Controlling Complex Networks: When Control Theory Meets Network Science

Satellite symposium of NetSci2018, Paris, France

Date: June 11, 2018

Venne: L'École de Musique, Châteauform (8 Bis Rue de la Fontaine au Roi, 75011 Paris)

Registration of this symposium is free of charge. Yet, symposium participants still need to register for the NetSci main conference.

Organizers:
Yang-Yu Liu
Gang Yan
Marco Tulio Angulo
Pau Vilimelis Aceituno

SYMPOSIUM

CONTROLLING
COMPLEX NETWORKS
from Biological to Social and Technological Systems

June 11 2018
Paris, France

Speakers (in alphabetic order):
Aditya Gilra
Aming Li
Anna Niarakis
Christian Commault
Giulia Cencetti
Kaj-Kolja Kleineberg
Marco Tulio Angulo
Ming Cao
Mustafa Kammash
Sergio Pequito
Shi Gu

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NetSci

NetSci Satellite Symposium – *Controlling Complex Networks*
June 11, 2018

Program

8:45-8:55	Sign in
8:55-9:00	Welcome address (Yang-Yu Liu)
	Session I (Chair: Marco Tulio Angulo)
9:00-9:40	**Mustafa Kammash**: *Cybergenetics: Control Theory and Design at the Biomolecular Scale*
9:40-10:20	**Anna Niarakis**: *Executable Disease Networks: Adding Dynamics to Molecular Maps*
10:20-11:00	**Ming Cao**: *Controlling evolutionary network games*
11:00-11:20	Break
	Session II (Chair: Gang Yan)
11:20-12:00	**Christian Commault***: Generic controllability of networks with dynamical nodes*
12:00-12:40	**Sergio Pequito:** *Trade-offs between driving nodes and time-to-control in complex networks*
12:40-2:30	Break
	Session III (Chair: Pau Vilimelis Aceituno)
2:30-3:10	**Aditya Gilra**: *Local, stable learning in spiking neural networks based on adaptive control*
3:10-3:50	**Shi Gu**: *Attempts of Analyzing Brain Networks from the Controllability Perspective*
3:50-4:30	**Marco Tuilo Angulo**: *System's theory for understanding and controlling complex microbial communities*
4:30-4:50	Break
	Session IV (Chair: Gang Yan)
4:50-5:10	(Contributed Talk) **Giulia Cencetti**: *Dynamical invariant network generation*
5:10-5:50	**Kai-Kolja Kleineberg**: *Towards controlling evolutionary dynamics through network geometry: some very first steps*
5:50-6:30	**Aming Li:** *Controlling Temporal Networks*
6:30-6:35	Conclusion (Yang-Yu Liu)

Abstracts

Aditya Gilra, University of Bonn, Germany

Title: Local, stable learning in spiking neural networks based on adaptive control

Abstract: Learning weights in a spiking neural network with hidden neurons, distinct from input or output neurons, typically requires computations that are global in space or time. This is because we need to assign credit or blame to internal weights for an error in the output, which these weights influence only indirectly. We propose a supervised local scheme, Feedback-based Online Local Learning Of Weights (FOLLOW), to train a network of heterogeneous spiking neurons with up to two hidden layers, to learn arbitrary non-linear dynamics. We construct an error feedback architecture and derive local, biologically-plausible, and stable learning rules from adaptive control theory. Strong error feedback entrains the activity of hidden neurons, enabling a modification rule on the internal weights proportional to pre-synaptic activity and fedback post-synaptic error, both of which are available locally in the post-synaptic neuron. We further propose how networks of neurons in the brain might learn forward and inverse models of the dynamics of the muscle-body system, here demonstrated for a two-link arm under gravity. We use a recurrent network to learn the forward model i.e. to predict the arm state given the time-varying control input, and a configuration termed differential feedforward to learn the inverse model, i.e. to infer the control input given the desired arm state trajectory. We use the inverse model in a further feedback loop to control the arm to reproduce a desired trajectory. We believe our FOLLOW learning scheme predicts not only a feedback architecture and learning rules in our brain for motor control, but also enables computationally-inexpensive learning in energy-efficient neuro-morphic hardware for neuro-robotics and beyond.

