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Dániel Leitold · Ágnes Vathy-Fogarassy ·
János Abonyi

Network-Based Analysis of Dynamical Systems

Methods for Controllability and Observability Analysis, and Optimal Sensor Placement

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Dániel Leitold
Department of Computer Science
and Systems Technology
University of Pannonia
Veszprém, Hungary

Ágnes Vathy-Fogarassy
Department of Computer Science
and Systems Technology
University of Pannonia
Veszprém, Hungary

János Abonyi
MTA-PE Lendület Complex Systems
Monitoring Research Group
University of Pannonia
Veszprém, Hungary

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Preface

Network science for the analysis of dynamical systems has become a widely applied methodology over the past decade. Representing the system as a mathematical graph enables several network-based methods to be applied and centrality and clustering measures calculated to characterise and describe the behaviour of dynamical systems. Through the application of network-related algorithms in complex interconnected systems, the methodology created a strong connection between computer science, control theory and other fields where the approach is applicable, e.g. in biology.

The key idea of this book is that the dynamical properties of complex systems can be determined by the effective calculation of specific structural features by network science-based analysis. Furthermore, certain dynamical behaviours can originate from the existence of specific motifs in the network representation or can be determined by network segmentation. Although the applicability of the methods and results was highlighted in the operability analysis of dynamical systems, the proposed methods can be utilised in various fields that will be mentioned at the end of each chapter.

Chapter 1 of this book provides a brief introduction to the methodology that utilises the network science-based representation of dynamical systems to determine the location of the inputs and outputs such that their cardinality is also minimised. Then the scientific impact and main applications, e.g. in biology, sociology or physics, of the methodology are expounded on.

Chapter 2 deals with the structural analysis of the network-based representation of dynamical systems and defines those motifs that are specified by the dynamics of networks, e.g. integrating behaviour of a state variable, the diffusion of communication or changes in a temporal network. It was pointed out that these motifs are usually missing from benchmark networks. The significant reduction in the number of necessary inputs and outputs according to the presence of these motifs is also presented.

Chapter 3 deals with the improvement of the input and output configurations of dynamical systems, and presents five methods that can be used to decrease their relative degree according to the revealed motifs of the networks.

Chapter 4 deals with the analysis of the correlation between the structural properties of network-based representations and dynamical behaviours of dynamical systems. A general workflow is proposed, which was presented through a case study, that involved more than 600 heat exchanger networks.

Finally, an Octave- and MATLAB-compatible toolbox is introduced which is capable of conducting the analysis introduced in the previous chapters. The implemented functions are presented in the form of an artificial example that clearly shows the connection between the structural as well as dynamical features and highlights the differences between the centrality measures.

The applicability of the developed algorithms is presented in the form of well-known benchmark examples. An in-depth knowledge of the benchmark examples is not required from the reader, however, this may be beneficial to understand the proposed approaches. The reader is encouraged to unleash his/her imagination in terms of the applicability of the methods in other fields since the problems and results can be transferred to other networks and system classes. The introduction of the proposed algorithms is supported by in excess of 50 figures and more than 170 references that provide a good overview of the current state of the network science-based analysis of dynamical systems and suggest further reading material for researchers and students. The files of the proposed toolbox are downloadable from the website of the authors (www.abonyilab.com).

We hope, with the help of this book, that computer scientists can take on new challenges as further algorithms are necessary to reveal all the information that is hidden behind the structure of the networks. What is more, control engineers will acquaint themselves with a new tool applicable to the analysis of interconnected and structurally complex systems. Additionally, other experts, e.g. biologists, physicists, pharmacists, doctors and logisticians, will receive an overview of how the analysis of the dynamic-related properties of networks can support their analysis.

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Dániel Leitold
Ágnes Vathy-Fogarassy
János Abonyi

Contents

Symbols and Acronyms

Symbols

State-Space Representation

$\boldsymbol{x}$	Vector of state variables
$\boldsymbol{u}$	Vector of inputs
$\boldsymbol{d}$	Vector of disturbances
$\boldsymbol{y}$	Vector of outputs
$\mathbf{A}$	State-transition matrix
$\mathbf{B}$	Input matrix
$\mathbf{E}$	Disturbance matrix (linear)
$\mathbf{C}$	Output matrix
$\mathbf{D}$	Feedthrough (or feedforward) matrix
$\boldsymbol{b}^j$	jth column of matrix $\mathbf{B}$
$\boldsymbol{c}_j$	jth row of matrix $\mathbf{C}$
$\mathcal{C}$	Controllability matrix
$\mathcal{O}$	Observability matrix
$\mathbf{I}_N$	Identity matrix of size $N \times N$
N	Number of state variables
M	Number of inputs
K	Number of outputs
f	State-transition function
t	Time

Network Representations

$G(V, E)$	Network representation of the system
G^u	Undirected representation of G

V	Set of vertices of the network representation of the system
E	Connections between the state variables
V_i	Node i from the node set V
E_i	Edge i from the edge set E
G_{SS}	SS-based graph
V_{SS}	Set of nodes of SS-based representation
E_{SS}	Set of edges of SS-based representation
G_{SM}	SM-based graph
V_{SM}	Set of nodes of SM-based representation
E_{SM}	Set of edges of SM-based representation
G_{DAE}	DAE-based graph
V_{DAE}	Set of nodes of DAE-based representation
E_{DAE}	Set of edges of DAE-based representation
V_{hs}	Set of nodes of hot streams in SM-based representation
V_{cs}	Set of nodes of cold streams in SM-based representation
V_{hp}	Node of high pressure steam in SM-based representation
V_{cw}	Node of cold water in SM-based representation
E_{he}	Set of edges of heat exchangers in SM-based representation
E_{uh}	Set of edges of utility heaters in SM-based representation
E_{uc}	Set of edges of utility coolers in SM-based representation

