Passivity and Symmetry in the Control of Cyber-Physical Systems

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CPS issues

- Assuming exact knowledge of the components and their interconnections may not be reasonable.
- Dynamic change. The physical part may cause the CPS to change. Links disappear. Modules stop operating. These are to be expected when we are interested in the whole life cycle of the system.
- If the system was safe, verified to be safe, can we guarantee that it will still be? Can we do something about it? Is it resilient? High autonomy.
- If secure originally can we still guarantee that property?
- Connections to linear programming, optimization. Simplex and sensitivity analysis.

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Approach

- Perhaps it is more reasonable to aim for staying in operating regions. Operating envelope.
- Flight envelope. The pilot is not allowed to take certain actions that may stall the aircraft (Airbus). Flight envelope.
- In DES supervisory control actions are allowed or not allowed to occur and so behavior is restricted
- Lyapunov stability implies that the states are bounded-asymptotic stability implies that the state will also go to the origin as time goes to infinity. Restrictions on behavior.
- Feedback interconnection of stable systems may not be stable. Switching among stable systems may lead to unstable systems.
- Is there any similar, energy like concept where guarantees can be given about properties in, say, feedback configurations?

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Passivity and Symmetry in CPS

- In CPS, heterogeneity causes major challenges. In addition network uncertainties-time-varying delays, data rate limitations, packet losses.

-Need to guarantee properties of networks of heterogeneous systems that dynamically expand and contract.

-Need results that offer insight on how to do synthesis – how to grow the system to preserve certain properties.

- We impose passivity constraints on the components and use wave variables, and the design becomes insensitive to network effects. Stability and performance.

- Symmetry.

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- **Vijay Gupta, Bill Goodwine**

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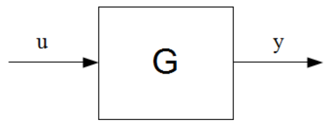
Background on Passivity

Definition of Passivity in Continuous-time

- Consider a continuous-time nonlinear dynamical system

$$\dot{x} = f(x,u)$$
$$y = h(x,u).$$



- This system is *passive* if there exists a continuous storage function *V(x) ≥ 0 (for all x)* such that

$$\int_{t_1}^{t_2} u^T(t)y(t)dt + V(x(t_1)) \geq V(x(t_2))$$

for all $t_2 \geq t_1$ and input $u(t) \in U$.

- When V(x) is continuously differentiable, it can be written as:

$$u^T(t)y(t) \geq \dot{V}(x(t))$$

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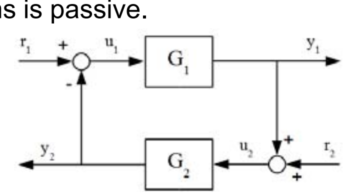
Interconnections of Passive Systems

- One of the strengths of passivity is when systems are interconnected. Passive systems are stable and passivity is preserved in many practical interconnections.

- For example, the negative feedback interconnection of two passive systems is passive.



- If $u_1 \rightarrow y_1$ and $u_2 \rightarrow y_2$ are passive then the mapping $r = \begin{bmatrix} r_1 \\ r_2 \end{bmatrix} \rightarrow y = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix}$ is passive

- Note: the other internal mappings ($u_1 \rightarrow y_2$ and $u_2 \rightarrow y_1$) will be stable but may not be passive

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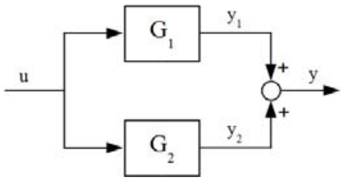
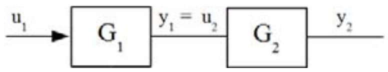
Other Interconnections

- The parallel interconnection of two passive systems is still passive



- However, this isn't true for the series connection of two systems



- For example, the series connection of any two systems that have 90° of phase shift have a combined phase shift of 180°

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Dissipativity, conic systems, and passivity indices

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Definition of Dissipativity (CT)

- This concept generalizes passivity to allow for an arbitrary energy supply rate *ω(u,y)*.
- A system is *dissipative* with respect to supply rate *ω(u,y)* if there exists a continuous storage function $V(x) \geq 0$ such that

$$\int_{t_1}^{t_2} \omega(u,y)dt \geq V(x(t_2)) - V(x(t_1))$$

for all t_1, t_2 and the input $u(t) \in U$.

