Controlling Complex Networks: When Control Theory Meets Network Science

Satellite Symposium of NetSci2021

Date: June 23-24, 2021

Venue: Virtual

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

Organizers:
Yang-Yu Liu
Raissa M. D'Souza
Mario di Bernardo

Program

Day-1: June 23

Session I (Moderator: Yang-Yu Liu)
10:00-10:30AM Invited Talk 1: **Claudio Altafini**: Minimum energy network controllability problem: role of eigenvalues and network nonnormality

10:30-11:00AM Invited Talk 2: **Sandro Zampieri**: Recent results and open problems on energy related controllability of complex networks

11:00-11:30AM Invited Talk 3: **Markus Brede**: Strategies for opinion control on social networks

11:30AM-12:00PM Break

Session II (Moderator: Raissa D'Souza)
12:00-12:30PM Invited Talk 4: **Lorenzo Zino**: Consensus over activity driven networks: a starting point to examine model-based control with heterogeneous and time-varying patterns of interactions (with Maurizio Porfiri and Alessandro Rizzo)

12:30-1:00PM Invited Talk 5: **Emma Towlson**: Maximizing subnetwork engagement in the human brain via individualized target search and network control theory

1:00-1:30PM Invited Talk 6: **Samir Suweis**: Warning, Caveats and Perspectives in Brain Controllability

Day-2: June 24
Session III (Moderator: Mario di Bernardo)
10:00-10:30AM Invited Talk 7: **Alex Olshevsky**: Optimal Shutdown for Pandemic Control

10:30-11:00AM Invited Talk 8: **Giacomo Baggio**: Network Non-Normality: A Desirable Feature for Communication and Control

11:00-11:30AM Invited Talk 9: **Mattia Frasca**: Control of multi-consensus through distributed proportional controllers

11:30AM-12:00PM Break

Session IV (Moderator: Yang-Yu Liu)
12:00-12:30PM Invited Talk 10: **Mario di Bernado:** Closing the loop across different scales: can network science meet control theory?

12:30-1:00PM Invited Talk 11: **Raissa D'Souza:** Complex networks with complex nodes

Session V (Moderator: Raissa D'Souza)
1:00-2:00PM Panel Discussion

<u>Invited Speakers (in alphabetic order):</u>

Alex Olshevsky
Boston University

TITLE: Optimal Shutdown for Pandemic Control

ABSTRACT: We consider the problem of pandemic stabilization through a non-uniform lockdown, where our goal is to reduce economic activity as little as possible while sending the number of infected patients to zero at a prescribed rate. We consider several different models of epidemic spread over networks, including SIS/SIR/SEIR models as well as a new model of COVID-19 transmissions with symptomatic and asymptomatic individuals. We provide two efficient algorithms which can compute the optimal lockdown, with one of our algorithms having a running time which scales only linearly in the number of edges in the network and is applicable to the vast majority of epidemic models we have tested. We further demonstrate a number of previously-unknown counter-intuitive phenomena by numerically computing the optimal lockdown on a number of test cases.

BIOSKETCH: Alex Olshevsky received the B.S. degree in applied mathematics and the B.S. degree in electrical engineering from the Georgia Institute of Technology, Atlanta, GA, USA, both in 2004, and the M.S. and Ph.D. degrees in electrical engineering and computer science from the Massachusetts Institute of Technology, Cambridge, MA, USA, in 2006 and 2010, respectively. He was a postdoctoral scholar at Princeton University from 2010 to 2012, and an Assistant Professor at the University of Illinois at Urbana-Champaign from 2012 to 2016. He is currently an Associate Professor with the ECE department at Boston University. Dr. Olshevsky is a recipient of the NSF CAREER Award, the Air Force Young Investigator Award, the INFORMS Computing Society Prize for the best paper on the interface of operations research and computer science, a SIAM Award for annual paper from the SIAM Journal on Control and Optimization chosen to be reprinted in SIAM Review, and an IMIA award for best paper on clinical medical informatics in 2019.

Claudio Altafini
Linkoping University

TITLE: Minimum energy network controllability problem: role of eigenvalues and network nonnormality

ABSTRACT: The aim of this presentation is to shed light on the problem of controlling a complex network with minimal control energy. We show that the control energy depends on at least two distinct factors. The first is the time constant of the modes of the network: the closer the eigenvalues are to the imaginary axis of the complex plane, the less energy is required for complete controllability. The second is the nonnormality (i.e., the 'skewness') of the network. In particular the latter factor can be captured by a combination of two centrality measures: a node-to-network centrality and a network-to-node centrality. Both these centralities can be quantified in terms of Gramians, and their difference corresponds to the non-normality of the network. In particular, the combinations of Gramian-based centrality measures we consider can be used for driver node selection in a complex network in order to simultaneously take into account conflicting control energy requirements, like minimizing the average energy needed to steer the state in any direction and the energy needed for the worst direction.

