Controlling Complex Networks: When Control Theory Meets Network Science

Satellite symposium of NetSci2014, Berkeley, CA, USA

Date: June 2, 2014

Venue: Clark Kerr Campus of the University of California (UCBerkeley).

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

Organizers:
Yang-Yu Liu
Jianxi Gao
Gang Yan

CONTROLLING COMPLEX NETWORKS

A NetSci2014 satellite symposium

June 2nd 2014 - Berkeley, California, USA

Invited Speakers

(in alphabetical order)

D'Souza, Raissa
Lai, Ying-Cheng
Mesbahi, Mehran
Nacher, Jose
Nishikawa, Takashi
Ruths, Derek
Sorrentino, Francesco
Sundaram, Shreyas
Wang, Wenxu
Wang, Xiaofan

Organizers

Yang-Yu Liu
Jianxi Gao
Gang Yan

Time: June 2, 2014 (Monday), 8:00am--6:20pm.
Venue: Clark Kerr Campus of the University of California (UCBerkeley).
Calling for posters: Please email the title/abstract of your poster to yyl@channing.harvard.edu by May 1st, 2014.
More details: http://barabasilab.neu.edu/people/yangliu/networkcontrol/2014final.htm

Satellite Symposium of NetSci --- "*Controlling Complex Networks*"
June 2, 2014

Program

8:00-8:25	Registration open
8:25-8:30	Welcome address (Yang-Yu Liu)
	Session I (Chair: Gang Yan)
8:30-9:15	**Mehran Mesbahi** *Control Theory of Networked Systems: Influence Geometry, Compositional Algebra, and Distributed Learning*
9:15-10:00	**Ying-Cheng Lai** *Controlling Nonlinear Dynamics on Complex Networks*
10:00-10:45	**Shreyas Sundaram** *Structural Strong Observability of Networks with Applications to Resilient Information Diffusion*
10:45-11:00	Tea break
11:00-11:45	**Zengru Di** *Exact controllability of complex networks*
11:45-12:30	**Derek Ruths** *Dissecting the control structures of complex networks*
12:30-2:00	**Lunch break**
	Session II (Chair: Jianxi Gao)
2:00-2:45	**Raissa D'Souza** TBA
2:45-3:30	**Takashi Nishikawa** *Control of Synchronization in Smart Grids*
3:30-4:15	**Jose Nacher** *On the Controllability of Complex Networks Using the Minimum Dominating Set*
4:15-4:30	**Tea break**
4:30-5:15	**Xiaofan Wang** *Analysis and Control of Competitive Dynamics on Complex Networks*
5:15-6:00	**Francesco Sorrentino** *Optimal driver node selection in complex networks*
6:00-6:10	Conclusion (Yang-Yu Liu)

Controlling Nonlinear Dynamics on Complex Networks

Ying-Cheng Lai
School of Electrical, Computer and Energy Engineering
Arizona State University

Controlling nonlinear dynamics has mostly been achieved for low-dimensional systems, and the recent frameworks of controllability of complex networks have been developed exclusively for linear dynamics. We articulate a general framework for controlling nonlinear dynamics on complex networks whereby we nudge the system from attractor to attractor through small perturbations to a set of experimentally feasible parameters. This principle enables us to formulate a general controllability framework for nonlinear dynamical networks. An interesting consequence is that, thanks to the interplay between nonlinearity and stochasticity, control of nonlinear dynamical networks can be facilitated by noise, leading to the surprising phenomenon of noise-enhanced controllability. These ideas are illustrated using a class of synthetic biological networks.

This is joint work with ASU PhD students Mr. Riqi Su and Ms. Lezhi Wang, and with Prof. Xiao Wang from ASU Bioengineering.

Control Theory of Networked Systems: Influence Geometry, Compositional Algebra, and Distributed Learning

Mehran Mesbahi
Department of Aeronautics and Astronautics
University of Washington

In this talk, I will explore certain results and observations at the intersection of systems and control and the theory of networks that hint at the emergence of yet another sub-discipline in control theory. Along the way, I will discuss a compositional system theory for networks-of-networks, controllability properties of circulant networks, and structural controllability of networks and its relation to matching and matrix rank maximization and minimization problems. We also explore distributed learning algorithms on networks as a way to enhance the network with an adaptation mechanism. Along the way, examples and motivations for studying such systems in the context of social networks and human-swarm interaction will be discussed.