Bio: Aditya Gilra works in computational neuroscience, studying how neural networks in the brain can learn to control movement and perform cognitive functions, using insights from control theory and machine learning. He is a post-doc, currently at the University of Bonn, Germany, and was earlier at the EPFL, Switzerland. His background is in computational neuroscience (PhD), physics (Master's) and electrical and electronics engineering (Bachelor's).
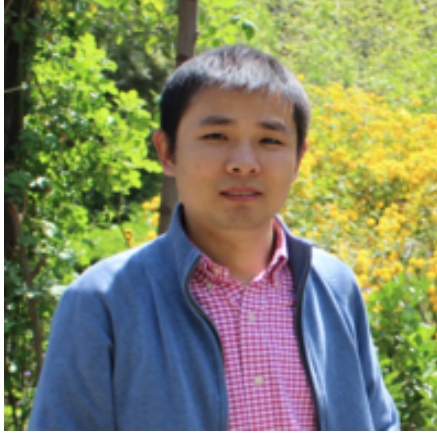
[Aming Li](), Chair of Systems Design, ETH Zürich, Switzerland.

Title: Controlling Temporal Networks

Abstract: In practical terms, controlling a network requires manipulating a large number of nodes with a comparatively small number of external inputs, a process that is facilitated by paths that broadcast the influence of the (directly-controlled) driver nodes to the rest of the network. In temporal networks, such paths are normally seldom instantaneously available. In this talk, I will show a counterintuitive conclusion that temporal networks can, compared to their static (i.e. aggregated) counterparts, reach controllability faster, demand orders of magnitude less control energy, and the control trajectories are more compact. I will also show that the energy costs of controlling temporal networks are determined solely by the spectral properties of an "effective" Gramian matrix, analogous to the static network case. And the scaling of control energy is largely dictated by the first and the last network snapshot in the temporal sequence, independent of the number of intervening snapshots, the initial and final states, and the number of driver nodes.

Bio: Aming currently works as an academic guest (postdoc) at ETH Zurich in Prof. Dr. Dr. Frank Schweitzer's group. His research interests cover network control and evolution of cooperation. Aming received his B.Sc. degree from Department of Mathematics, Zhejiang University of Technology, Hangzhou, China, 2011. Surprised by Prof. Long Wang, he got his Ph.D. in July 2017 from Center for Systems and Control, College of Engineering, Peking University, China. During Aming's PhD program, from Oct. 2014 to Feb. 2017, he worked as a visiting research scholar in Center for Complex Network Research (Northeastern University, USA) under the direction of Prof. Albert-László Barabási. From Oct. 2015 to Feb. 2017, Aming also worked in Prof. Jeff Gore's group as a visiting student at Massachusetts Institute of Technology.

[Anna Niarakis](), University of Evry, Paris-Saclay, Department of Biology

Title: Executable Disease Networks: Adding dynamics to molecular maps

Abstract: Biological processes rely on the concerted interactions and regulations of thousands of molecules that form complex molecular and signaling networks. The analysis of their structure and organization can reveal interesting topological properties that shed light onto the basic mechanisms that control normal cellular processes. Disruption and dysregulation of these complex molecular and signaling networks can lead to disease. Therefore, the mapping and accurate representation of pathways implicated is a primary but essential step for elucidating the mechanisms underlying disease pathogenesis. However, as all living systems are dynamic in nature, static representations of molecular networks can provide useful but relatively limited understanding. A dynamical study can reveal information about the system's behavior under different conditions by *in silico* simulations, perturbations, hypotheses testing and predictions. In order to address the lack of kinetic data, discrete logical modelling can be used as an alternative way to study the system's qualitative dynamic behavior. In this talk I will present a systematic effort to summarize current biological knowledge concerning Rheumatoid Arthritis in the form of a fully detailed disease network, and its subsequent automatic translation to a dynamical (Boolean) model, based on network topology and semantics, creating thus "executable" disease networks. As further experimental data will be gathered this logical model for RA could serve as a template to design continuous or stochastic models enabling more quantitative predictions. At this point, we try to understand in more details how the major functional outcomes of RA fibroblasts (apoptosis, pro-inflammatory response, chemokine secretion, bone erosion and matrix degradation) are articulated at the level of the underlying molecular network, and to what extend it might be possible to uncouple these functions and delineate means to control them separately or collectively.