- A special case of dissipativity is the QSR definition where the energy supply rate takes the following form:

$$\omega(u,y) = y^T Qy + 2y^T Su + u^T Ru.$$

- *QSR dissipative systems are* L_2 *stable when* $Q<0$

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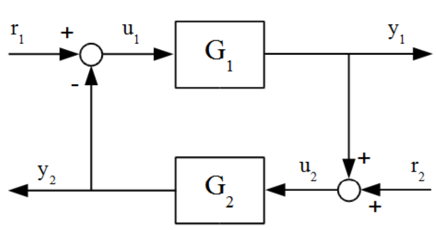
QSR Dissipativity (CT)

- Consider the feedback interconnection of G_1 and G_2
  - G_1 is QSR dissipative with Q_1, S_1, R_1
  - G_2 is QSR dissipative with Q_2, S_2, R_2
- The feedback interconnection

$$r = \begin{bmatrix} r_1 \\ r_2 \end{bmatrix} \rightarrow y = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix}$$

is stable if

$$\tilde{Q} = \begin{bmatrix} Q_1 + R_2 & S_1 - S_2^T \\ S_1^T - S_2 & Q_2 + R_1 \end{bmatrix} < 0$$



- Other mappings ($r_1 \rightarrow y_2$ and $r_2 \rightarrow y_1$) are stable but may not be passive
- Large scale sytems (with multiple feedback connections) can be analyzed using QSR dissipativity to show stability of the entire system

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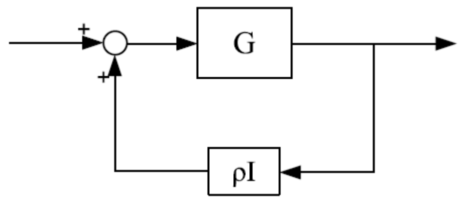
Output Feedback Passivity Index

The output feedback passivity index (OFP) is the largest gain that can be put in positive feedback with a system such that the interconnected system is passive.



Equivalent to the following dissipative inequality holding for G

$$\int_{t_1}^{t_2} u^T y dt \geq V(x(t_2)) - V(x(t_1)) + \rho \int_{t_1}^{t_2} y^T y dt$$

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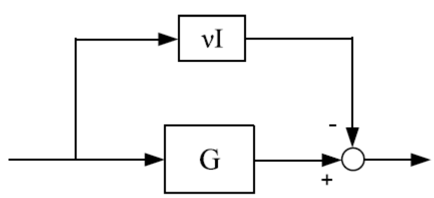
Input Feed-Forward Passivity Index

The input feed-forward passivity index (IFP) is the largest gain that can be put in a negative parallel interconnection with a system such that the interconnected system is passive.

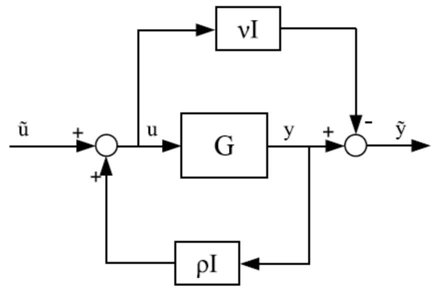


Equivalent to the following dissipative inequality holding for G

$$\int_{t_1}^{t_2} u^T y dt \geq V(x(t_2)) - V(x(t_1)) + \nu \int_{t_1}^{t_2} u^T u dt$$

Simultaneous Indices

When applying both indices the physical interpretation as in the block diagram



Equivalent to the following dissipative inequality holding for G

$$(1+\rho\nu)\int_{t_1}^{t_2} u^T y\,dt \geq V(x(t_2)) - V(x(t_1)) + \rho\int_{t_1}^{t_2} y^T y\,dt + \nu\int_{t_1}^{t_2} u^T u\,dt$$

