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From Hybrid to Networked Cyber-Physical Systems

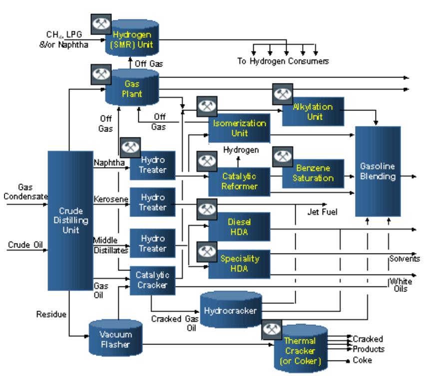
Panos J. Antsaklis

www.nd.edu/~pantsakl

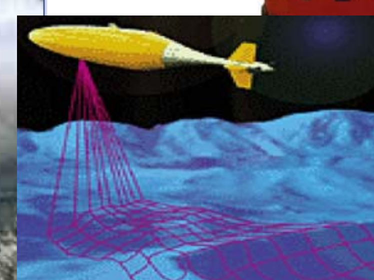
Plenary Talk

2009 ACC, St. Louis, Missouri

Thursday, June 11, 2009




UAVs operating together



Cyber-Physical Systems (CPS)

-As computers become ever-faster and communication bandwidth ever-cheaper, computing and communication capabilities will be embedded in all types of objects and structures in the physical environment.

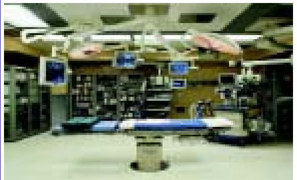
-***Cyber-physical systems (CPS)*** are physical, biological and engineered systems whose ***operations are monitored, coordinated,* controlled *and integrated by a computing and communication core***.

-This intimate coupling between the cyber and physical will be manifested from the nano-world to large-scale wide-area systems of systems. And at multiple time-scales.

-Applications with enormous societal impact and economic benefit will be created.

-Cyber-physical systems will transform how we interact with the physical world just like the Internet transformed how we interact with one another.

A Few *Example* Opportunities*

Transportation	▪ Faster and more energy efficient aircraft ▪ Improved use of airspace ▪ Safer, more efficient cars	
Energy and Industrial Automation	▪ Homes and offices that are more energy efficient and cheaper to operate ▪ Distributed micro-generation for the grid	
Healthcare and Biomedical	▪ Increased use of effective in-home care ▪ More capable devices for diagnosis ▪ New internal and external prosthetics	
Critical Infrastructure	▪ More reliable and efficient power grid ▪ Highways that allow denser traffic with increased safety	

* Cyber-Physical Systems Executive Summary, CPS Steering Group, March 6, 2008. Available on-line: http://varma.ece.cmu.edu/summit/

- Next generation healthcare -- biomedical devices and systems engineering (wearable/implantable, minimally-invasive, bio-aware, bio-compatible, patient-specific, open, configurable, portable, universal point-of-care safety)
- Next generation energy systems (distributed, intermittent, renewable sources; shifting topology for generation, storage/transfer/transmission, distribution; smart loads, better control of dynamic demand-response; new sources/sinks: cars, buildings)
- Next generation environmental systems (in situ co-generation, multi-source energy harvesting, geo-thermal/ground-source heating and cooling; integrated environmental control: light, thermal, air- and water-quality, noise abatement, physical access)
- Next generation transportation (autonomous systems, energy-efficient, high-performance, multi-modal: air, automotive, rail, maritime systems, enhanced and affordable personal mobility and transport)
- Next generation manufacturing (flexible/configurable, multi-scale, interoperable line components, self-assembly, multi-process bio/chemical/mechanical engineering; precision next-generation - laser/thermal/EMF/bio/mechanical tooling and monitoring)
- Next generation agriculture (pervasive sensing, precision micro-climates/micro-cultures, pervasive animal health monitoring and veterinary medicine),
- Next generation water systems (atmospheric sources, reuse, quality sensing, exploration, hazard alerts)
- …

Source: NSF

On the way to CPS - Outline

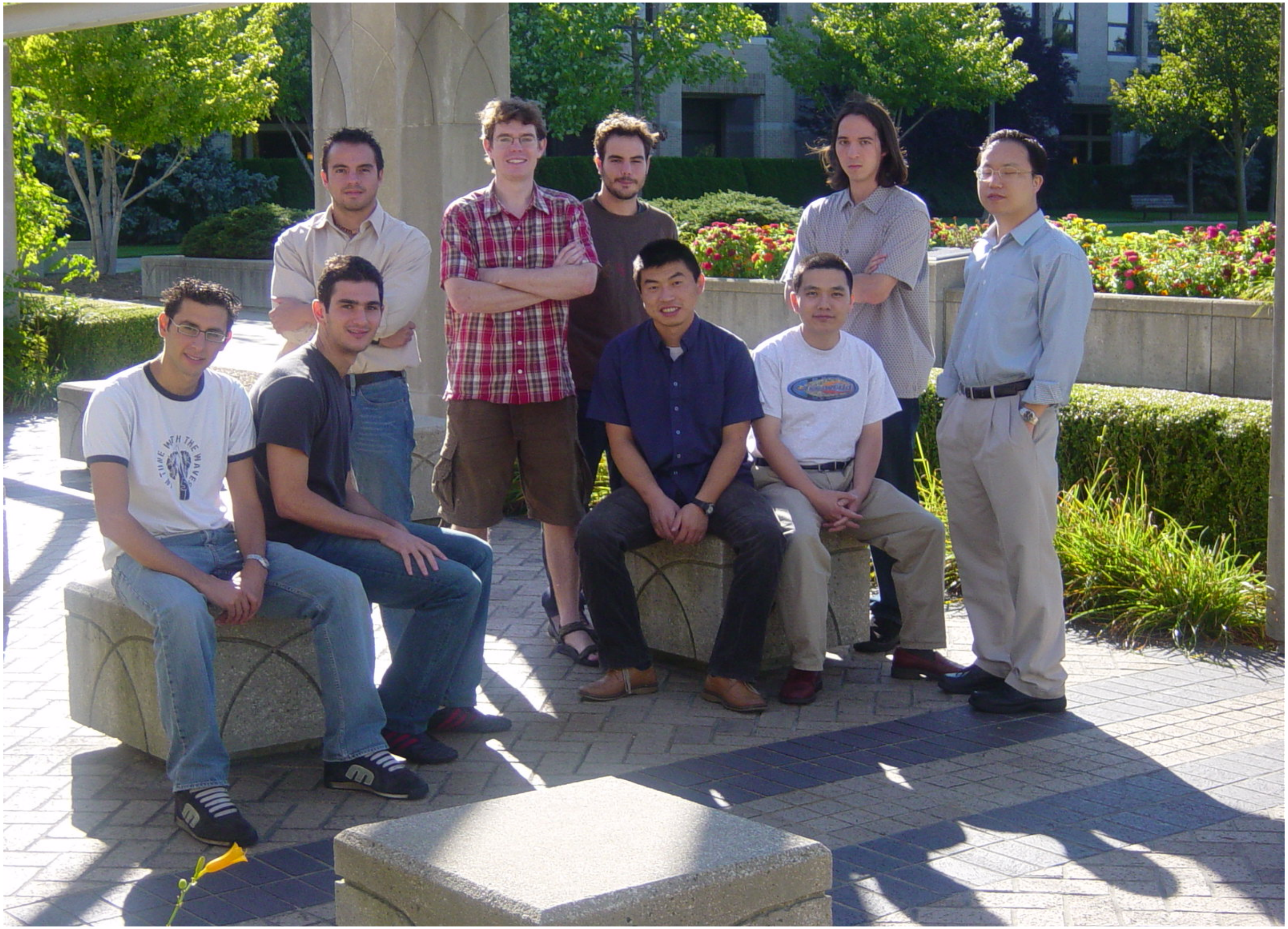
- A glimpse at **Feedback Fundamentals** - can they give us some of the needed insights? Some elementary examples.
- The **Quest for Autonomy** leads to **DES and Hybrid** models - can they provide some of the needed foundations?
- **Networked Control Systems** - A different approach. **Model-Based and Intermittent Feedback**. How didn't we think of them before?
- **Cyber-Physical Systems**: What are they? Are there any design principles, general concepts that may be helpful here with the cyber, physical, human-in-the loop (feedback) network interconnections? **Passivity** appears promising.
- **In Closing** - what did we learn? A call to join the **Quest for Autonomy**

Thanks to:

- **Kevin Passino - *Intelligent Autonomous Control***
- **John Moody, Marian Iordache - *Supervisory Control of DES using Petri Nets***
- **Jim Stiver, Xenofon Koutsoukos, Xuping Xu, Hai Lin - *Hybrid Systems***
- **Luis Montestruque, Tomas Estrada - *Model Based Control***
- **Nicholas Kottenstette - *Passivity in NCS***
- **Hui Fang, Lei Fang - *Multi-agent systems***
- ***Oscar Gonzalez, Zhiqiang Gao – PMD, Linear Systems***

- **Mike McCourt, Cherry Yu, Eloy Garcia, Po Wu, Feng Zhu**

GRADUATE STUDENTS



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Outline

- A glimpse at **Feedback Fundamentals.**

- *The **Quest for Autonomy** leads to **DES and Hybrid** models.*
- ***Networked Control Systems**-A different approach.* ***Model-Based and Intermittent Feedback**.*
- ***Cyber-Physical Systems**: What are they?*

  ***Passivity** appears promising.*
- ***In Closing**-A call to join the **Quest for Autonomy***

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A FUNDAMENTAL PROPERTY OF FEEDBACK

Elementary examples and the beginnings of a study with conjectures.

