Recent Results in Resilient CPS Design using Passivity and Dissipativity

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Control Systems and the Quest for Autonomy
28th October, 2018
Overview

System Level
- Local Passivity (and indices) of Nonlinear Systems
- Adaptation Methods Based on Experimental Passivity Indices

Connection Level
- Security Design for Data Injection Attack
- Design Strategy over Imperfect Network

Interconnection Level
- Applications to Network of Microgrids
- Compositional Control of Large-Scale Systems
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Local Passivity Indices of Nonlinear Systems

- Behaviors of nonlinear systems change in different regions
- Examples: stability, controllability, and even uniqueness and existence
- Even systems that are passive around one equilibrium and non-passive around another
- Limited course of action in most physical systems bounded control input
- Controllers and feedback loops “tame” the system to operate around an equilibrium
- Solution: studying IO properties (particularly passivity indices) with respect to regions of state space and known bounds on input signal
- New definitions for passivity indices with respect to restrictions on the state and input spaces
Example

Figure: OFP index $\rho$, for $X = \{ x \mid \|x\|_2^2 \leq r \}$

For an example nonlinear system
Approximate Methods For Passivity Indices

1. Approximate $f$ and $h$ as polynomials with remainder
2. Find bounds for remainder/error
3. Incorporate the bounds in the inequalities
4. Incorporate the sets $\mathcal{X}$ and $\mathcal{U}$ in the inequalities
5. Solve/reduce size if necessary
Adaptation Method Based on Experimental Passivity Indices

- Experimental passivity indices of the system (with respect to current input)
- A measure of failure in the system (data-driven, no model)
- Adaptive method to mitigate any shortage with changing the controller
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Challenge in Connection Level

Analyze behavior from its approximation considering model discrepancies

Analyze energy dissipation under a digital control framework for high-dimensional systems

Preserve passivity and stability properties over imperfect communication networks

Design a joint disturbance monitor and robust controller framework facing uncertainties and adversarial attacks
Joint Disturbance Observer and Controller Design

The **immune system** (from the Latin work immunis, meaning: “untouched”) protects the body like a guardian from harmful influences from the environment and is essential for survival*. 


Joint Disturbance Observer and Controller Design

Attack Monitor:

\[ \dot{e} = -l(x)e + l(x)(-Ax - Bu - \rho(x)) \]
\[ \hat{w} = e + \rho(x) \]
\[ \frac{d}{dt} \rho(x) = l(x) \dot{x} \]

Nonlinear function to be designed
Detection filter gain
Internal state variable
Output of the detection filter

Switching the controller:

LMI of stable performance under attack
Design passivation linear transformation \( M \)
Self-Triggered Strategy under DoS Attack

A denial-of-service (DoS attack) is a cyber-attack where the perpetrator seeks to make a machine or network resource unavailable to its intended users by temporarily or indefinitely disrupting services of a host connected to the Internet*.


Self-Triggered Strategy under DoS Attack

*Attack*: communication through the network is not ideal

*Objective*:
- Maximum tolerable length of attack
- Switching strategy

\[
y_1(t_k) = G_2 r_1(t) + e_1(t)\]

Packet Dropouts

\[
y_2(t) = \text{Controller} y_2(t)
\]

\[
e_2(t) = y_1(t_k) - G_2 r_1(t)
\]

\[
\text{Threshold event error}
\]

\[
\text{Time}
\]

\[
\Sigma_1 \rightarrow \text{Attack} \rightarrow \Sigma_2
\]

\[
\text{Control}
\]

\[
\text{DoS Attack}
\]

\[
\Sigma_1 \rightarrow \text{Attack} \rightarrow \Sigma_2
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Microgrids

Color Key:
Black: Generation
Blue: Transmission
Green: Distribution

Intra-grid

Inter-grid

μG
Distributed Mixed Voltage Angle and Frequency Droop Control of Microgrid Interconnections with Loss of Distribution-PMU Measurements

D-MAFD

- Passivity under loss of PMU-measurement
- Robustness to topology changes

Next question – How do we facilitate ad-hoc connections of microgrids?