On the Controllability of Complex Networks Using the Minimum Dominating Set

Jose C. Nacher[1] **and Tatsuya Akutsu**[2]
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The combination of control theory concepts with a complex network framework may lead to novel applications in engineering and biomedical fields. Lombardi and Hörnquist were pioneers to illustrate controllability analysis of complex networks [1]. By following Lombardi and Hörnquist, Liu *et al.* described a relationship that connects the structural controllability of a network with the maximum matching (MM) of the corresponding bipartite graph to find the minimum set of drivers (controllers) [2]. Their theoretical analysis showed that many drivers (more than 80%) are required to control scale-free networks $k^{-\gamma}$, where k is the node degree, with scaling exponent in the vicinity of γ=2. Therefore, the driver nodes tend to avoid the high-degree nodes and apparently inhomogeneous networks are more difficult to control. In contrast, the Minimum Dominating Set (MDS) approach [3] has shown that scale-free networks are easier to control. We apply the MDS concept to complex networks with scale-free structure and assume that a node controls itself and each of its adjacent nodes through its links. Our analytic calculations, computer simulations and data analysis of real-world networks demonstrate that the more heterogeneous a network's degree distribution is, the smaller the fraction of individuals, devices or molecules required to control the entire system is. Our approach, however, can be connected to [2] assuming that every edge in a network is bi-directional and every node in MDS can control all of its outgoing links separately [3, 4]. It is worth noticing that our approach has some conceptual similarities with the edge dynamics [5], although we are tackling the problem from MDS view point.

References

[1] Lombardi, A. & Hornquist, M. Controllability analysis of networks. *Phys. Rev. E.* **75**, 56110 (2007).
[2] Liu Y-Y, Slotine J-J and Barabási A-L, Controllability of complex networks. *Nature* **473**, 167-173, 2011.
[3] Nacher JC and Akutsu T, Dominating scale-free networks with variable scaling exponent: heterogeneous networks are not difficult to control. *New Journal of Physics* **14**, 073003 (24 pages), 2012.
[4] Nacher JC and Akutsu T, Structural controllability of unidirectional bipartite networks. *Scientific Reports* **3**, 1647, 2013.
[5] Nepusz T and Vicsek T, Controlling edge dynamics in complex networks. *Nature Physics* **8**, 568-573, 2012

Control of Synchronization in Smart Grids

Takashi Nishikawa
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An imperative condition for the functioning of a power-grid network is that its power generators remain synchronized. Disturbances can prompt desynchronization, which is a process that has been involved in large power outages. In this talk, I will present a study of spontaneous synchronization of power generators, which leads to a potential real-time control strategy that keeps the network optimized for maximum synchronization stability. Using a power-grid model in which the dynamics of the generators are coupled through a network of effective interactions, we derive a condition under which the desired synchronous state is stable and use the condition to identify tunable parameters of the generators that are determinants of spontaneous synchronization. This analysis gives rise to a methodology to specify parameter assignments that can enhance synchronization of any given network, which I will demonstrate for a selection of both test systems and real power grids. These parameter assignments can be realized through very fast control loops, and this may help devise new control schemes that offers an additional layer of protection, thus contributing to the development of smart grids that can recover from failures in real time.

Structural Strong Observability of Networks with Applications to Resilient Information Diffusion

Shreyas Sundaram
Department of Electrical and Computer Engineering
University of Waterloo

We consider a class of information diffusion dynamics on networks where each node's state evolves as a linear combination of the states of neighboring nodes. We allow for the possibility that certain malicious or malfunctioning nodes inject extraneous values into the network to disrupt the flow of information. We show that this setting can be represented as a linear dynamical system with unknown inputs, where the network structure maps into the sparsity pattern for the system matrices. We then use structured system theory to study the property of strong observability of the resulting system, where correctly behaving nodes can reconstruct the state of the system despite worst case inputs injected by a bounded number of adversaries. We show that when there are F sources of unknown inputs (corresponding to F unknown malfunctioning nodes), the state can be reconstructed correctly by the other nodes if and only if the network is 2F+1 connected. Time permitting, we will also discuss a class of opinion dynamics on networks where each node disregards extreme values in its neighborhood before averaging the rest. We show that traditional graph properties such as connectivity are no longer capable of characterizing such dynamics, and instead require a certain notion of graph robustness. We show that common random graph models for complex networks possess structure that allows such dynamics to be effective at facilitating consensus of opinion among the nodes, despite the actions of extreme individuals in the network.