Feedback-Setting the Stage

- Many powerful methodologies have been introduced in the past half century to design controllers that stabilize and achieve desired performance in a robust way.

- Significantly less effort has been spent on understanding exactly how and why feedback works so well not only in the control of engineered systems but in social, economic, natural systems as well.

- Is there a property that transcends models and is omnipresent the moment the loop is closed?

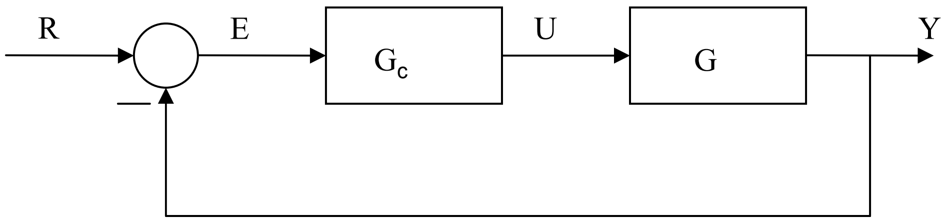
  -A property that does not depend on the choice of feedback gains.

  -What is the most fundamental property of feedback, if one exists?

- These fundamental mechanisms should be independent of the particular type of mathematical models used, that is the system may be described by differential equations, by automata, by logic expressions, by natural language, since we do know that feedback is ubiquitous and works!

Feedback-High Gains

- Feedback control can be seen as a mechanism that approximately inverts the plant dynamics, producing an “approximate” inverse of the plant at its control input.



$$\frac{Y}{R} = T = \frac{GG_c}{1+GG_c} \quad and \quad \frac{U}{R} = M = \frac{G_c}{1+GG_c}$$

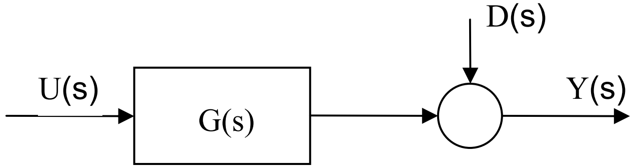
- If then $|GG_c| >> 1$ $\quad \frac{Y}{R} = T \cong 1 \quad and \quad \frac{U}{R} = M \cong \frac{1}{G}$

- That is at the control input of the plant, the external input acts through an inverse of the plant so to cancel all plant dynamics and produce an output, which is approximately equal to the reference input.

Open Loop (Feed-forward) Control

- Y(s)/U(s) = $G(s) = \frac{1}{as+1}$

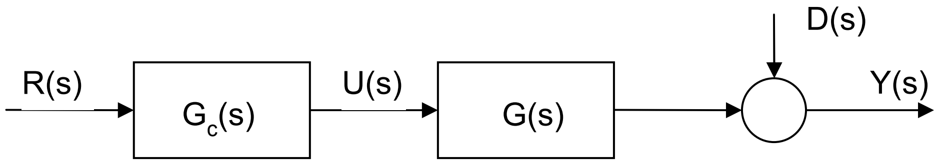
$$a(sY_p(s) - y(0)) + Y_p(s) = U(s)$$



$$Y(s) = \frac{a}{as+1} y(0) + \frac{1}{as+1} U(s) + D(s)$$

$$G_c(s) = \frac{bs+1}{cs+1}$$

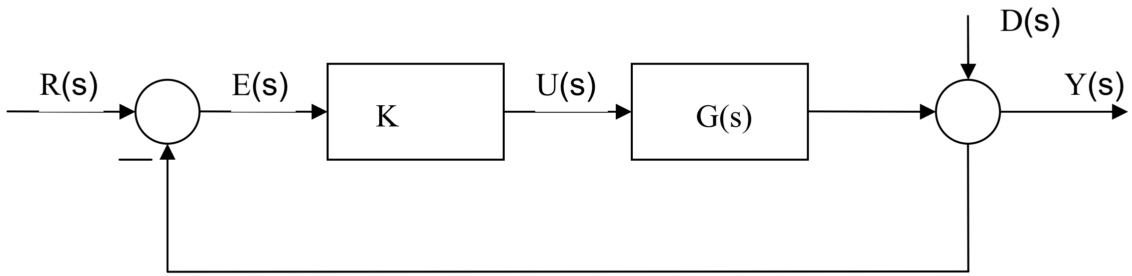
$$U(s) = \frac{cu(0) - br(0)}{cs+1} + \frac{bs+1}{cs+1} R(s)$$



$$Y(s) = \frac{(cs+1)ay(0) + cu(0) - br(0)}{(as+1)(cs+1)} + \frac{bs+1}{(as+1)(cs+1)} R(s) + D(s)$$

$$b = a \qquad (a-c)y(0) + cu(0) - br(0) = 0$$

Closed Loop (Feedback) Control



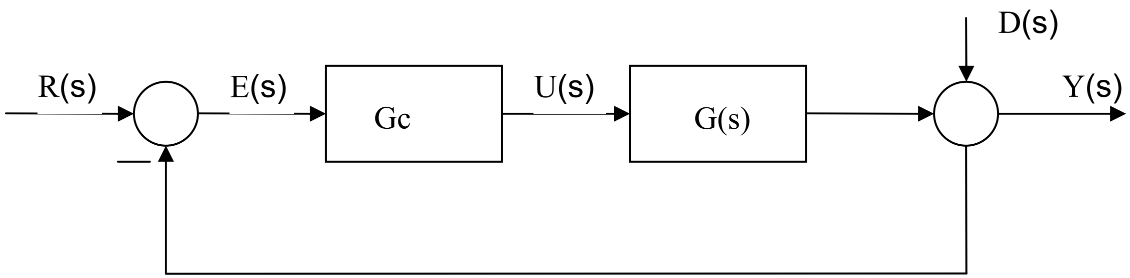
$$Y(s) = \frac{a}{as+1} y(0) + \frac{1}{as+1} U(s) + D(s)$$

$$U(s) = -\frac{Kay(0)}{as+1+K} + \frac{K(as+1)}{as+1+K} R(s) - \frac{K(as+1)}{as+1+K} D(s)$$

$$\begin{aligned}
Y(s) &= [\frac{a}{as+1} y(0) - \frac{Kay(0)}{(as+1)(as+1+K)}] + \frac{K(as+1)}{(as+1+K)(as+1)} R(s) - \frac{K(as+1)}{(as+1+K)(as+1)} D(s) \\
&= \frac{a(as+1)y(0)}{(as+1+K)(as+1)} + \frac{K(as+1)}{(as+1+K)(as+1)} R(s) - \frac{K(as+1)}{(as+1+K)(as+1)} D(s) \\
&= \frac{ay(0)}{as+1+K} + \frac{K}{as+1+K} R(s) - \frac{K}{as+1+K} D(s)
\end{aligned}$$

- When a > 0, G stable, for K > -1 the closed loop system is stable
- When a < 0, G unstable, for K < -1 the closed loop system is stable

Closed Loop (Feedback) Control



G(s)=n/d $G_c(s)=n_c/d_c$

$$Y(s)=\frac{n_o}{d}+\frac{n}{d}U(s)+D(s)$$

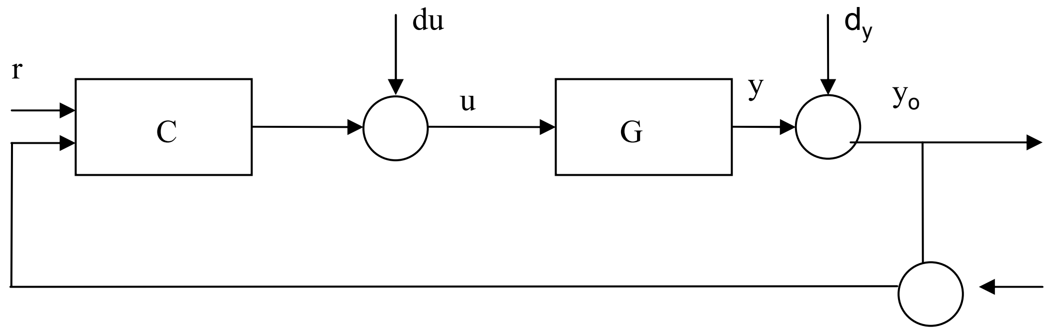
$$U(s)=\frac{n_{co}d-n_cn_o}{dd_c+nn_c}+\frac{n_cd}{dd_c+nn_c}R(s)-\frac{n_cd}{dd_c+nn_c}D(s)$$

$$U(s)=\frac{n_{co}}{d_c}+\frac{n_c}{d_c}E(s)$$

$$Y(s)=\frac{d(n_od_c+nn_{co})}{d(dd_c+nn_c)}+\frac{d(n_cn)}{d(dd_c+nn_c)}R(s)+\frac{d(d_cd)}{d(dd_c+nn_c)}D(s)$$

$$=\frac{n_od_c+nn_{co}}{dd_c+nn_c}+\frac{n_cn}{dd_c+nn_c}R(s)+\frac{d_cd}{dd_c+nn_c}D(s)$$