BIOSKETCH: Claudio Altafini received a Master degree ("Laurea") in Electrical Engineering from the University of Padova, Italy, in 1996 and a PhD in Optimization and Systems Theory from the Royal Institute of Technology, Stockholm, Sweden in 2001. From 2001 till 2013 he was with the International School for Advanced Studies (SISSA) in Trieste, Italy. Since 2014 he is a Professor of Automatic Control in the Dept. of Electrical Engineering of Linkoping University, Sweden. His research interests are in the areas of nonlinear systems dynamics and control, with applications to quantum mechanics, systems biology, social networks and complex networks in general.

Emma Towlson

University of Calgary

ABSTRACT: In recent years, the ability to non-invasively interact with the human brain has led to diagnostic and therapeutic opportunities for a number of brain diseases and disorders, including depression. However, the vast majority of approved interventions still rely on anatomical landmarks and rarely the individual distribution of subnetworks in the brain, drastically reducing the potential efficacy of brain stimulation. Here we implement a stimulation target search algorithm that leverages tools from network control theory. The approach identifies stimulation sites that we predict will induce maximal subnetwork engagement, and greatly outperform traditionally employed stimulation sites.

BIO: Dr. Emma Towlson is an Assistant Professor at the University of Calgary, with appointments in the Computer Science Department and the Department of Physics and Astronomy, and membership in the Hotchkiss Brain Institute, Complexity Science Group, and Alberta Children's Hospital Research Institute. She is a network (neuro)scientist who believes complex systems science is at the heart of understanding our interconnected world, and the organisms that share it. Dr. Towlson completed her postdoctoral training at the Center for Complex Network Research at Northeastern University. She received her PhD from the University of Cambridge (2015), and holds a Masters in Mathematics and Physics from the University of Warwick (2011). She is invested in bringing transdisciplinary approaches to broader audiences and educational settings. Dr. Towlson is part of the Homeward Bound network, a value-driven global leadership program that aims to change the narrative around leadership and promote the impact of women in science on decisions that shape the future of our planet.

Giacomo Baggio
University of Padova

TITLE: Network Non-Normality: A Desirable Feature for Communication and Control

ABSTRACT: Highly disordered, anisotropic networks are found ubiquitously in both natural and man-made systems. In this talk, I will provide theoretical arguments in support of this empirical evidence. First, I will mathematically characterize anisotropic networks in terms of the "degree" of non-normality of their connectivity matrices, and discuss structural indicators that effectively capture network non-normality. Then, I will illustrate how strong departure from normality benefits the controllability of, and the propagation of information over complex dynamical networks. I will focus, in particular, on the communication aspect, and show that non-normal networks yield higher information throughput in the high-noise regime. Analytical results will be complemented by numerical examples ranging from simple, structured topologies to random, heterogenous, and real networks.

BIOSKETCH: Giacomo Baggio received the Ph.D. degree in Information Engineering from the University of Padova, Italy, in 2018. From October 2015 to June 2016, he was a visiting scholar in the Control Group at the Department of Engineering, University of Cambridge, UK. From March 2018 to September 2019, he was a postdoctoral scholar at the Department of Mechanical Engineering, University of California at Riverside, CA, USA. He is currently an assistant professor at the Department of Information Engineering of the University of Padova, Italy. He was the recipient of the Best Student Paper Award at the 2018 European Control Conference (as a first author), and of the Best Student Paper Award at the 2019 American Control Conference (as a co-author). His research interests are in the areas of systems and control theory, learning and estimation, and control and analysis of dynamical networks.

Lorenzo Zino
University of Groningen

TITLE: Consensus over activity driven networks: a starting point to examine model-based control with heterogeneous and time-varying patterns of interactions (with Maurizio Porfiri and Alessandro Rizzo)

ABSTRACT: Network dynamical systems are often characterized by heterogeneous and time-varying patterns of interactions. Understanding their role is key to shed light on the emergence of collective dynamics and to establish effective control strategies. In this talk, we present recent results along these research directions by focusing on consensus problems over activity driven networks, a versatile model of temporal networks that cogently accounts for inherent heterogeneities in the link formation process. By leveraging stochastic stability theory and eigenvalue perturbation techniques, we establish closed-form results for the rate of convergence to consensus, unveiling a detrimental effect of heterogeneity on the consensus dynamics. Different is the role of heterogeneity in the presence of leaders, tasked with controlling the system evolution. In agreement with biological observations on social groups, our analysis suggests that leaders can benefit from the network heterogeneity, thereby speeding-up the convergence process. Building on these closed-form results, we elaborate on some of the open challenges in the development of realistic, but analytically-tractable models for network dynamical systems that could beget the synthesis of model-based control strategies.

