Data-based diagnosis of networked dynamical systems

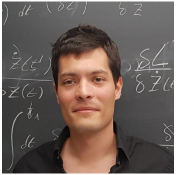
Wednesday October 27, 2021

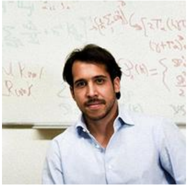
Location: **Cité | Centre de Congrès | Lyon, Room St Clair 3B** *Zoom link:* https://us02web.zoom.us/j/82853421277

9:30 am	Organizers	Welcome address
9:35 am	Melvyn Tyloo	Locating line and node disturbances in networks of diffusively coupled dynamical agents
9:55 am	Philippe Jacquod	Reconstructing network structures from partial measurements
10:20 am	Tiago de Paula Peixoto	Network reconstruction from indirect observation
10:45 am	*Coffee Break*	
11:15 am	Pietro De Lellis	Detecting salient features of network dynamical systems from time series
11:40 am	Leonardo Rydin Gorjão	Spatio-temporal complexity of power-grid frequency recordings in the Nordic grid
12:05 pm	Marc Timme	Network structure from observed dynamics
12:30 pm	*To be confirmed*	
1:00 pm	*Lunch Break*	
2:30 pm	Enrique Mallada	Coherence and concentration in tightly connected networks
2:55 pm	Gil Zussman	Physics-Informed Deep Neural Network for Partially Observable Distribution Grid State Estimation
3:20 pm	Andrey Lokhov	Prediction-centric learning of independent cascade dynamics from partial observations
3:45 pm	Misha Chertkov	Graphical models of pandemic
4:15 pm	*Coffee Break*	
4:45 pm	Nathan J. Kutz	Coarse graining and control of networked dynamical systems
5:10 pm	Marc Vuffray	Exponential Reduction in Sample Complexity with Learning of Ising Model Dynamics
5:35 pm	Edward Ott	Using machine learning and causality-destroyed surrogate data to infer network links from nodal time series

website: https://www.delabaysrobin.site/ccs-satellite

Data-based diagnosis of networked dynamical systems





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Swiss National Science Foundation

Data-based diagnosis of networked dynamical systems

$$\{x_i(t), \dot{x}_i(t), \ldots\}$$

- Social media
- Power systems
- Biological systems
- Transportation
- Finance
- Epidemic spreading
- ...

Data-based diagnosis of networked dynamical systems

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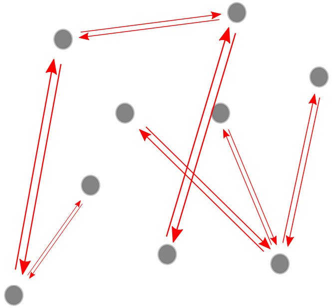

- Social media
- Power systems
- Biological systems
- Transportation
- Finance
- Epidemic spreading
- ...
- Infer interaction
- Infer parameters
- Detect anomalies
- Predict future behavior
- ...

Mathematics, physics, control theory, power systems, machine learning.

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Locating line and node disturbances in networks of diffusively coupled dynamical agents

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CCS 2021
Data-based diagnosis of networked dynamical systems

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R. Delabays, L. Pagnier, MT, New Journal of Physics **23** (4), 043037 (2021)

Large-scale coupled system

Large-scale coupled system

- Faults on lines or nodes.

R. Delabays, L. Pagnier, MT, New Journal of Physics **23** (4), 043037 (2021)

Large-scale coupled system

- Faults on lines or nodes.
- Lines less investigated:
  -Soltan et al. IEEE TCNS
  -Coletta et al. IEEE TCNS
  - Schaub et al. Network Science
  - Delabays et al. Chaos