Closed Loop (Feedback) Control



$$u = [C_y, C_r]\begin{bmatrix} y + d_y + \eta \\ r \end{bmatrix} + d_u$$

$$y = G(I - C_y G)^{-1}[C_r r + C_y d_y + C_y \eta + d_u]$$
$$u = (I - C_y G)^{-1}[C_r r + C_y d_y + C_y \eta + d_u]$$

$$G = ND^{-1}$$

$$u = D[Xr + Ld_y + L\eta + (I + LN)D^{-1}d_u]$$
$$y = N[Xr + Ld_y + L\eta + (I + LN)D^{-1}d_u]$$

$$y = Tr + (S_o - I)d_y + GQ\eta + GS_i d_u$$
$$u = Mr + Qd_y + Q\eta + S_i d_u$$

$$T = G(I - C_y G)^{-1}C_r = GM = NX$$
$$M = (I - C_y G)^{-1}C_r = DX$$
$$Q = (I - C_y G)^{-1}C_y = DL$$
$$S_o = (I - GC_y)^{-1} = I + GQ$$
$$S_i = (I - C_y G)^{-1} = I + QG$$

$$y_o = y + d_y = Tr + S_o d_y + GQ\eta + GS_i d_u.$$

Related Result-Realizing Stable Transfer Functions with Internal Stability

- Given y/u = G = ND^{-1} the stable rational function matrices (T, M) in y = T r and u = M r are realizable with internal stability by means of a two degrees of freedom control configuration if and only if there exists stable rational function matrix X so that

$$\begin{bmatrix} T \\ M \end{bmatrix} = \begin{bmatrix} N \\ D \end{bmatrix} X.$$

- D appears always in M, that is u = M r = DX r

- D cancels at the input of the plant – poles of the plant (in D) always cancel with zeros of the map generated between the input to the plant u and the external input r (in D), same as in the simpler cases discussed before.

Feedback Fundamental Mechanism-1

- ***The feedback mechanism always generates a signal u the behavior of which is modified by D, the inverse of the map D^{-1} which is the transfer function between z and u in the plant Dz=u. y=Nz.***

$$z = D^{-1} u$$

- ***D appears in the numerator of the transfer function between u and r***

$$u = M\, r = DX\, r$$

and it has the effect that for such u the behavior of the plant state

$$z = D^{-1} u = D^{-1} DX\, r = X\, r$$

is completely freed from behavior determined by the plant modes.

- **So feedback does not really invert the plant y = G u.**
- **It inverts the map between z and u, namely the map $z = D^{-1} u$, to generate u = DX r.**

Feedback Fundamental Mechanism-2

- **Arbitrary feedback will result to a closed loop system with dynamics (poles) different from the open loop dynamics (poles).**
  Examples: Root-Locus; A-BK; A-BHC; D (s)D_c(s) + N(s)N_c(s).
  Comments: *K that preserves open loop locations*; *Assumption of controllability and observability*;

- **Sampled data; nonlinear systems;**

- **Human-in-the loop. Example car and driver.**

- ***For almost any feedback gains the dynamics are completely reassigned, that is the plant behavior drastically changes.***

- ***In feedback control, gains are chosen to assign the new dynamics and not to cancel the old ones.***

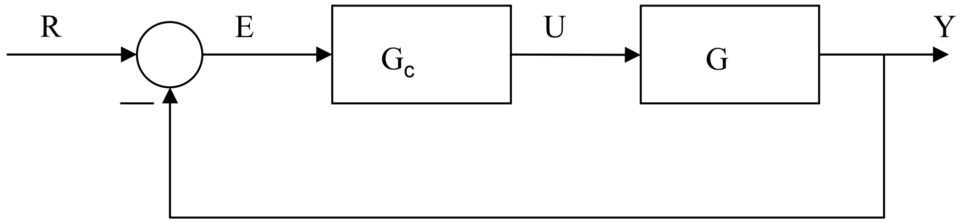
Open vs Closed Loop

- **Complete change of plant dynamics takes place:**
  a. almost always in closed loop feedback control
  b. almost never in open loop feedforward control.

- **Complete change of the dynamics of the compensated system to desirable dynamics is:**
  a. easy in the open loop feedforward control case
  b. harder in the closed loop feedback case, although typically there is a large range of controller choices that satisfy the requirements for desirable dynamics (control specifications) as one must consider the trade-offs.

- In the closed loop control the choice of the appropriate controller is non trivial matter and the field of Control Theory has been studying this problem intensively for at least the past 50 years. Certainly a topic that requires deep understanding. About 25 years ago all stabilizing controllers were conveniently parameterized a result that also showed formally the large number of choices one has.

Connection to Return Difference (1+GGc)



- At the output the connection enforces (R=0)

$$Y = (-GG_cY), \quad (1+GG_c)Y = 0$$

$$\text{or } Y = (-GG_cY) + GW + (n_o/dd_cy_o)$$
$$Y = (1+GG_c)^{-1}GW + (1+GG_c)^{-1}(n_o/dd_cy_o)$$

- For the Return Difference equality to be satisfied D needs to cancel out.

- Cancellation is due to the creation of the “Return Difference” or “Forcing the Interconnection” or “Closing the Loop”

FEEDBACK FUNDAMENTALS-REMARKS

- **Closing the loop with arbitrary feedback gains will result almost always in a closed loop system with dynamics (poles) different from the open loop dynamics (poles). In feedback all plant poles cancel out automatically. Behavior due to IC different.** ***The Fundamental property(?).***

- **Open vs Closed Loop.**
  Two steps: ***Canceling old dynamics and inserting new dynamics***
- **Connections to Return Difference**
- **There are also connections to Internal Models**
- **There are connections to Sampled-data, Recursive Relations**
- **There are connections to Internal Feedback-FIR and IIR**

- **Best seen as pole/zero cancellation via D and PMD.**
  The control input generates the exact inverse of the input to state map $z = D^{-1}u$***, always.***

- ***Applicable to general feedback systems*****: While driving the sensor input and the subsequent driver action makes the car behave very differently in response to a side wind gust from the case where no sensor feedback is received and no action is taken.**

Outline

- *A glimpse at* ***Feedback Fundamentals***

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- ***Networked Control Systems****-A different approach.* ***Model-Based and Intermittent Feedback****.*
- ***Cyber-Physical Systems****: What are they?*

  Passivity *appears promising.*
- ***In Closing****-A call to join the* ***Quest for Autonomy***