Bio: Lorenzo Zino is a postdoctoral researcher with the Faculty of Science and Engineering, University of Groningen, Groningen, The Netherlands, since 2019. He received the Laurea Magistrale degree (M.S.) in Mathematical Modeling (summa cum laude) from Politecnico di Torino, in 2014, and the Ph.D. in Pure and Applied Mathematics (with honours) from Politecnico di Torino and Università di Torino (joint doctorate program), in 2018. Before joining the University of Groningen, he was a Research Fellow at Politecnico di Torino in 2018--19 and a Visiting Research Assistant at New York University Tandon School of Engineering, Brooklyn NY, US, in 2017--18 and in 2019. His current research interests include the modeling, analysis, and control aspects of dynamical processes over complex networks, applied probability, network analysis, game theory, and mathematical epidemiology.

Mario di Bernardo
University of Naples Federico II

TITLE: Closing the loop across different scales: can network science meet control theory?

ABSTRACT: Network control systems are the subject of much ongoing research in our community but what about very large-scale systems? From large flocks of minidrones or flying insects to cellular populations, finding a way to close the loop between the microscale, where agents live, and the macroscopic properties that typically need to be controlled is a crucial open challenge for network control. What and how many agents need to be controlled/sensed and at what scale is a question beyond the current state-of-the-art that requires a new holistic approach to modelling/analysing and controlling large scale network systems. In this talk I will give snapshots into some recent work from my group aimed at addressing the problem of combining network science concepts and ideas for the solution of different classes of network control problems.

BIO: 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 Deputy pro-Vice Chancellor for Internationalization at the University of Naples 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. He was elevated to the grade of Fellow of the IEEE in January 2012 for his contributions to the analysis, control and applications of nonlinear systems and complex networks. In 2009, he was elected President of the Italian Society for Chaos and Complexity for the term 2010-2013. He was re-elected in 2013 for the term 2014-2017. In 2006 and again in 2009 he was elected to the Board of Governors of the IEEE Circuits and Systems Society. From 2011 to 2014 he was Vice President for Financial Activities of the IEEE Circuits and Systems Society. In 2015 he was appointed to the Board of Governors of the IEEE Control Systems Society. He was Distinguished Lecturer of the IEEE Circuits and Systems Society for the two-year term 2016-2017. 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. In 2017, he received the IEEE George N. Saridis Best Transactions Paper Award for Outstanding Research. He serves on the Editorial Board of several international scientific journals and conferences. He is Senior Editor of the IEEE Transactions on Control of Network Systems and Associate Editor of the IEEE Control Systems Letters, the Conference Editorial Board of the IEEE Control System Society and the European Control Association (EUCA).

Mattia Frasca
University of Catania

TITLE: Control of multi-consensus through distributed proportional controllers

ABSTRACT: In this talk, I will start discussing the notion of equitable partitions for complex networks and how they impact the dynamics on the networks, focusing in particular on multi-consensus. The dynamical state observed and, more specifically, the clusters where nodes with identical dynamical behavior are grouped are related to the properties of the structures of the interactions among the units. Then, it will be shown how these results could be exploited to design control strategies for inducing multi-consensus regimes in the multi-agent system. I will discuss tree optimization problems to obtain the distributed proportional controllers achieving the multi-consensus. They differ from the hypotheses on the connectivity of the network and the type of intervention performed by the controllers. From one of them I will also illustrate a constructive algorithm solving the problem.