Bio: Anna Niarakis is an Associate Professor (Maître de Conferences) at the University of Evry, Paris-Saclay, Department of Biology, affiliated with GenHotel EA-3886, Genopole since September 2015. She holds a bachelor in Chemistry, Master in Applied Biochemistry and Biotechnology, and a PhD in Biochemistry and Cellular and Molecular Biology, from the University of Patras, Greece, with research focusing on connective tissue diseases (Rheumatoid Arthritis, Osteoarthritis, and Loose Arthroplasty Endoprosthesis). She has also a two years training in Pharmaceutical Technology and Drug Design for Alzheimer's' disease and her post-doctoral studies were in the fields of Computational Systems Biology for Allergy (Ecole Normale Superieure, Paris) and Bioinformatics and Computational Systems Biology Analyses for Cancer (Institut Gustave Roussy, Villejuif). She is a member of the Disease Maps consortium, responsible for the Map of Rheumatoid Arthritis and a member of CoLoMoTo (Consortium for Logical Modelling Tools). Her current research interests focus on computational systems biology approaches aiming at integrating different biological data in forms of networks, and subsequent structural and dynamical studies in order to elucidate pathogenetic mechanisms in complex human disease.

Christian Commault, Univ. Grenoble Alpes, CNRS, GIPSA-lab, France.

Title: Generic controllability of networks with dynamical nodes

Abstract : In this talk we consider networks which are governed by external controls. The internal nodes of the network are composed of linear dynamic systems, in such a way that the network graph is a static structure, while the life of the system is located in the nodes. Moreover, we assume that each node is a linear structured system with a single ingoing state vertex and a single outgoing state vertex. To such structured systems, one can associate a directed graph that allows to study a lot of generic properties of the system. Combining the network graph with the node graphs provides with a global graph which will allow the study of the structural controllability of the global system. We give necessary and sufficient controllability conditions for the global system, with respect to the controllability of the nodes and to the properties of the network graph. The conditions are expressed in terms of an auxiliary graph which has the same size as the network graph, but takes into account important features of the node graphs. Besides its interest in terms of insight in the controllability of networks with dynamical nodes, this approach is also more efficient computationally than a direct checking of the controllability of the global graph.

Bio: Christian Commault is an emeritus professor at the Grenoble INP Institute of Engineering (France). He is a researcher of GIPSA-Lab (Grenoble Image, Speech Signal and Control) and his main research interests are in linear multivariable systems (mainly in structured systems both for control and diagnosis). He received the Engineer degree, the Doctor-Engineer degree and the Docteur d'Etat degree from the Institut National Polytechnique de Grenoble in 1973, 1978 and 1983 respectively. In 1975 and 1976, he taught in the Dakar Institute of Technology (Senegal). He was a visiting researcher in the department of mathematics at the University of Groningen (The Netherlands) in 1979. From 1986 to 1988 he worked in the Research Centre of Renault, Rueil-Malmaison.
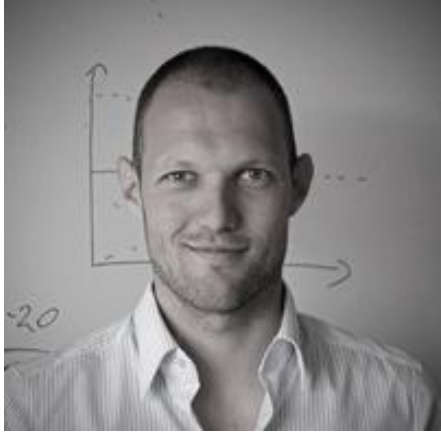
Kaj-Kolja Kleineberg, Dept. of Humanities, Social and Pol. Sc., ETH Zürich, Switzerland

Title: Towards controlling evolutionary dynamics through network geometry: some very first steps

Abstract: In this talk, I will focus on spatial patterns that emerge from evolutionary dynamics on complex networks. These patterns become visible in metric spaces that underlie the observed topologies of real and synthetic networks. I will show that in some cases these patterns can be exploited to control the dynamics by using different initial spatial configurations. These findings provide a first step towards developing a geometric theory of controlling evolutionary dynamics on complex networks.