THE QUEST FOR AUTONOMY

Pervasive theme in man-made systems through the centuries

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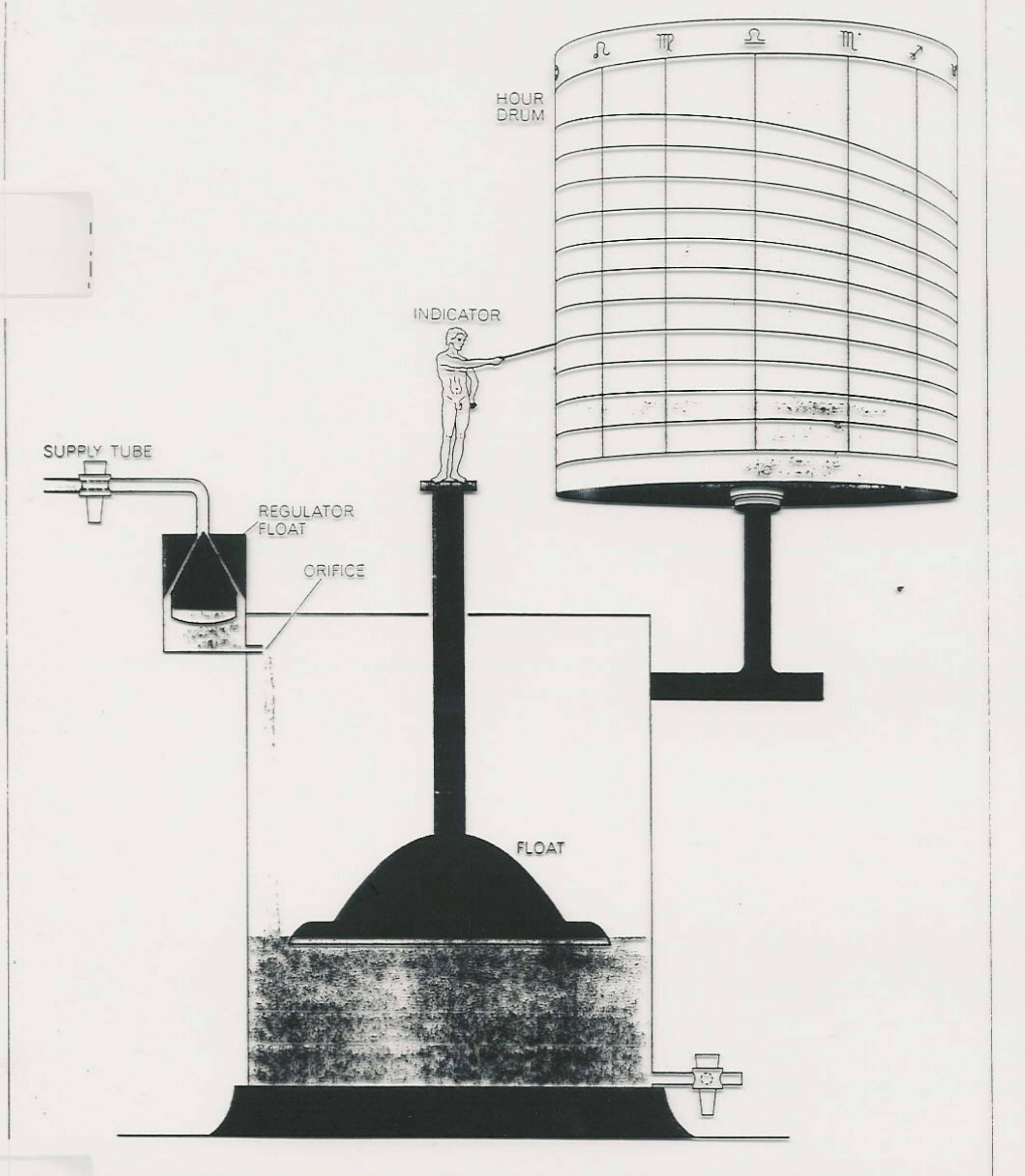
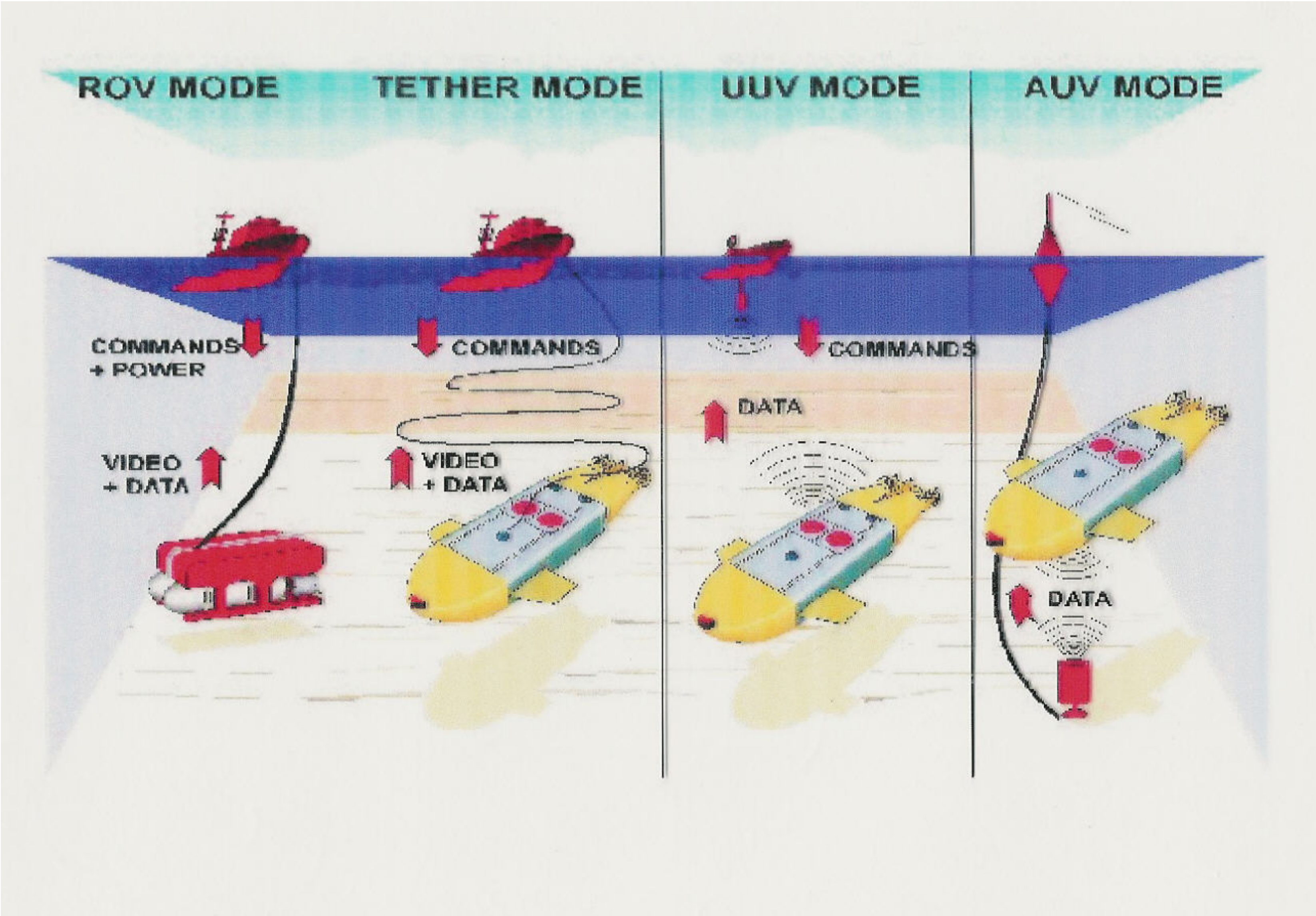


ANCIENT WATER CLOCK is the earliest known device for feed-back control. It was invented in the third century B.C. by a Greek mechanician named Ktesibios, working in Alexandria. This drawing is based on a reconstruction by the German classicist Hermann Diels. The indicator figure is mounted on a large float (*bottom*), which rises inside a tank as a result of a slow trickle of water into the tank. The 12 hours, which vary in length with the seasons of the year, are indicated on the drum at top right. The change in the length of the hours can be represented by simply turning the drum to the proper month. The float regulator at top left controls the rate of water flowing into the main tank by maintaining a constant water level in the adjacent regulator vessel. If the level rises (as a result, say, of an increase of static pressure in the external supply line), the regulator float will rise, throttling the inflow into the regulator vessel. The device is remarkably similar in operation to the carburetor of a modern automobile.


ROV MODE
TETHER MODE
UUV MODE
AUV MODE
COMMANDS
+ POWER
VIDEO
+ DATA
COMMANDS
VIDEO
+ DATA
COMMANDS
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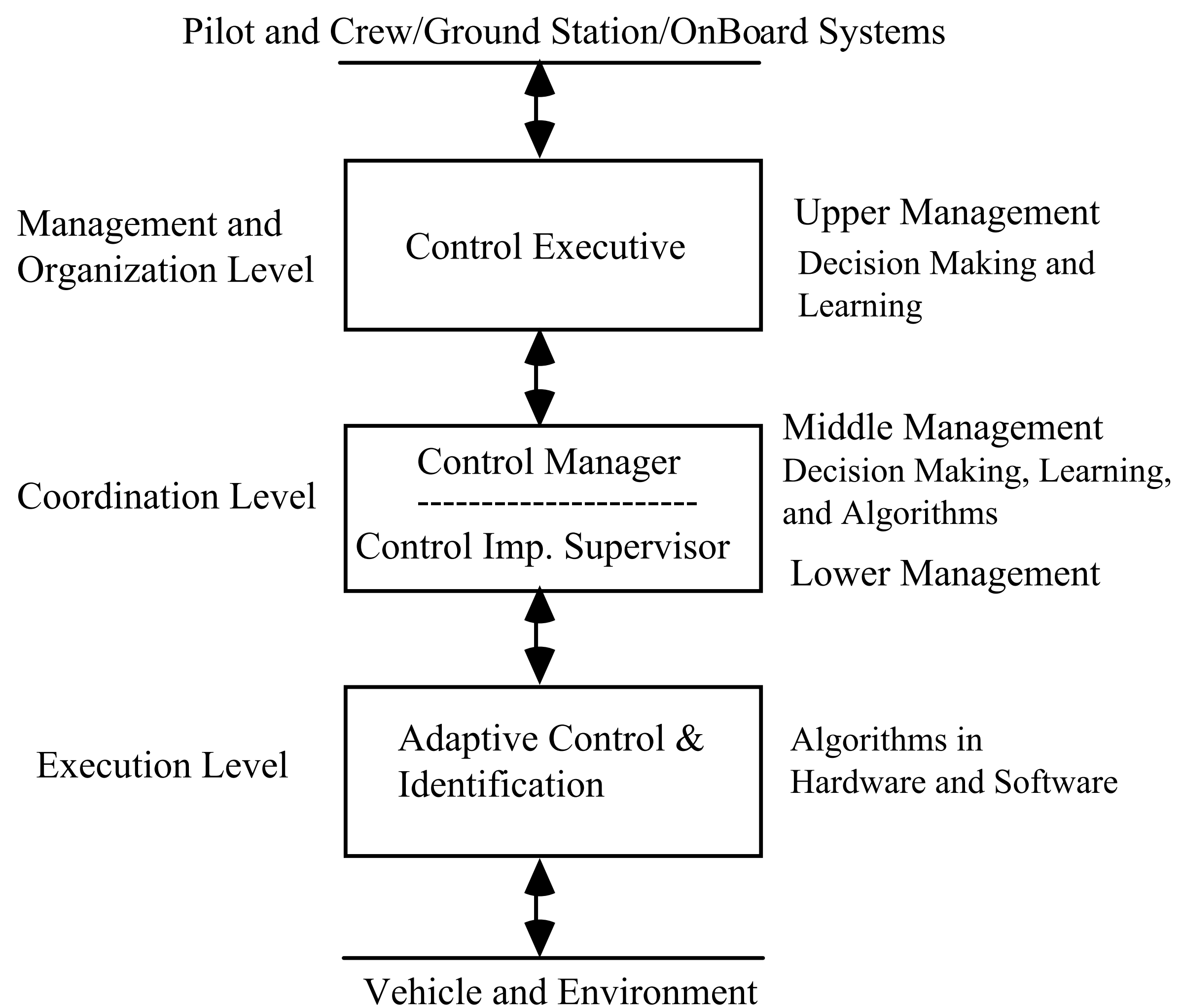
DATA



Autonomous Controller Functional Architecture – Spacecraft JPL

DES Supervisory Control using Petri Nets

Discrete Event Systems Supervisory Control via Petri Nets

- The controller is a Petri net, it is maximally permissive. It consists only of places and arcs and its size is proportional to the number of constraints. The closed loop model is also a Petri net. Standard tools for Petri nets can then be used to further analyze and study the supervised plant.