BIOSKETCH: Mattia Frasca was born in Siracusa, Italy, in 1976. He graduated in Electronics Engineering in 2000 and received the Ph.D. in Electronics and Automation Engineering in 2003, at the University of Catania, Italy. Currently, he is associate professor at the University of Catania, where he also teaches process control and complex adaptive systems. His scientific interests include nonlinear systems and chaos, control of complex networks and bio-inspired robotics. He is involved in many research projects and collaborations with industries and academic centers. He is referee for many international journals and conferences, Associate Editor of the Journal of Complex Networks and Editor of Chaos, Solitons and Fractals. He served as Associate Editor for IEEE Transactions on Circuits and Systems I in 2012-15 and as Associate Editor of the International Journal of Bifurcations and Chaos. He was one of the organizers of the 10th “Experimental Chaos Conference”, co-chair of the 4th International Conference on Physics and Control and chair of the European Conference on Circuit Theory and Design 2017. He is coauthor of one research monograph with Springer, three with World Scientific, and one book on Optimal and robust control and one on Nonlinear Cicruits with CRC Press. He published more than 250 papers on refereed international journals and international conference proceedings and is co-author of two international patents. He is member of the IEEE CAS Education Technical Committee and IEEE CNN Technical Committee. He was selected as member of the IEEE Forum for Leading Researchers, Amsterdam, in 2013. He is the President of the Italian Society for Chaos and Complexity (SICC) and member of the Accademia Gioenia.

Maurizio Porfiri
New York University

TITLE: Consensus over activity driven networks: a starting point to examine model-based control with heterogeneous and time-varying patterns of interactions
Authors: Maurizio Porfiri (with Lorenzo Zino and Alessandro Rizzo)

ABSTRACT: Network dynamical systems are often characterized by heterogeneous and time-varying patterns of interactions. Understanding their role is key to shed light on the emergence of collective dynamics and to establish effective control strategies. In this talk, we present recent results along these research directions by focusing on consensus problems over activity driven networks, a versatile model of temporal networks that cogently accounts for inherent heterogeneities in the link formation process. By leveraging stochastic stability theory and eigenvalue perturbation techniques, we establish closed-form results for the rate of convergence to consensus, unveiling a detrimental effect of heterogeneity on the consensus dynamics. Different is the role of heterogeneity in the presence of leaders, tasked with controlling the system evolution. In agreement with biological observations on social groups, our analysis suggests that leaders can benefit from the network heterogeneity, thereby speeding-up the convergence process. Building on these closed-form results, we elaborate on some of the open challenges in the development of realistic, but analytically-tractable models for network dynamical systems that could beget the synthesis of model-based control strategies.

BIOSKETCH: Dr. Maurizio Porfiri is an Institute Professor at New York University Tandon School of Engineering, with appointments in the Departments of Mechanical and Aerospace Engineering, Biomedical Engineering, and Civil and Urban Engineering. He received M.Sc. and Ph.D. degrees in Engineering Mechanics from Virginia Tech, in 2000 and 2006; a “Laurea” in Electrical Engineering (with honours) and a Ph.D. in Theoretical and Applied Mechanics from the University of Rome “La Sapienza” and the University of Toulon (dual degree program), in 2001 and 2005, respectively. He has been on the faculty of the Mechanical and Aerospace Engineering Department since 2006, when he founded the Dynamical Systems Laboratory. Dr. Porfiri is a Fellow of the American Society of Mechanical Engineers (ASME) and the Institute of Electrical and Electronic Engineers (IEEE). He has served in the Editorial Board of ASME Journal of Dynamics systems, Measurements and Control, ASME Journal of Vibrations and Acoustics, IEEE Control Systems Letters, IEEE Transactions on Circuits and Systems I, and Mechatronics. Dr. Porfiri is engaged in conducting and supervising research on dynamical systems theory, multiphysics modeling, and underwater robotics. He is the author of more than 300 journal publications and the recipient of the National Science Foundation CAREER award. He has been included in the “Brilliant 10” list of Popular Science in 2010 and his research featured in all the major media outlets, including CNN, NPR, Scientific American, and Discovery Channel. Other significant recognitions include invitations to the Frontiers of Engineering Symposium and the Japan-America Frontiers of Engineering Symposium organized by National Academy of Engineering; the Outstanding Young Alumnus award by the college of Engineering of Virginia Tech; the ASME Gary Anderson Early Achievement Award; the ASME DSCD Young Investigator Award; and the ASME C.D. Mote, Jr. Early Career Award.

Raissa D'Souza
UC Davis

TITLE: Complex networks with complex nodes

ABSTRACT: The statistical physics perspective has provided a wealth of understanding about massive networks, revealing the implications that network structure can have on network function and resilience. Systems with simple nodes connected together in complex network structures are typically studied. Yet, complementary to this perspective, systems with nonlinear nodes connected together in simple networks have been studied extensively in the fields of dynamical systems and control theory. Real world networks -- from brain networks to social networks to critical infrastructure networks -- lie at the interface of both, with nonlinear nodes coupled together via highly non-trivial network structures. This talk we present our recent attempts to bring the approaches together. The first part will discuss systems of nonlinear phase-amplitude oscillators coupled together by simple ring networks and by hypergraph structures. We show that the interplay of nodal dynamics and coupling structure give rise to emergent long-range order and cluster synchronization. The second part will focus on social networks, starting by modeling humans as nodes with underlying attributes coupled in complete graphs, and moving on to real-world multiplex social networks in macaque monkey societies.