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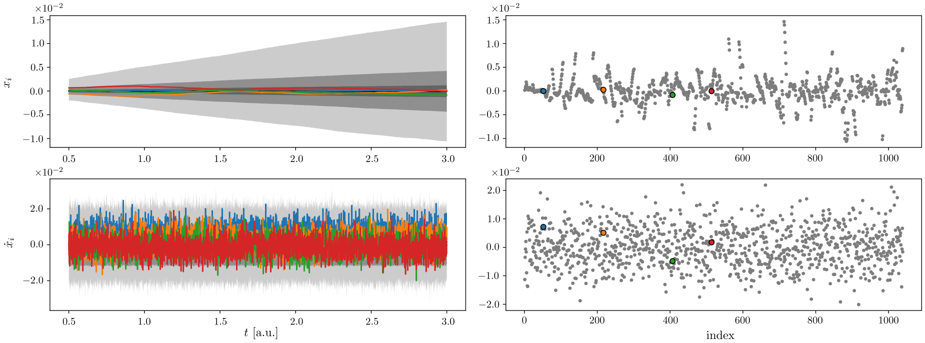
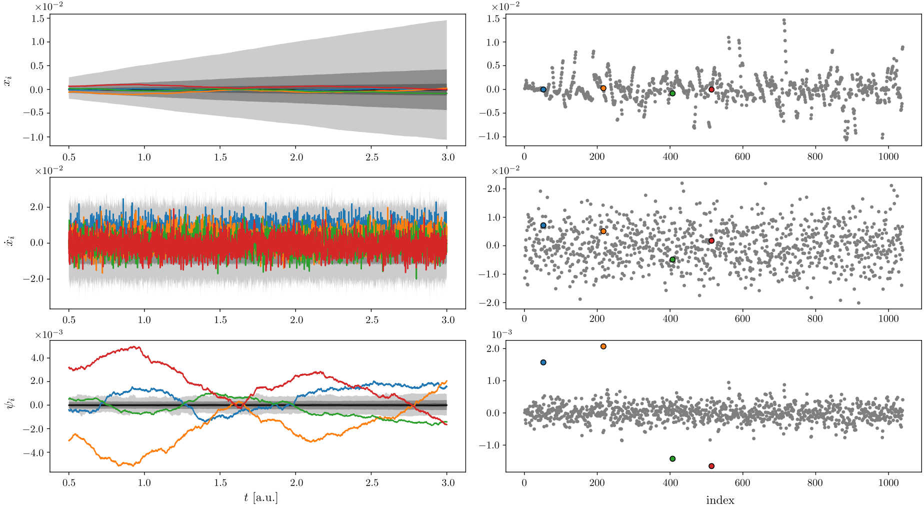
Large-scale coupled system: fault detection



Large-scale coupled system: fault detection



Coupled oscillators:

$$m_i\ddot{x}_i + d_i\dot{x}_i = \omega_i - \sum_j a_{ij} f(x_i - x_j) \ \ , \ i = 1, ..., n.$$

$a_{ij} = a_{ji} \geq 0$.

Steady-state solutions: Synchronous state $\{x_i^0\}$ such that:

$$\omega_i = \sum_j a_{ij} f(x_i^0 - x_j^0) \ \ , \ i = 1, ..., n.$$

Not too heterogeneous:

$$\omega_i = \sum_j a_{ij} f'(x^0)(x_i^0 - x_j^0) \ \ , \ i = 1, ..., n.$$

$$\rightarrow \boldsymbol{\omega} = \mathrm{L}\mathrm{x}^0 \ \ , \ i = 1, ..., n.$$

Diffusively Coupled Agents on Complex Networks

Coupled oscillators:

$$m_i\ddot{x}_i + d_i\dot{x}_i = \omega_i - \sum_j a_{ij}\sin(x_i - x_j) \ \ , \ i = 1, ..., n.$$

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Perturbations:

- at nodes $\omega_i = \omega_i^0 + \xi_n(t)$,
- on lines $a_{ij}(t) = a_{ij}^0 + \xi_l(t)$.

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$$m_i \ddot{x}_i + d_i \dot{x}_i = \omega_i - \sum_j a_{ij} \sin(x_i - x_j) \ \ , \ i = 1, ..., n.$$

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Results:

If $\max_t |\dot{\xi}_{\rm n,l}(t)| \ll \min\left\{\frac{d_i}{m_i}, \frac{\lambda_j}{\sqrt{m_i}}, \frac{\lambda_j}{d_i}\right\} \to$ Identify faulty element(s).

λ_j: eigenvalues of the Laplacian matrix.

Diffusively Coupled Agents on Complex Networks

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λ_j: eigenvalues of the Laplacian matrix.

$$\max_t |\xi_{\rm n}(t)| \ll \omega_i^0 \,, \qquad \max_t |\xi_{\rm l}(t)| \ll a_{ij}^0 \,. \tag{1}$$

The Sherman-Morrison-Woodbury formula:

$$\left(\mathsf{A} + \mathsf{u}\mathsf{v}^\top\right)^{-1} = \mathsf{A}^{-1} - \frac{\mathsf{A}^{-1}\mathsf{u}\mathsf{v}^\top\mathsf{A}^{-1}}{1 + \mathsf{v}^\top\mathsf{A}^{-1}\mathsf{u}}\,, \tag{2}$$

where u and v are vectors characterizing the rank-1 perturbation.