- The design approach enforces linear inequality constraints on the markings of the plant.

- Constraints can model a variety of important control specifications including forbidden state and general mutual exclusion constraints, finite resource management and allocation constraints, liveness and deadlock avoidance constraints.

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Discrete Event Systems
Supervisory Control via Petri Nets

- Petri nets with uncontrollable and unobservable transitions. Deadock Prevention, *T*-Liveness. Decentralized Supervisory Control.

- *Supervisory Control of Concurrent Systems: A Petri Net Structural Approach.* 281 pages, *Birkhauser*, 2006. (Iordache, PJA)
- *Supervisory Control of Discrete Event Systems using Petri Nets*. 216 pages, *Kluwer*, 1998. (Moody, PJA)

- Used to identify deadlocks in existing commercial software (Lafortune)

- Novel Approach to Concurrent Programming.
  Software Development.

- Paper FrB12.1 13:40-14:00,
  Petri Nets and Programming: A Survey Iordache, PJA

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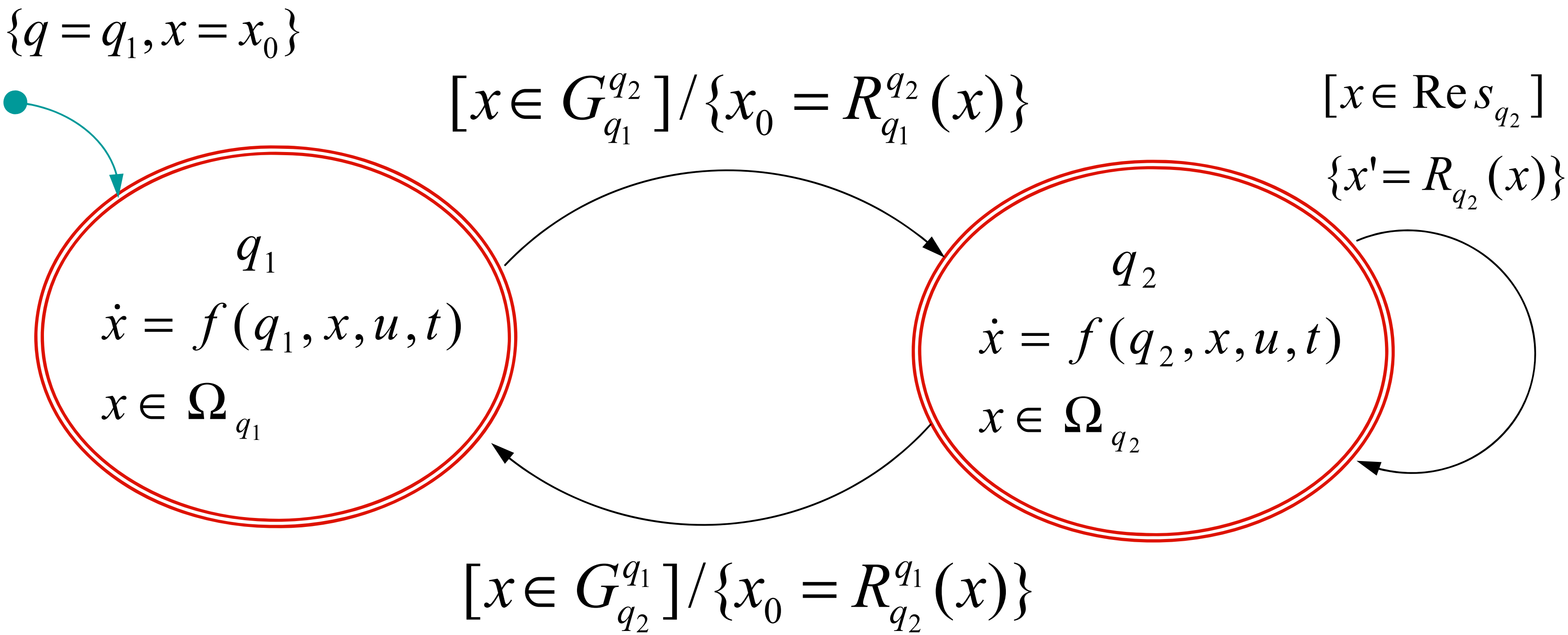
HYBRID SYSTEMS

HYBRID SYSTEMS

- *Hybrid dynamical systems contain continuous and discrete dynamics that interact with each other.* Time and event driven.
- It is important to develop models that accurately describe the dynamic behavior of such hybrid systems. (*when specifications are tight*)
- Reducing complexity.

  Thermostat sees a very simple, but adequate for the task in hand, model of the complex heat flow dynamics.
- Modeling physical phenomena. To avoid dealing directly with a set of nonlinear equations one may choose to work with sets of simpler equations (e.g. linear), and switch among these simpler models.
- In control, switching among simpler dynamical systems.

Hybrid Automata



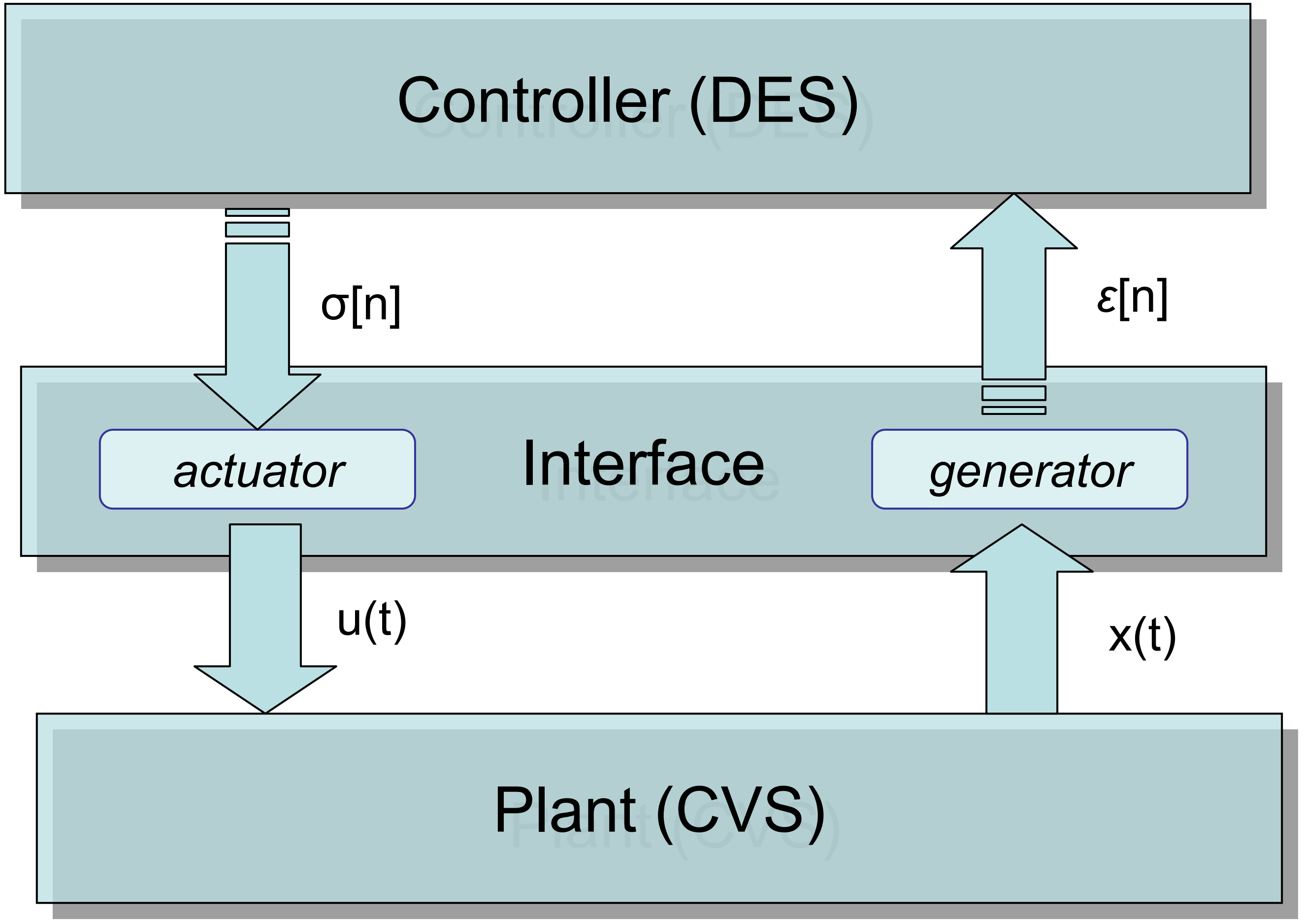
Why Use Hybrid Models - More

- Computer program may depend on values of continuous variables within that program (e.g. continuous time clocks). Real time systems

- Interest in hybrid systems among computer scientists and logicians with emphasis on verification of design.