BIOSKETCH: Raissa D'Souza is Professor of Computer Science and of Mechanical Engineering at the University of California, Davis, as well as an External Professor at the Santa Fe Institute. She received a PhD in Statistical Physics from MIT in 1999, then was a postdoctoral fellow, first at Bell Laboratories, and then in the Theory Group at Microsoft Research. Her work spans the fields of statistical physics, computer science and applied math. She is a Fellow of the American Physical Society, a Fellow of the Network Science Society, recipient of the 2019 Euler Award and the 2017 Outstanding mid-career research award from the UC Davis College of Engineering. She serves as Lead Editor at Physical Review Research and on the Board of Reviewing Editors at Science. She has organized key scientific meetings like NetSci 2014, was a member of the World Economic Forum's Global Agenda Council on Complex Systems, and served as the President of the Network Science Society from 2015 - 2018.

Samir Suweis
University of Padova

TITLE: Warning, Caveats and Perspectives in Brain Controllability

ABSTRACT: In the last years, an increasing number of studies have applied the tools of control theory on brain networks to quantify how anatomical network structure, defined by human connectome data, constrain or facilitate changes in brain state trajectories. Here we present new results based on the analysis of four human anatomical brain connectivity datasets, data on C. Elegans connectomes and numerical simulations, highlighting some warning and caveats in the use of brain controllability. In particular we show that there is no statistical evidence that brain networks are Kalman controllable from one single region and that biophysically irrelevant null models produce identical quantitative results presented in other works, highlighting the crucial role of proper experimental control and hypothesis-testing.

BIO: Samir Suweis is Assistant Professor (RTDB) at the University of Padova, Physics and Astronomy Department, member of the Padova Neuroscience Center (www.pnc.unipd.it) and the European Center of Living Systems (https://www.unive.it/pag/23664/). He co-lead the Laboratory of Interdisciplinary Physics (www.liphlab.com). His main research themes can be classified in three broad areas: 1) The formulation of simple principles to explain self-organization and emergent simplicity in nature; 2) Data analysis and complex network modeling and non-linear dynamics in socio-ecological systems; 3) Criticality in living systems, with a particular focus on brain criticality. In particular, his work focuses on the study of complex living systems under a theoretical framework provided by statistical mechanics. It addresses a wide range of related topics, including ecosystem organizations, ecological networks, stochastic modelling of ecosystems dynamics and eco-hydrological processes, sustainability and ecosystems services, brain networks and whole brain models. He served as member of the steering committee of the Complex System Society from 2018 to 2021 and he is vice-president of the Italian chapter of the Complex System Society. Further info: https://suweis.github.io/ @SamirSuweis

Sandro Zampieri
University of Padova

TITLE: Recent results and open problems on energy related controllability of complex networks

ABSTRACT: In recent years there has been an intense research activity devoted to a better understanding of the structural controllability of complex networks, activity that led important advances in that area. Instead, less attention has been devoted by the research community to the energy related controllability questions. It is well-known that there are classes of complex networks that are controllable, but for which the energy needed for their control is huge, making them uncontrollable in practice. For this reason, the question of practical controllability is of paramount importance. Nevertheless, the understanding of many questions are still limited to the evidence given by numerical experiments, while few analytical results are available. In this presentation I will list what I think are the most important open problems in this area.

BIOSKETCH: Sandro Zampieri received the Laurea degree in Electrical Engineering and the Ph.D. degree in System Engineering from the University of Padova, Italy, in 1988 and 1993, respectively. Since 2002 he is Full Professor in Automatic Control at the Department of Information Engineering of the University of Padova. He has been the head of the Department of Information Engineering from 2014 until 2018. Prof. Zampieri has published more than 150 journal and conference papers. He has delivered several invited seminars and he was member of the Technical Program Committee for several international conferences. He was general chair of the 1st IFAC Workshop on Estimation and Control of Networked Systems 2009, program chair of the 3rd IFAC Workshop on Estimation and Control of Networked Systems 2012 and publication chair of the IFAC World Congress 2011. He served as an Associate Editor of the Siam Journal on Control and Optimization on 2002-2004 and of the IEEE Transactions of Automatic Control on 2012-2014. He was the chair of the IFAC technical committee "Networked systems" on 2005-2008. His research interests include networked control, control of complex systems and distributed control and estimation with applications to the smart grids.