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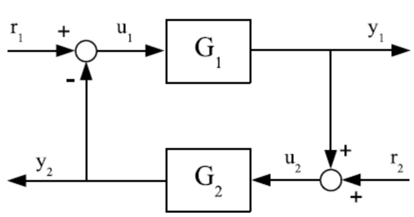
Stability

We can assess the stability of an interconnection using the indices for G_1 and G_2



G_1 has indices ρ_1 and ν_1

G_2 has indices ρ_2 and ν_2

The interconnection is $\mathcal{L}_2$ stable if the following matrix is positive definite

$$\begin{bmatrix} (\rho_1+\nu_2)I & \frac{1}{2}(\rho_2\nu_2-\rho_1\nu_1)I \\ \frac{1}{2}(\rho_2\nu_2-\rho_1\nu_1)I & (\rho_2+\nu_1)I \end{bmatrix} > 0$$

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Networked passive systems

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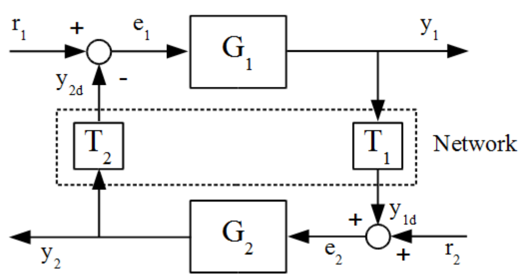
Networked Systems

- Motivating Problem: The feedback interconnection of two passive systems is passive and stable. However, when the two are interconnected over a delayed network the result is not passive so stability is no longer guaranteed. How do we recover stability?



The systems G_1 and G_2 are interconnected over a network with time delays T_1 and T_2

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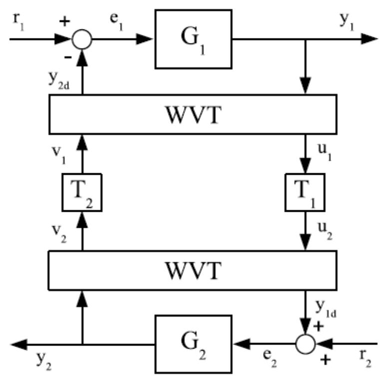
Stability of Networked Passive Systems

- One solution to interconnecting passive systems over a delayed network is to add an interface between the systems and the network
- The wave variable transformation forces the interconnection to meet the small gain theorem. Stability is guaranteed for arbitrarily large time delays
- The WVT is defined below



$$\begin{bmatrix} u_1 \\ v_1 \end{bmatrix} = \frac{1}{\sqrt{2b}} \begin{bmatrix} bI & I \\ bI & -I \end{bmatrix} \begin{bmatrix} y_1 \\ y_{2d} \end{bmatrix} \qquad \begin{bmatrix} u_2 \\ v_2 \end{bmatrix} = \frac{1}{\sqrt{2b}} \begin{bmatrix} bI & I \\ bI & -I \end{bmatrix} \begin{bmatrix} y_{1d} \\ y_2 \end{bmatrix}$$

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Passivity and CPS

1. A Passivity Measure Of Systems In Cascade Based On Passivity Indices
2. Passivity-Based Output Synchronization With Application To Output Synchronization of Networked Euler-Lagrange Systems Subject to Nonholonomic Constraints
3. Event-Triggered Output Feedback Control for Networked Control Systems using Passivity
4. Output Synchronization of Passive Systems with Event-Driven Communication
5. Quantized Output Synchronization of Networked Passive Systems with Event-driven Communication

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Passivity and Dissipativity in Networked Switched Systems

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Passivity for Switched Systems