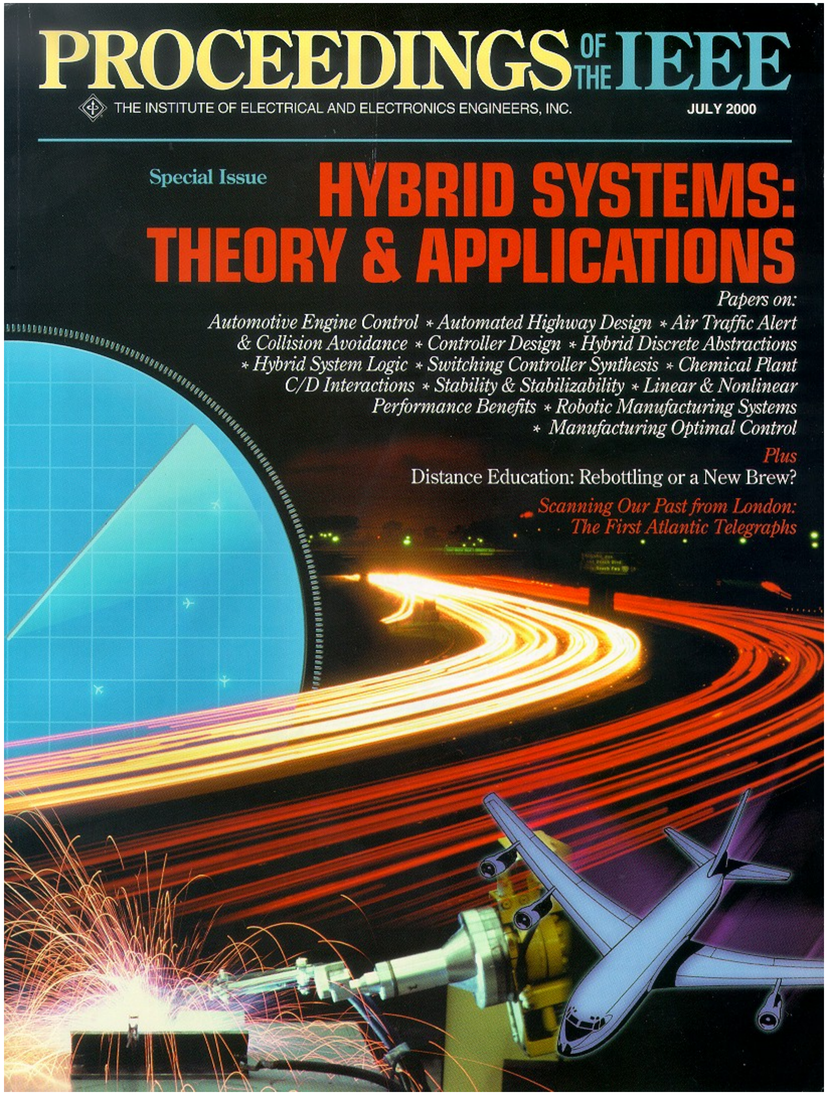
  Of primary interest is the safe operation of the hybrid system, expressed in terms of formal specifications that must be verified.

Supervisory Control of HDS



Control of HDS

- A more accurate approximation of the plant's behavior can be obtained by considering a finer partitioning of the state space for the extraction of the DES plant. (Raisch, Tabuada)
- Discretization and Continualization
- Special cases. Switched linear systems.
- Hai Lin, PJA, "Stability and Stabilizability of Switched Linear Systems: A Survey of Recent Results," *IEEE Trans. Auto.Control,* February 2009.


PROCEEDINGS OF THE IEEE
THE INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS, INC.
JULY 2000
Special Issue
HYBRID SYSTEMS: THEORY & APPLICATIONS
Papers on:
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Scanning Our Past from London: The First Atlantic Telegraphs

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- **Networked Control Systems**-A different approach. **Model-Based and Intermittent Feedback**. How didn't we think of them before?

- ***Cyber-Physical Systems**: What are they?*
  ***Passivity** appears promising.*
- ***In Closing**-A call to join the **Quest for Autonomy***

Networked Sensing & Control- Setting the Stage

-Spatially distributed sensing and control systems have existed for decades (e.g. SCADA systems). Centralized decision making with wired connections.

-Technology Driven- Low cost processing (intelligence) at remote locations with substantial communication capabilities

Leads to Embedded Systems, Networked, Shared Digital Networks Wired and Wireless.

-Embedded systems that interact, autonomously, with the physical world (e.g. in Health Care, Transportation, Process Control, Defense, Large Scale Infrastructure). Cyber-Physical Systems. Challenging area for CS, Engineering, Physical & Social Sciences.

Networked Sensing & Control- Setting the Stage

-Two main changes in control systems analysis and design.

-A new component. The effect of **the Network**.

Information constraints.

Shared communication channels. Media Access.

Delays. Dropped packets.

Fading. Time varying throughput.

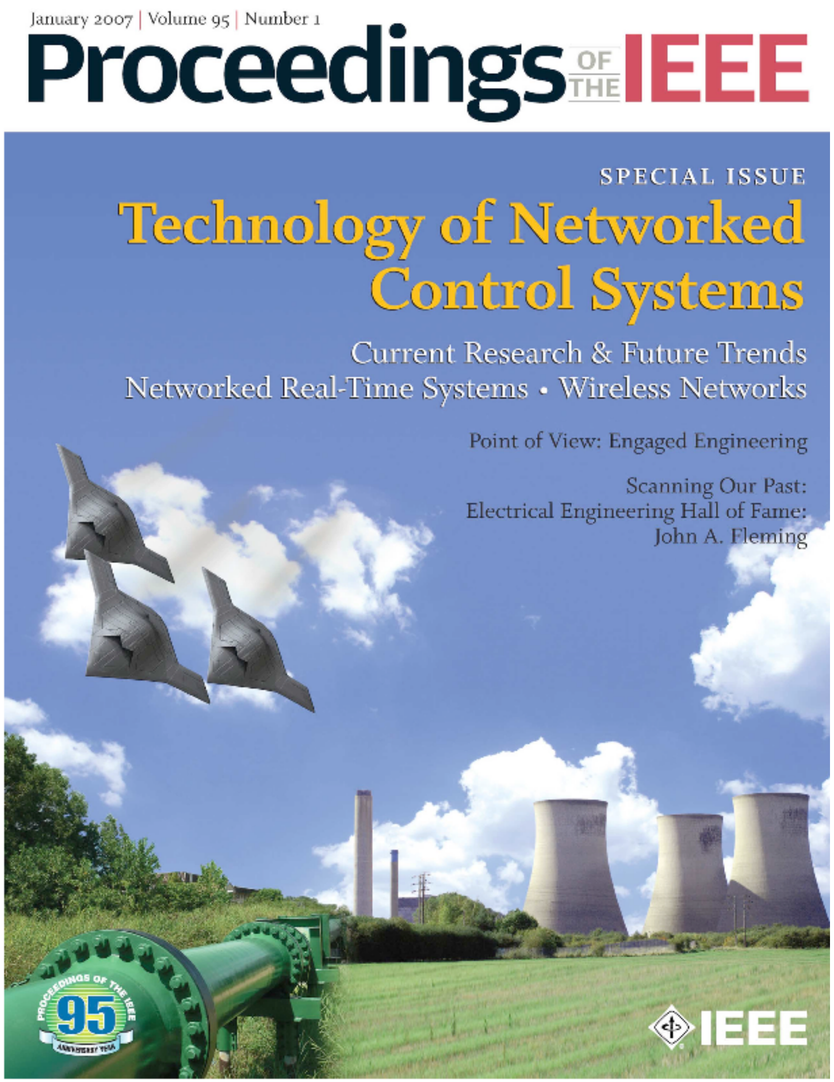
-Renewed emphasis on **Distributed Control**

Potential for superior performance.

Loosely interconnected clusters of control systems.