Bio: Kolja received his diploma in theoretical Physics from the University of Muenster and his PhD from Universitat de Barcelona. He is now a postdoc at the chair of Computational Social Science at ETH Zurich. He works in the area of complex networks, in particular the evolution and competition of social networks, network geometry and multiplex networks, as well as pattern formation in evolutionary dynamics on complex networks.
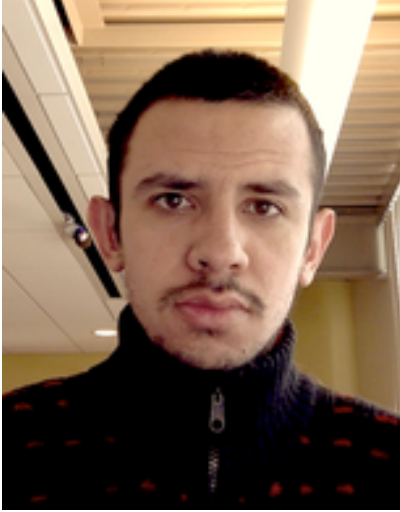
Marco Tulio Angulo (Universidad Nacional Autónoma de México, Mexico)

Title: Systems theory to understand and control complex microbial communities.

Abstract: Microbes form complex communities that play critical roles in human health and the integrity of many other ecosystems on Earth. Controlling these microbial communities as efficiently as we can control robots and industrial biotechnological processes could provide novel ways to prevent and treat human diseases, and address other essential challenges including sustainable agriculture and global warming. In this talk, I present our recent theoretical work to map ecological networks of microbial communities with nonlinear and unknown population dynamics, and how to use those inferred networks to identify the "driver species" that allows efficiently controlling large complex communities. Our results pave the way to designing more effective bacteriotherapies by efficiently controlling complex microbial communities.

Bio: Marco Tulio got his Dr.Eng. degree in Automatic Control from UNAM, México, in 2012. He was a Visiting Research Scholar (2014) and Postdoctoral Research Fellow (2015) in the Center for Complex Network Research (CCNR), Northeastern University, Boston. During 2015, he was also Sponsored Staff Collaborator in the Channing Division of Network Medicine, Harvard Medical School, and Brigham and Women's Hospital, Boston. In 2016, he joined the Institute of Mathematics, UNAM, as a CONACyT Research Fellow. His research interest are focused on understanding, diagnosing and controlling complex systems by blending Systems Theory (e.g., control theory and system identification) with Network Science. In particular, his research interests include rigorous methods for network reconstruction, control of microbial communities, and understanding the performance tradeoffs giving rise to the network structures we observe in nature.

[Ming Cao](), Faculty of Science and Engineering, Univ. of Groningen, Netherlands

Title: Controlling evolutionary network games

Abstract: Whether humans in a community, ants in a colony, or neurons in a brain, simple decisions or actions by interacting individuals can lead to complex and unpredictable outcomes in a population. Research on these systems at a broader scale, perhaps subject to substantial simplication of the agent-level dynamics, can help to characterize critical properties such as convergence, stability, controllability, robustness, and performance. In this context, evolutionary game theory has emerged as a vital toolset for analysis and control of a range of social, economic, and biological systems from a control theoretic perspective. In this talk, I will report a series of our recent results on the global convergence of evolutionary network game dynamics and the corresponding control in the form of providing incentives to change game payoffs to steer the evolutionary dynamics. I will also discuss some current challenges and open problems.