- The notion of passivity has been defined for switched systems

$$\dot{x} = f_\sigma(x,u)$$
$$y = h_\sigma(x,u)$$

A *switched system* is *passive* if it meets the following conditions

1. Each subsystem i is passive when active:

$$\int_{t_1}^{t_2} u^T y dt \geq V_i(x(t_2)) - V_i(x(t_1))$$

2. Each subsystem i is dissipative w.r.t. ω_j^i when inactive:

$$\int_{t_1}^{t_2} \omega_j^i(u, y, x, t) dt \geq V_j(x(t_2)) - V_j(x(t_1))$$

3. There exists an input u so that the cross supply rates (ω_j^i) are integrable on the infinite time interval.

[McCourt & Antsaklis 2010 ACC, 2010 CDC]

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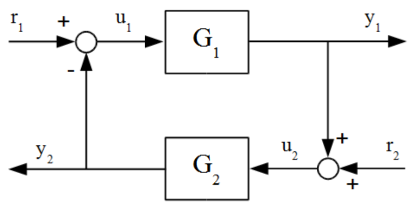
QSR Dissipativity for Switched Systems

- QSR dissipativity uses a quadratic supply rate to capture energy

$$\omega_l(u,y) = \begin{bmatrix} y \\ u \end{bmatrix}^T \begin{bmatrix} Q_l & S_l \\ S_l^T & R_l \end{bmatrix} \begin{bmatrix} y \\ u \end{bmatrix}$$

- Stability of switched systems can be assessed using Q_l



- Dissipativity of the feedback interconnection of two switched systems can be assessed with Q_l, S_l, R_l of both systems
- Large scale systems can be analyzed or designed using QSR dissipativity to ensure that the entire system is stable
- When dealing with passive switched systems ($Q_l = 0, S_l = {}^1\!/_2 I, R_l = 0$), any sequential combination of systems in feedback or parallel can be shown to be passive and stable

[McCourt &Antsaklis 2012 ACC]

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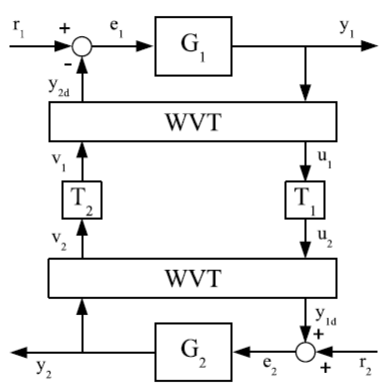
Stability of Networked Passive Systems

- When interconnecting passive discrete-time switched systems over a network, delays must be considered
- The transformation approach can be generalized to apply to switched systems
- The approach can compensate for time-varying delays
- The wave variable transformation is defined below



$$\begin{bmatrix} u_1 \\ v_1 \end{bmatrix} = \frac{1}{\sqrt{2b}} \begin{bmatrix} bI & I \\ bI & -I \end{bmatrix} \begin{bmatrix} y_1 \\ y_{2d} \end{bmatrix} \qquad \begin{bmatrix} u_2 \\ v_2 \end{bmatrix} = \frac{1}{\sqrt{2b}} \begin{bmatrix} bI & I \\ bI & -I \end{bmatrix} \begin{bmatrix} y_{1d} \\ y_2 \end{bmatrix}$$

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Models, Approximations and Passivity

- In the following passivity results on approximations that involve passivity indices
- **Modeling. Mathematical models and approximations.**
- How do we determine stability, and other properties of physical systems? Models and physical systems.
- Passivity in software. How do we define it so it is useful and makes sense.

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Passivity and QSR-dissipativity Analysis of a System and its ***Approximation***

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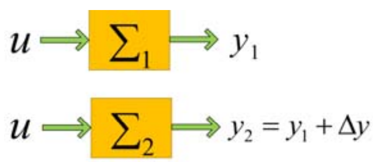
Problem Statement

- Motivation: *tradeoff* between model accuracy and tractability.
- Examples: linearization; feedback linearization; model reduction...
- Principle: *preserve* some fundamental properties or features: ***passivity***, stability, Hamiltonian structure...

- System Model:



  – view Σ_1 as the system we are interested in and view Σ_2 as an approximated model
  – the error is given through Δy (maybe modeling, linearization...)