Special Issues on **Networked Control Systems:**

***Proceedings of the IEEE*, January 2007**. *IEEE Trans. on Auto. Control*, September 2004. **(PJA & JB)**


January 2007 | Volume 95 | Number 1
Proceedings OF THE IEEE
SPECIAL ISSUE
Technology of Networked Control Systems
Current Research & Future Trends
Networked Real-Time Systems • Wireless Networks
Point of View: Engaged Engineering
Scanning Our Past:
Electrical Engineering Hall of Fame:
John A. Fleming
95
IEEE

A Model-Based Networked Control System

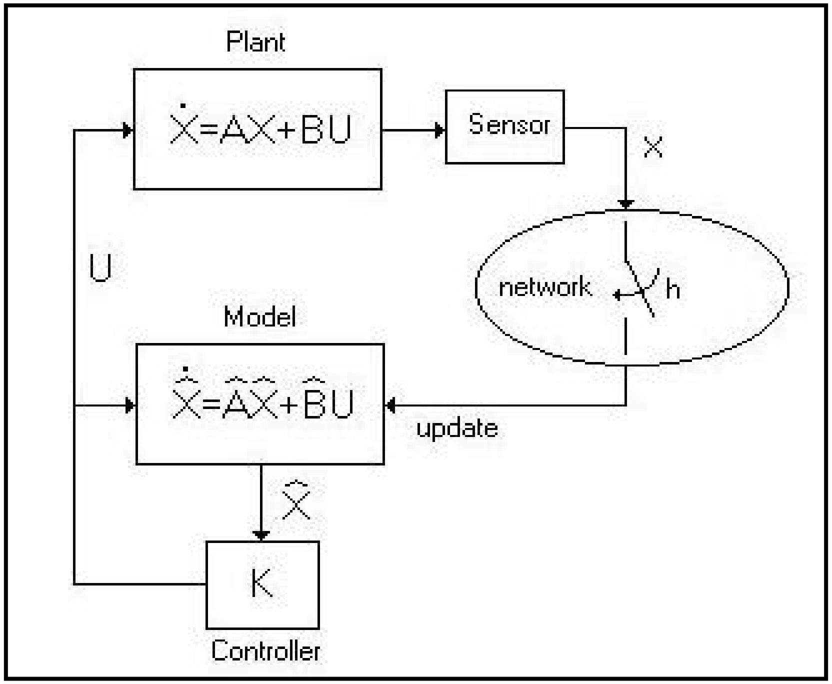
Sensor information is sent to controller every **h** seconds.

Sensor node transmits measurements of plant state to controller/actuator node.

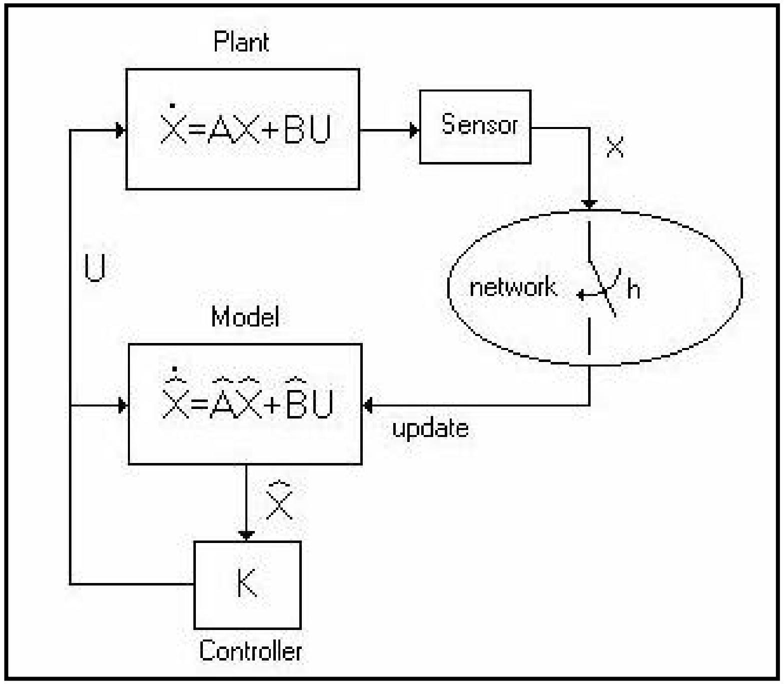
Plant model's state is updated with sensor information every **h** seconds.

Controller/actuator node contains plant model. Model-Based architecture.

Attempts to reduce the number of packets sent over the network.



Definitions



Plant: $\dot{x} = Ax + Bu$

Model: $\dot{\hat{x}} = \hat{A}\hat{x} + \hat{B}u$

Controller: $u = K\hat{x}$

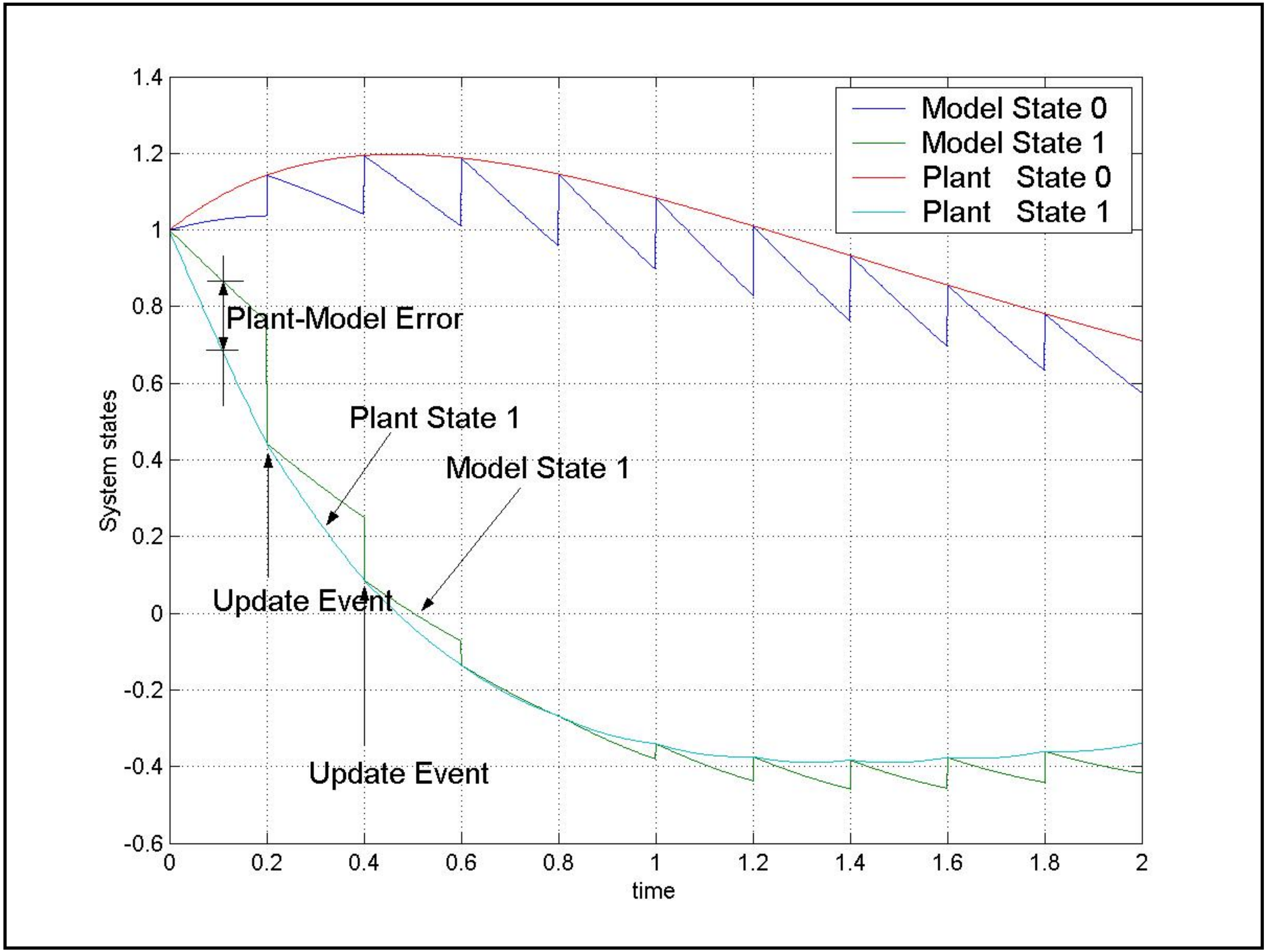
State Error: $e = x - \hat{x}$

Error Matrices: $\tilde{A} = A - \hat{A},\ \tilde{B} = B - \hat{B}$

With update times t_k,

and where $t_k - t_{k-1} = h_k$ for all k and

$e(t_k)=0$ for $k=0,1,2...$


Model State 0
Model State 1
Plant State 0
Plant State 1
Plant-Model Error
Plant State 1
Model State 1
Update Event
Update Event
System states
time
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

Contributions to MB-NCS

- Stability of MB-NCS with Constant Update Times.
- State and Output Feedback. Delays.
- Continuous and Discrete -Time.

- Stability of MB-NCS with Time-Varying Update Times.
  – Lyapunov. Stochastic stability.
- Stability of Nonlinear MB-NCS
- Performance of MB-NCS with Constant Update Times.

- Quantization on MB-NCS.
  – Static, uniform & logarithmic. Dynamic.

- Connections to multi-rate control.