Compositional Control of Large-Scale Systems

“We refer to a system as large-scale if it is more appropriate to consider the system as an interconnection of small sub-systems than dealing with it as a whole”

Objective:
Develop an algorithm to guarantee passivity of a dynamically growing interconnection, such that the addition of new subsystems does not require redesigning the pre-existing local controllers in the network.

- Distributed verification of passivity using equivalent analysis on passivity of individual subsystems and coupling at individual interconnections.
- Local synthesis of individual sub-system level controllers, with no direct knowledge of the dynamics of other subsystems, for passivity guarantees on large-scale system.
Sequential Synthesis of Distributed Controllers for Cascade Interconnected Systems

Thank You
For always being there for us, and for all your mentorship
Microgrids

**Intra-grid**
- Stability with respect to small disturbances
- Robustness to generation-load mismatch
- Information and network limitations

**Inter-grid**
- PMU-measurement loss
- Robustness to topology changes
- Facilitate ad-hoc connections of microgrids
Dissipativity of Networks of Hybrid Systems


Resilient Design for Connection Level


The system (1) is said to be dissipative with respect to the supply rate \( \omega(w(t), y(t)) \), if there exists a positive definite function \( V(x): \mathbb{R}^n \rightarrow \mathbb{R}^+ \) with \( V(0) = 0 \), called the storage function, such that

\[
\int_{t_0}^{t_1} \omega(w(t), y(t)) dt \geq V(x(t_1)) - V(x(t_0))
\]

holds, for all \( w \in \mathbb{R}^m \), and all \( t_1 \geq t_0 \geq 0 \), where \( x(t_1) \) is the state at time \( t_1 \) resulting from the initial condition \( x(t_0) \) and input \( w(\cdot) \).
Dissipativity

The system (1) is said to be dissipative with respect to the supply rate $\omega(w(t), y(t))$, if there exists a positive definite function $V(x): \mathbb{R}^n \rightarrow \mathbb{R}^+ \text{ with } V(0) = 0$, called the storage function, such that

$$\int_{t_0}^{t_1} \omega(w(t), y(t)) dt \geq V(x(t_1)) - V(x(t_0))$$

holds, for all $w \in \mathbb{R}^m$, and all $t_1 \geq t_0 \geq 0$, where $x(t_1)$ is the state at time $t_1$ resulting from the initial condition $x(t_0)$ and input $w(\cdot)$. 
# Dissipativity

<table>
<thead>
<tr>
<th>Supply rate</th>
<th>Dissipativity</th>
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<tbody>
<tr>
<td></td>
<td>– Dissipativity</td>
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<tr>
<td>Passivity</td>
<td></td>
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<tr>
<td>State Strict Passivity;</td>
<td></td>
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<tr>
<td>Input Feed-Forward Passivity (IFP); ISP if</td>
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<tr>
<td>Output Feedback Passivity (OFP); OSP if</td>
<td></td>
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<tr>
<td>Finite Gain stability,</td>
<td></td>
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</tbody>
</table>

- Passivity, ISP, OSP
- State Strict Passivity
- – Dissipativity,
- OSP
  - Lyapunov Stability
  - Asymptotic stability
  - Finite Gain Stability
  - Finite Gain Stability
Dissipativity

Passivity, ISP, OSP
State Strict Passivity
– Dissipativity,
OSP

Lyapunov Stability
Asymptotic stability
Finite Gain Stability
Finite Gain Stability
Cyber-Physical Systems

CPS are engineered systems that are built from, and depend upon, the seamless integration of computational algorithms and physical components.

Large scale interconnection – Compositional design tools

1http://www.nsf.gov/funding/pgm\_summ.jsp?pims\_id=503286