Line perturbations: $\tilde{\mathsf{L}}(t) = \mathsf{L} + \xi_l(t)\mathsf{e}_{ij}\mathsf{e}_{ij}^\top$

$\mathsf{e}_{ij} = (\ldots \underbrace{1}_{i} \ldots \underbrace{-1}_{j} \ldots)^\top$

The Kron reduction

$$\mathrm{x} = \begin{pmatrix} \mathrm{x}^g \\ \mathrm{x}^c \end{pmatrix}, \quad \boldsymbol{\omega} = \begin{pmatrix} \omega^g \\ \omega^c \end{pmatrix}, \quad \mathrm{L} = \begin{pmatrix} \mathrm{L}^{gg} & \mathrm{L}^{gc} \\ \mathrm{L}^{cg} & \mathrm{L}^{cc} \end{pmatrix}. \tag{3}$$

Generators:

$$\mathrm{L}^r = \mathrm{L}^{gg} - \mathrm{L}^{gc}(\mathrm{L}^{cc})^{-1}\mathrm{L}^{cg}. \tag{4}$$

Natural velocities:

$$\omega^r = \omega^g - \mathrm{L}^{gc}(\mathrm{L}^{cc})^{-1}\omega^c. \tag{5}$$

Non-reduced nodes:

$$\omega^r = \mathrm{L}^r \mathrm{x}^g. \tag{6}$$

which allows to solve the equations for the subset of nodes I_g.

Frequency mismatch:

$$\psi(t) = \mathsf{L}^r \mathsf{x}^g(t) = \mathsf{L}^r \left[\tilde{\mathsf{L}}^r(t)\right]^\dagger \tilde{\boldsymbol{\omega}}^r(t)\,, \tag{7}$$

Between non-reduced end-nodes:

$$\tilde{\boldsymbol{\omega}}^r(t) = \boldsymbol{\omega}^r\,, \qquad \tilde{\mathsf{L}}^r(t) = \mathsf{L}^r + \xi_{\rm l}(t)\mathsf{e}_{ij}\mathsf{e}_{ij}^\top\,, \tag{8}$$

Frequency mismatch:

$$\begin{aligned}
\boldsymbol{\psi}(t) &= \mathsf{L}^r\left[\mathsf{L}^r + \xi_{\rm l}(t)\mathsf{e}_{ij}\mathsf{e}_{ij}^\top\right]^\dagger \boldsymbol{\omega}^r \\
&= \mathsf{L}^r\left[(\mathsf{L}^r)^\dagger - \frac{\xi_{\rm l}(t)(\mathsf{L}^r)^\dagger\mathsf{e}_{ij}\mathsf{e}_{ij}^\top(\mathsf{L}^r)^\dagger}{1+\xi_{\rm l}(t)\mathsf{e}_{ij}^\top(\mathsf{L}^r)^\dagger\mathsf{e}_{ij}}\right]\boldsymbol{\omega}^r \\
&= \boldsymbol{\omega}^r - \alpha(t)\left[\mathsf{e}_{ij}^\top(\mathsf{L}^r)^\dagger\boldsymbol{\omega}^r\right]\mathsf{e}_{ij}\,,
\end{aligned} \tag{9}$$

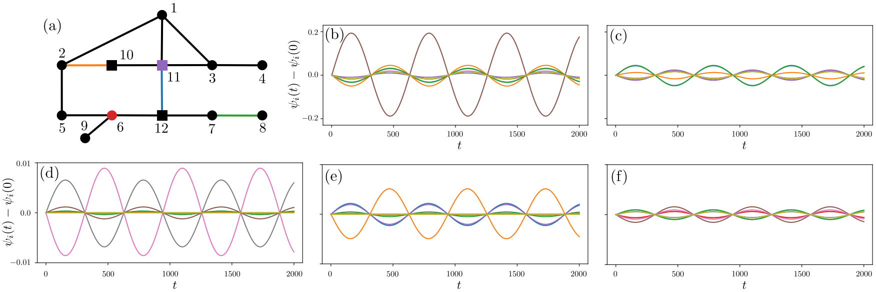
Line disturbances: Theory

Line disturbance with at least one reduced end-node:

$$\boldsymbol{\psi}(t) = \boldsymbol{\omega}^r + \tilde{\gamma}(t)\tilde{\mathrm{v}}\,, \tag{10}$$

where

$$\tilde{\mathrm{v}} = \mathrm{e}_i + \mathrm{L}^{gc}(\mathrm{L}^{cc})^{-1}\mathrm{e}_j\,, \tag{11}$$