Exact controllability of complex networks

Wen-Xu Wang
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Controlling complex networks is of paramount importance in science and engineering. Despite the recent development of structural controllability theory, we continue to lack a framework to control undirected complex networks, especially given link weights. Here we introduce an exact controllability paradigm based on the maximum multiplicity to identify the minimum set of driver nodes required to achieve full control of networks with arbitrary structures and link-weight distributions. The framework reproduces the structural controllability of directed networks characterized by structural matrices. We explore the controllability of a large number of real and model networks, finding that dense networks with identical weights are difficult to be controlled. An efficient and accurate tool is offered to assess the controllability of large sparse and dense networks. The exact controllability framework enables a comprehensive understanding of the impact of network properties on controllability, a fundamental problem towards our ultimate control of complex systems.

Analysis and Control of Competitive Dynamics on Complex Networks

Xiaofan Wang
Shanghai Jiao Tong University, China

We investigate competitive dynamics on complex networks in which a set of agents compete with each other for obtaining a maximum number of votes from a network. This is both an important and common phenomena, from leader-selection in a small group to president-election in a whole country. Although the plurality rule, i.e., the single person that receives the most votes wins the election, has been viewed as the truly fair rule, voting outcomes are influenced by a number of factors, including voting rules and human behavior.

The question we address in this work is: How do positions of competitors in a social network affect voting outcome? To answer this question, without loss of generality, we assume that there are two competitors in a network. We develop a dynamical model in which each competitor has a fixed state (+1 or -1) and each other agent adjusts its state at current step as the average states of its neighbors at last step. We prove that the state of each agent converges to a constant value between [-1, +1]. A positive (negative) state implies that the corresponding agent will support competitor n+ (n-), and the larger the amplitude of the state, the stronger the supporting. We find that the Katz Centrality is a good index to predict which competitor will win. We also propose and compute a topology-based influence matrix in which each element characterizes the impact of one agent on another. Furthermore, we investigate how a competitor could control the voting outcome via tuning the structure of the underlying network.

Dissecting the control structures of complex networks

Derek Ruths
McGill University

In the past three years, a number of frameworks for characterizing control structures have been developed and proposed. Each one emphasizes different aspects of the control structures embedded within complex systems. In this talk, we will survey these frameworks in order to understand the different insights they offer into the design, structure, and function of complex networks as well as the directions they have created for future work.

Bio: Derek Ruths is an assistant professor of Computer Science at McGill University. He joined the faculty in 2009 after completing his PhD in Computer Science at Rice University. Major research directions in his group include characterizing the controllability of complex networks as well as the problem of characterizing and predicting the large-scale dynamics of human behavior in online social platforms. His work has been published in top-tier journals and conferences including Science, EMNLP, ICWSM, and PLoS Computational Biology. Moreover, his research is currently funded by a wide array of organizations including NSERC, SSHRC, tech companies, and the US National Science Foundation - underscoring the broad, interdisciplinary nature of his work.

Optimal driver node selection in complex networks

Francesco Sorrentino
University of New Mexico

Due to their ubiquity in both natural and artificial settings, complex networks have drawn considerable attention from both the physics and engineering community. Nevertheless, only in recent years, geometrical conditions guaranteeing controllability and observability have been derived. Specifically, Liu et al. have outlined strategies for driver nodes and sensor nodes selection so as to guarantee full controllability and observability of complex networks. Nevertheless, they have also shown that in some cases, gaining full control of a network requires controlling a very large number of nodes, in some cases up to 80% of the vertices. Here, in a first line of research, we develop tools for the selection of a set of driver nodes with fixed cardinality able to maximize the controllability of a network, i.e. to ensure the controllable subspace is as big as possible. Moreover, we show how, for some notable families of topologies, it is possible to control a large fraction of the nodes of a network with a relatively small fraction of the actuators required to control the whole system.

In a second research effort we show how feedback may be very attractive in the networks scenario due to its key features (disturbance rejection, stabilization, and so on). Motivated by this consideration, we provide guidelines for the placement of sensors and actuators, which maximize our ability to control the network.