neuronal Dynamics* and has published many articles on learning and the information processing capabilities of neuronal networks.