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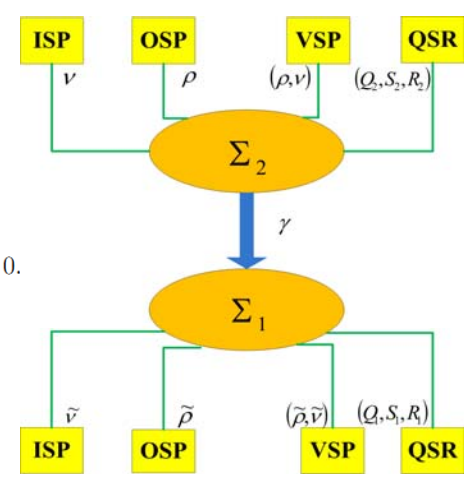
Problem Statement contd

- Suppose the approximate model is: ISP/OSP/VSP (having an ***excess*** of passivity) or QSR dissipative

- Suppose the error between the two systems is ***small,*** i.e.

$$\|\Delta y\|_T \leq \gamma \|u\|_T, \quad \forall u \text{ and } \forall T \geq 0.$$

- ***The interested system****:*
  – *Passive?*
  – *How passive?*
  – *QSR dissipative?*



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Main Results 1: ISP

- *Input strictly passive*:
  - ***passivity level:***

    Theorem 1 (ISP): Consider Σ_1 and Σ_2 in Fig. 1. Suppose (8) is satisfied for some $\gamma > 0$. If Σ_2 has IFP(ν) and $\gamma < \nu$, then, Σ_1 will be ISP for $\tilde{\nu} = \nu - \gamma$.

  - ***passive***:

    Corollary 1: Consider Σ_1 and Σ_2 in Fig. 1. Suppose (8) is satisfied for some $\gamma > 0$. If Σ_2 has IFP(ν) and $\gamma \leq \nu$, then, Σ_1 will be passive.

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Passivity and QSR-Dissipativity of a Nonlinear System and its ***Linearization***

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Symmetry in Systems

- Symmetry: A basic feature of shapes and graphs, indicating some degree of repetition or regularity
  - (Approximate) symmetry in characterizations of information structure
  - (Approximately) identical dynamics of subsystems
  - Invariance under group transformation e.g. rotational symmetry

- Why Symmetry?
  - Decompose into lower dimensional systems with better understanding of system properties such as stability and controllability
  - Construct symmetric large-scale systems without reducing performance if certain properties of low dimensional systems hold

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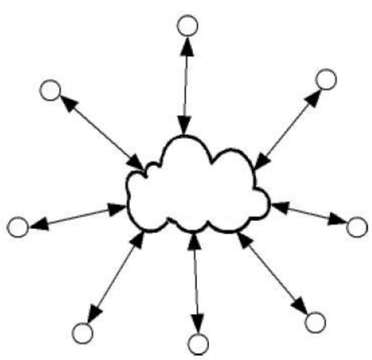
Simple Examples

Star-shaped Symmetry and Hierarchies



$$u = u_e - \tilde{H}y$$

$$\tilde{H} = \begin{bmatrix} H & b & \cdots & b \\ c & h & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ c & 0 & \cdots & h \end{bmatrix}$$

$$u_0 = u_{e0} - Hy_0 - by_1 - \cdots - by_m$$
$$u_1 = u_{e1} - cy_0 - hy_1$$
$$\vdots$$
$$u_m = u_{em} - cy_0 - hy_m$$

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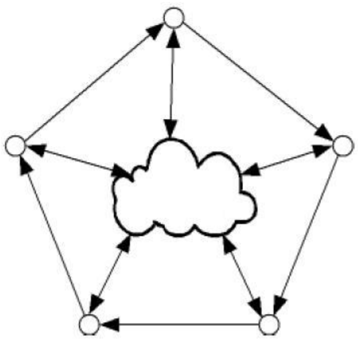
Simple Examples