Short bio: Ming Cao is currently professor of systems and control with the Engineering and Technology Institute (ENTEG) at the University of Groningen, the Netherlands, where he started as a tenure-track assistant professor in 2008. He received the Bachelor degree in 1999 and the Master degree in 2002 from Tsinghua University, Beijing, China, and the PhD degree in 2007 from Yale University, New Haven, CT, USA, all in electrical engineering. From September 2007 to August 2008, he was a postdoctoral research associate with the Department of Mechanical and Aerospace Engineering at Princeton University, Princeton, NJ, USA. He worked as a research intern during the summer of 2006 with the Mathematical Sciences Department at the IBM T. J. Watson Research Center, NY, USA. He is the 2017 and inaugural recipient of the Manfred Thoma medal from the International Federation of Automatic Control (IFAC) and the 2016 recipient of the European Control Award sponsored by the European Control Association (EUCA). He is an associate editor for IEEE Transactions on Automatic Control, IEEE Transactions on Circuits and Systems, IEEE Circuits and Systems Magazine and Systems and Control Letters. He is vice chair of the IFAC Technical Committee on Large Scale Complex Systems. His main research interest is in autonomous agents, multi-agent systems, and distributed control.

[Mustafa Kammash](), Control Theory and Systems Biology Lab, ETH Zürich, Switzerland

Title: Cybergenetics: Control Theory and Design at the Biomolecular Scale

Abstract: Humans have been influencing the DNA of plants and animals for thousands of years through selective breeding. Yet it is only over the last 3 decades or so that we have gained the ability to manipulate the DNA itself and directly alter its sequences through the modern tools of genetic engineering. This has revolutionized biotechnology and ushered in the era of synthetic biology. Among the possible applications enabled by synthetic biology is the design and engineering of feedback control systems that act at the molecular scale in real-time to steer the dynamic behavior of living cells. Here I will present our theoretical framework for the design and synthesis of such control systems, and will discuss the main challenges in their practical implementation. I will then present the first designer gene network that attains integral feedback in a living cell and demonstrate its tunability and disturbance rejection properties. A growth control application shows the inherent capacity of this integral feedback control system to deliver robustness, and highlights its potential use as a universal controller for regulation of biological variables in arbitrary networks. Finally, I will discuss the potential impact of biomolecular control systems in industrial biotechnology and medical therapy and bring attention to the opportunities that exist for control theorists to advance this young area of research.

Bio: Mustafa Khammash is the Professor for Control Theory and Systems Biology at the Department of Biosystems Science and Engineering at ETH Zurich, Switzerland. He works in the areas of control theory, systems biology, and synthetic biology. His lab develops theoretical, computational, and experimental methods aimed at understanding the role of dynamics, feedback, and randomness in biology. He is currently developing new theoretical and experimental approaches for the design of biomolecular control systems and for their realization in living cells.

Prof. Khammash received his B.S. degree from Texas A&M University in 1986 and his PhD from Rice University in 1990, both in electrical engineering. In 1990, he joined the engineering faculty of Iowa State University, where he created the Dynamics and Control Program and led the control group until 2002. He then joined the engineering faculty at the University of California, Santa Barbara (UCSB), where he was Director of the Center for Control, Dynamical Systems and Computation (CCDC) until 2011 when he joined ETH Zurich. He is a Fellow of the IEEE, IFAC, and the Japan Society for the Promotion of Science (JSPS).

[Sergio Pequito](), Department of Industrial and Systems Engineering, RPI, USA

Title: Trade-offs between driving nodes and time-to-control in complex networks

Abstract: Recent advances in control of complex networks provide us with efficient tools to determine the minimum number of driving (or driven) nodes to steer a complex network towards a desired state. Furthermore, we often need to do it within a given time window, so it is of practical importance to understand the trade-offs between the minimum number of driving/driven nodes and the minimum time required to reach a desired state. Therefore, we introduce the notion of actuation spectrum to capture such trade-offs, which we used to find that in many complex networks only a small fraction of driving (or driven) nodes is required to steer the network to a desired state within a relatively small time window. Furthermore, our empirical studies reveal that, even though synthetic network models are designed to present structural properties similar to those observed in real networks, their actuation spectra can be dramatically different. Thus, it supports the need to develop new synthetic network models able to replicate controllability properties of real-world networks.