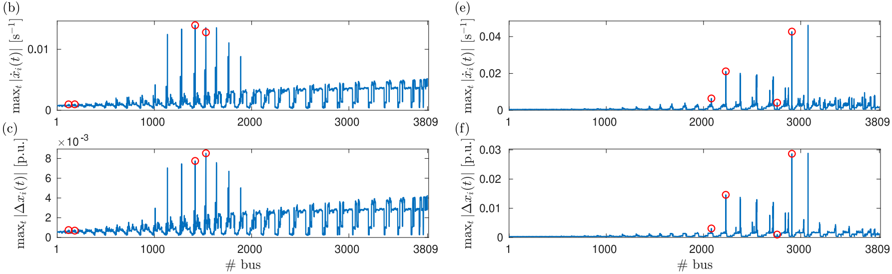


(b) 6; (c) 11; (d) 7-8; (e) 2-10; (f) 11-12

Line disturbances: Example

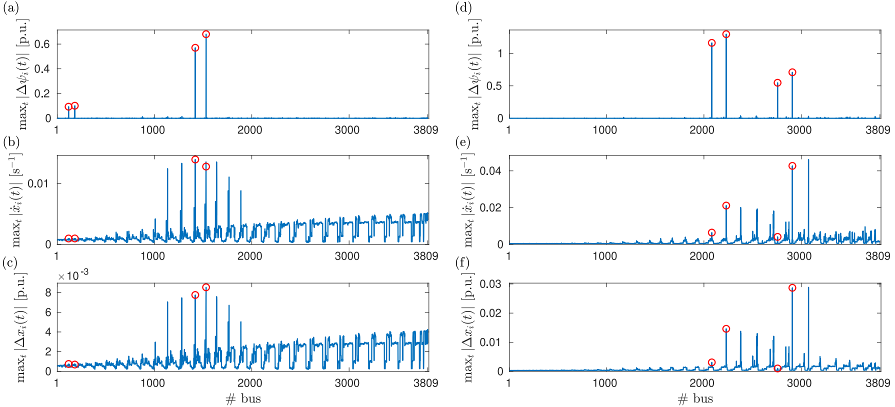
European Network:

3809 nodes
4944 lines



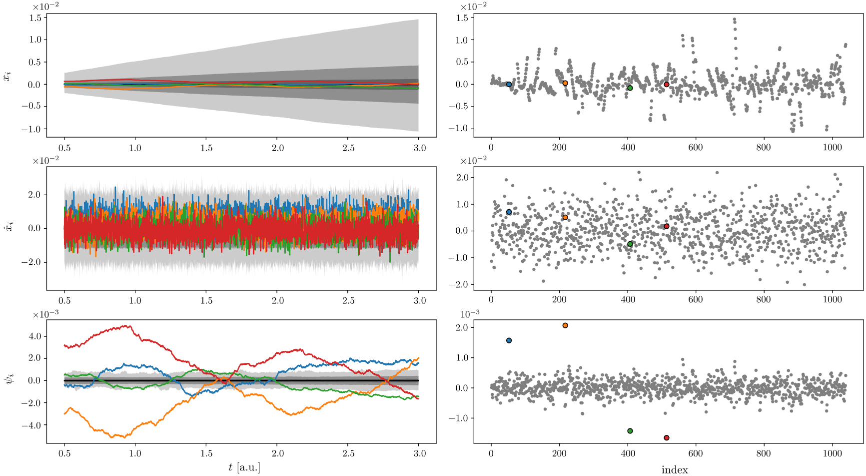
$$\xi(t) = \xi_0 \sin(\omega_m t) \tag{12}$$

European Network:



$$\xi(t) = \xi_0 \sin(\omega_m t) \tag{13}$$

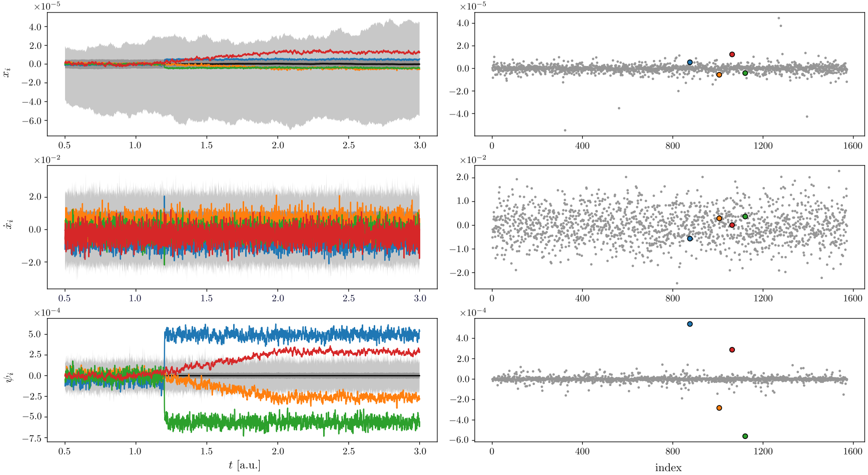
European roads: linear coupling



$\xi(t)$: Time correlated noise.

Line disturbances: Example

US Airports: third order Kuramoto coupling



$$\xi(t) = \xi_0\Theta(t - t_0) + \xi_0'\Theta(t - t_0)\Theta(t_1 - t)(t - t_0) + \xi_0''\Theta(t - t_1)$$

Fault detection in power networks

- Faults on lines or nodes
- Multiple faults at the same time
- Real-time monitoring
- Application to power grids
  $\rightarrow$ slow disturbances.

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