Cyclic Symmetry and Heterarchies



$$u = u_e - \tilde{H}y$$

$$\tilde{H} = \begin{bmatrix} H & b & \cdots & b \\ c & & & \\ \vdots & & \tilde{h} & \\ c & & & \end{bmatrix}$$

$$\tilde{h} = circ([v_1, v_2, \ldots, v_m])$$

$$u_0 = u_{e0} - Hy_0 - by_1 - \cdots - by_m$$
$$u_1 = u_{e1} - cy_0 - v_1 y_1 - v_2 y_2 - \cdots - v_m y_m$$
$$\vdots$$
$$u_m = u_{em} - cy_0 - v_2 y_1 - v_3 y_2 - \cdots - v_1 y_m$$

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Main Result (1)

Theorem (Star-shaped Symmetry)
Consider a (Q, S, R) – dissipative system extended by *m* star-shaped symmetric (q, s, r) – dissipative subsystems. The whole system is finite gain input-out stable if

$$m < \min\left(\frac{\underline{\sigma}(\hat{Q})}{\overline{\sigma}(c^T rc + \beta(\hat{q} - b^T Rb)^{-1}\beta^T)}, \frac{\hat{q}}{b^T Rb}\right)$$

where

$$\hat{Q} = -H^T RH + SH + H^T S^T - Q > 0$$
$$\hat{q} = -h^T rh + sh + h^T s^T - q > 0$$
$$\beta = Sb + c^T s^T - H^T Rb - c^T rh$$

$$\tilde{H} = \begin{bmatrix} H & b & \cdots & b \\ c & h & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ c & 0 & \cdots & h \end{bmatrix}$$

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Main Result (2)

Theorem (Cyclic Symmetry)
Consider a (Q, S, R) – dissipative system extended by *m* cyclic symmetric (q, s, r) – dissipative subsystems. The whole system is finite gain input-out stable if

$$m < \min\left(\frac{\underline{\sigma}(\hat{Q})}{\overline{\sigma}(c^T rc + \beta_m \Lambda^{-1} \beta_m{}^T)}, \frac{-r\sigma(\tilde{h})\overline{\sigma(\tilde{h})} + s(\sigma(\tilde{h}) + \overline{\sigma(\tilde{h})}) - q}{b^T Rb}\right)$$

where

$$\tilde{h} = circ([v_1, v_2, \ldots, v_m])$$

$$\sigma(\tilde{h}) = \sum_{j=1}^{m} v_j \lambda_i^j = \sum_{j=1}^{m} v_j e^{\frac{2\pi ij}{m}}$$

$$\tilde{H} = \begin{bmatrix} H & b & \cdots & b \\ c & & & \\ \vdots & & \tilde{h} & \\ c & & & \end{bmatrix}$$

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Main Result (3)

(cont.)

$$\Lambda = -r\tilde{h}^T\tilde{h} + s(\tilde{h}^T + \tilde{h}) - q \otimes I_m - b^T Rb \otimes circ([1,1,\ldots,1])$$

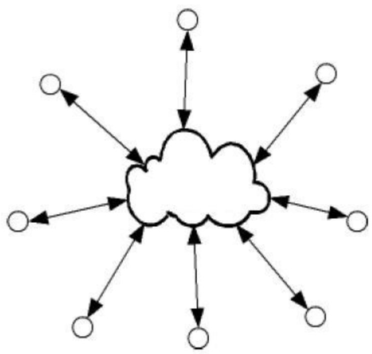
$$\beta = Sb + c^T s^T - H^T Rb - c^T r\tilde{h}$$

$$\beta_m = [\underbrace{\beta\beta\ldots\beta}_{m}]$$

the spectral characterization of $\tilde{h}$ should satisfy

$$\| \sigma(\tilde{h}) - \frac{s}{r} \| < \sqrt{\frac{s^2}{r^2} - \frac{q + mb^T Rb}{r}}$$