Configurations Extension

$N_R(i)$	Set of reachable nodes from node i
Z_i	Set of nodes to which the nearest sensor node is node i
W_i	Set of reachable nodes from node i in r_{max} steps
$\mathcal{U}$	Set of all state variables
C	Set of necessary driver nodes for structural controllability
O	Set of necessary sensor nodes for structural observability
J	Set of driver/sensor nodes of the input/output configuration
P	Set of state variables covered by set J
$Cc(i)$	Closeness centrality of node i
$Bc(i)$	Betweenness centrality of node i
σ_{st}	Number of shortest paths from node s to t
$\sigma_{st}(i)$	Number of shortest paths from node s to t that intercept node i
K^+	Number of additional sensor nodes
$\mathcal{L}$	Lie derivative
$r_{i,j}$	Relative degree of y_i and u_j
r_i	Relative degree of y_i
r	Relative order of the system
r_{max}	Upper bound for r
S	Set of sensor nodes

S_f	Set of fixed sensor nodes
S_c	Set of candidate sensor nodes
β	Weighting parameter of cost function
$M*$	Set of matched nodes
Δ	Difference between cost functions in SA
T_{max}, T_{min}	Maximum and minimum temperature in SA
m_{max}, m_{min}	Maximum and minimum fuzzy exponent in SA
T^i	Temperature in iteration i
m^i	Fuzzy exponent in iteration i
α	Reduction rate of temperature
α_m	Reduction rate of the fuzzy exponent
$maxiter$	Number of iterations of SA
$R(s_j)$	Set of the state variables of the cluster of sensor node s_j
$\mu_{i,j}$	Fuzzy membership function of x_j to y_i

Network Measures

n_i	Weight of node i
w_i	Weight of edge i
k_i^{out}, k_i^{in}, k_i	Out-, in-, and simple degree of node i
$\langle k_i \rangle$	Average node degree
ℓ_{ij}	Length of shortest path between nodes i and j
$\mathcal{D}$	Distance matrix
$TWC(G)$	Total walk count measure of graph G
$CNC(G)$	Coefficient of network complexity of graph G
$Ecc(i), Ecc(G)$	Eccentricity of node i, or graph G
$W(G)$	Wiener index of graph G
$AD(G)$	A/D index of graph G
$BJ(G)$	Balaban-J index of graph G
$CI(G)$	Connectivity index of graph G
d_{max}	Diameter of the network

Heat Exchanger Networks

T_{hi}	Hot input temperature of a heat exchanger
T_{ci}	Cold input temperature of a heat exchanger
T_{ho}	Hot output temperature of a heat exchanger
T_{co}	Cold output temperature of a heat exchanger
v_h	Flow rate of hot stream
v_c	Flow rate of cold stream

V_h	Volume of hot side of heat exchanger
V_c	Volume of cold side of heat exchanger
U	Heat transfer coefficient
A	Heat transfer area
c_{ph}	Heat capacity of hot stream
c_{pc}	Heat capacity of cold stream
ρ_h	Density of hot stream
ρ_c	Density of cold stream
U_{un}	Number of units
N_s	Number of streams
L	Number of independent loops
S	Number of separate components
H	Number of heat exchangers

Water Tanks

A_i	Area of water tank i
K_v	State of valve i (open/close)
F_i	Flow rate of valve i
x_i	Water level in tank i

Acronyms

ARR	Analytical redundancy relation
CFD	Computational fluid dynamics
CLASA	Clustering large applications based on simulated annealing
CNC	Coefficient of network complexity
CO	Combinatorial optimisation
DAE	Differential-algebraic system of equations
DN	Distribution network
DRSA	Dual representation simulated annealing
FDI	Fault detection and isolation
GA	Genetic algorithm
GD	Grid diagram
GDFCM	Geodesic distance-based fuzzy c-medoid clustering method
GDFCMSA	Geodesic distance-based fuzzy c-medoid clustering method with simulated annealing
HEN	Heat exchanger network
HLMN	Human liver metabolic network
HSCN	Human signalling cancer network

LCC	Longest control chain
LTI	Linear time-invariant
mCLASA	Modified clustering large applications based on simulated annealing
MDS	Minimum driver node set
MER	Maximum energy recovery or minimum energy requirements
MIMO	Multiple-input and multiple-output
MNA	Modified nodal analysis
ncRNA	Non-protein coding ribonucleic acid
NOCAD	Network-based observability and controllability analysis of dynamical systems
OSLP	Optimal sensor location problem
PEEC	Partial element equivalent circuit
PFD	Process flow diagram
PI	Process integration
PSO	Particle swarm optimisation
RI	Resilience index
SA	Simulated annealing
SCC	Strongly connected components
SHM	Structural health monitoring
SM	Streams and matches
SS	State-space approach
TAC	Total annualised cost
TCO	Target control problem with objectives-guided optimisation
TOG	Time-ordered graph
TWC	Total walk count