Short Bio: Sérgio Pequito is an assistant professor at the Department of Industrial and Systems Engineering at the Rensselaer Polytechnic Institute. From 2014 to 2017, he was a postdoctoral researcher in General Robotics, Automation, Sensing & Perception Laboratory (GRASP lab) at University of Pennsylvania. He obtained his Ph.D. in Electrical and Computer Engineering from Carnegie Mellon University and Instituto Superior Técnico, through the CMU-Portugal program, in 2014. Previously, he received his B.Sc. and M.Sc. in Applied Mathematics from the Instituto Superior Técnico in 2007 and 2009, respectively.

Pequito's research consists of understanding the global qualitative behavior of large-scale systems from their structural or parametric descriptions and provide a rigorous framework for the design, analysis, optimization and control of large-scale (real-world) systems. Currently, his interests span to neuroscience and biomedicine, where dynamical systems and control theoretic tools can be leveraged to develop new analysis tools for brain dynamics that, ultimately, will lead to new diagnostics and treatments of neural disorders. In addition, these tools can be used towards effective personalized medicine and improve brain-computer and brain-machine-brain interfaces that will improve people's life quality.

Pequito was awarded the best student paper finalist in the 48th IEEE Conference on Decision and Control (2009). Also, Pequito received the ECE Outstanding Teaching Assistant Award from the Electrical and Computer Engineering Department at Carnegie Mellon University, and the Carnegie Mellon Graduate Teaching Award (University-wide) honorable mention, both in 2012. Also, Pequito was a 2016 EECI European Ph.D. Award on Control for Complex and Heterogeneous Systems finalist and received the 2016 O. Hugo Schuck Award in the Theory Category.

Shi Gu, School of Computer Science and Engineering in University of Electronic Science and Engineering of China

Title: Attempts of Analyzing Brain Networks from the Controllability Perspective

Abstract: In this talk, I will focus on the control analysis on brain networks. First, I will review some of our previous works based on the analysis of structural connectivity matrices. Next, I will report some of our latest progresses on building the control frameworks on resting states fMRI data where we perform a system identification task followed by adapting control measurements to the identified systems. These efforts provide a novel approach of investigating brain networks with controllability tools.

Bio: Shi received his Ph.D. degree in Applied Mathematics and Computational Science from University of Pennsylvania. He is now a professor at the School of Computer Science and Engineering in University of Electronic Science and Engineering of China. He works in the area of network neuroscience, in particular the modelling of brain's evolutionary dynamics and the relationship between the network structures and dynamics.

Giulia Cencetti, Department of Information Engineering, University of Florence

(contributed talk)

Title: Dynamical invariant network generation

Abstract: With the main goal of controlling reaction-diffusion systems on complex networks, we propose two different techniques to modify the network topology while preserving the dynamical behaviour. In the region of parameters where the homogeneous solution represents an unstable equilibrium, a perturbation gives rise to irregular spatio-temporal patterns. We exploit the spectral properties of the Laplacian operator associated to the graph in order to identify the spectral manifold which is responsible of instability. The control method consists in modifying the network topology while preserving the unstable manifold. The new network therefore reproduces the dynamical response to a perturbation of the original system. The first method directly acts on the eigenmodes, thus generating a new network characterized by a general redistribution of link weights which in some cases can completely change the structure of the original graph. This indirectly implies that widely differing networks can be associated to the same time behavior. The second method instead restricts the differences between the new and the original graph to a sub-network identified by means of the spectral analysis. The modifications can be here performed directly at the level of single edges and this allows to progressively deviate from the original discrete support by applying minimal modifications, thus resulting in a more controlled network generation. This work opens a new perspective on the control of a discrete spatial support so as to obtain a chosen behavior as a result of a generic reaction-diffusion system.

Bio: Giulia Cencetti is a PhD student at the University of Florence. Her interdisciplinary background (one year studying biology, then Bachelor's and Master's Degree in physics and now a PhD in Information Engineering) took her to work on complex systems and in particular on the fascinating branch of dynamical systems on complex networks. She developed different models to explore the impact of network topology on the dynamical behaviour of a system, having as a ultimate goal to apply a strategic external control. Applications are in biology, ecosystems stability, urban traffic and information flow.