Simple Examples



$$u = u_e - \tilde{H}y$$

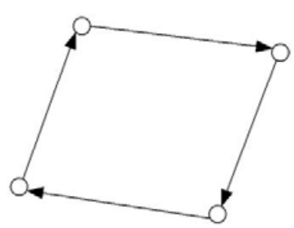
$$\tilde{H} = \underbrace{\begin{bmatrix} 0.9 & -0.8 & -0.8 & \cdots & -0.8 \\ -0.8 & 0.1 & 0 & \cdots & 0 \\ -0.8 & 0 & 0.1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ -0.8 & 0 & 0 & \cdots & 0.1 \end{bmatrix}}_{m+1}$$

$$Q = q = -I, S = s = 0, R = r = \tfrac{1}{4}I$$

$$\Rightarrow \quad m < \min(3.11, 6.25) = 3.11$$

Remark: $(-I, 0, \alpha^2 I)-\text{dissipative}$ systems corresponding to systems with gain less or equal to α (here $\alpha = \frac{1}{2}$)

Simple Examples



$$u = u_e - \tilde{H}y \qquad q = 0, s = \tfrac{1}{2}, r = 1$$

$$\tilde{H} = \tilde{h} = \underbrace{\begin{bmatrix} 0.1 & 0.2 & 0 & \cdots & 0 \\ 0 & 0.1 & 0.2 & \cdots & 0 \\ 0 & 0 & 0.1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0.2 & 0 & 0 & \cdots & 0.1 \end{bmatrix}}_{m}$$

The cyclic symmetric system is stable if

$$|\sigma(\tilde{h}) - \frac{s}{r}| = |\sum_{j=0}^{m-1} v_j e^{\frac{2\pi ij}{m}}| \le 0.3 < 0.5 = \sqrt{\frac{s^2}{r^2} - \frac{q}{r}}$$

The above stability condition is always satisfied. Also

$$m < \min(+\infty, +\infty)$$

Thus the system can be extended with infinite numbers of subsystems without losing stability.

Main Result (4)

Theorem (Star-shaped Symmetry for Passive Systems)
Consider a passive system extended by *m* star-shaped symmetric passive subsystems. The whole system is finite gain input-output stable if

$$m < \frac{\underline{\sigma}(\hat{Q})}{\overline{\sigma}(\beta \hat{Q}^{-1} \beta^T)}$$

where

$$\hat{Q} = \frac{H + H^T}{2} > 0$$

$$\hat{q} = \frac{h + h^T}{2} > 0$$

$$\beta = \frac{b + c^T}{2}$$

$$\tilde{H} = \begin{bmatrix} H & b & \cdots & b \\ c & h & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ c & 0 & \cdots & h \end{bmatrix}$$

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Main Result (5)

Theorem (Cyclic Symmetry for Passive Systems)
Consider a passive system extended by *m* cyclic symmetric passive subsystems. The whole system is finite gain input-output stable if

$$m < \frac{\underline{\sigma}(\hat{Q})}{\overline{\sigma}(\beta_m \Lambda^{-1} \beta_m{}^T)}$$

where

$$\hat{Q} = \frac{H + H^T}{2} > 0 \qquad \Lambda = \frac{\tilde{h} + \tilde{h}^T}{2}$$

$$\beta = \frac{b + c^T}{2} \qquad \beta_m = [\underbrace{\beta\beta\ldots\beta}_{m}]$$

$$\sigma(\tilde{h}) = \sum_{j=1}^{m} v_j \lambda_i^j = \sum_{j=1}^{m} v_j e^{\frac{2\pi i j}{m}}$$

$$\tilde{H} = \begin{bmatrix} H & b & \cdots & b \\ c & & & \\ \vdots & & \tilde{h} & \\ c & & & \end{bmatrix}$$

$$\tilde{h} = circ([v_1, v_2, \ldots, v_m])$$

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Concluding Remarks

- CPS, Distributed, Embedded, Networked Systems. Analog-digital, large scale, life cycles, safety critical, end to end high-confidence.
- Models, robustness, fragility, resilience, adaptation.
- New ways of thinking needed to deal effectively with the CPS problems. New ways to determine research directions.
- Passivity/Dissipativity and Symmetry are promising
- Circuit theory and port controlled Hamiltonian systems.
- Connections to Autonomy and Human in the Loop

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Most of the papers below maybe found at
http://www.nd.edu/~pantsakl/Publications/PublicationsListing.html

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