Response with Constant Update Times

The State Feedback MB-NCS with initial conditions ,

$$z(t_0) = \begin{bmatrix} x(t_0) \\ 0 \end{bmatrix} = z_0$$

and h_k=h has the following response:

$$z(t) = e^{\Lambda(t-t_k)} \left(\begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} e^{\Lambda h} \begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} \right)^k z_0$$

$$t \in [t_k,\ t_{k+1}), \quad with \quad t_{k+1} - t_k = h$$

Stability of State Feedback MB-NCS

The State Feedback MB-NCS is stable iff the eigenvalues of

$$M = \begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} e^{\Lambda h} \begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix}$$

are inside the unit circle. Where

$$\Lambda = \begin{bmatrix} A + BK & -BK \\ \tilde{A} + \tilde{B}K & \hat{A} - \tilde{B}K \end{bmatrix}$$

M will have its eigenvalues inside the unit circle iff the matrix N has its eigenvalues inside the unit circle (same nonzero eigenvalues), where:

$$N = e^{(\hat{A}+\hat{B}K)h} + e^{Ah} \int_0^h e^{-A\tau} (\tilde{A} + \tilde{B}K) e^{(\hat{A}+\hat{B}K)\tau} d\tau$$

Example of a Full State Feedback NCS

Consider the following unstable plant:

$$A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

We will use the state feedback controller given by $u = Kx$ with

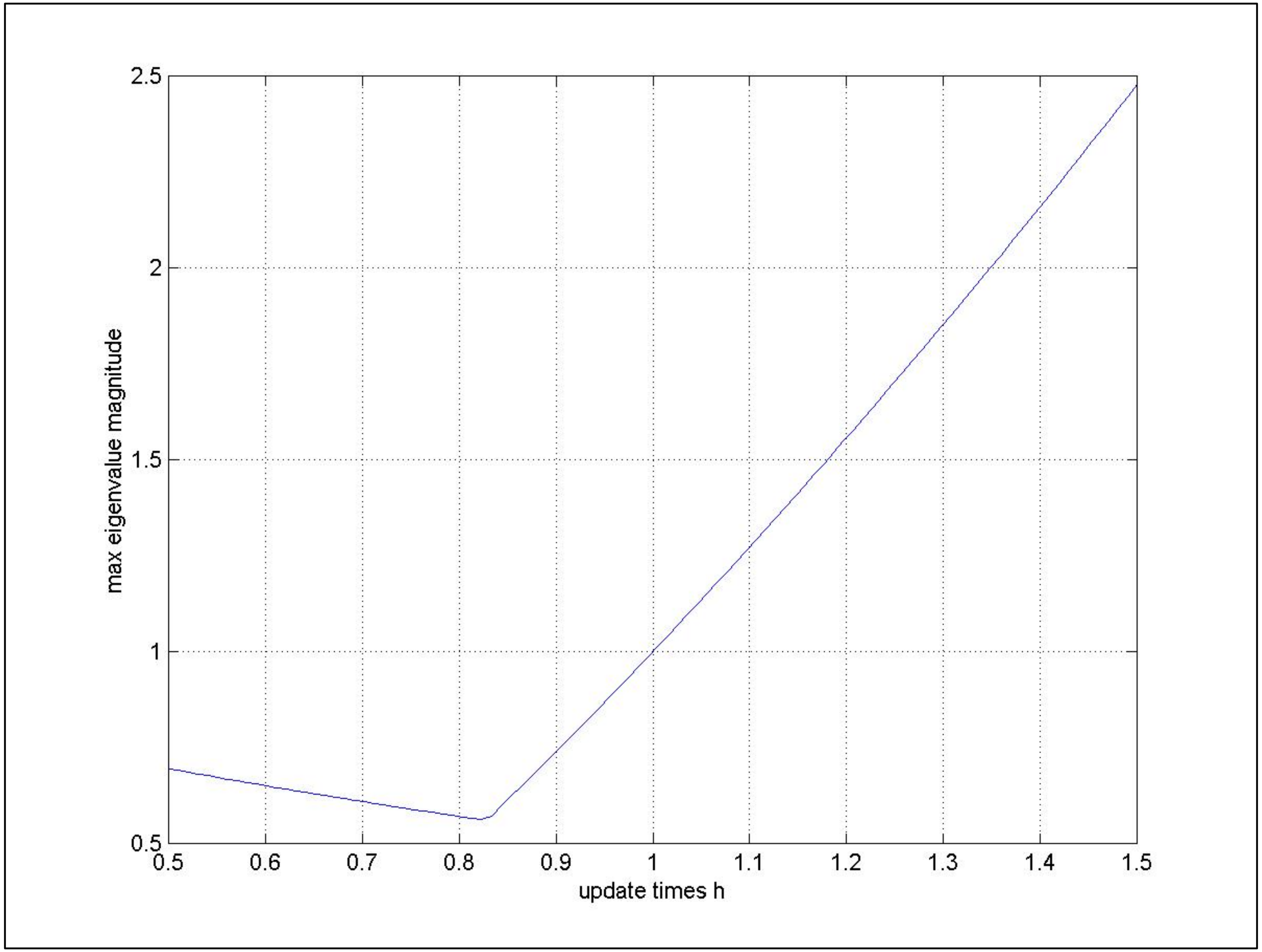
.

$$K = \begin{bmatrix} -1 & -2 \end{bmatrix}$$

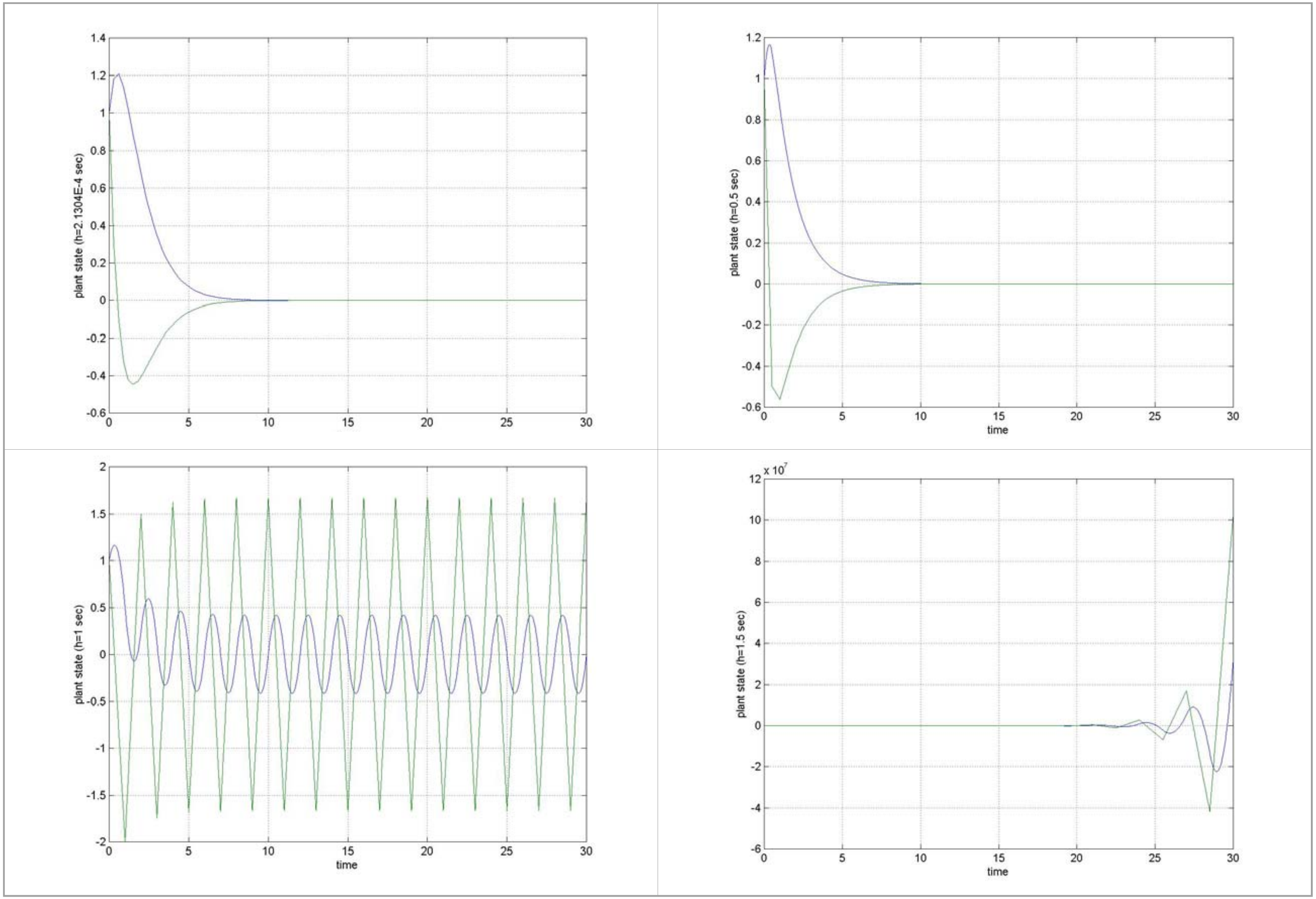
Considering a model that behaves like a ZOH:

$$\hat{A} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}, \quad \hat{B} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

So now we need to search for the largest* h *such that $\begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} e^{\Lambda h} \begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix}$ ***has its eigenvalues inside the unit circle.***



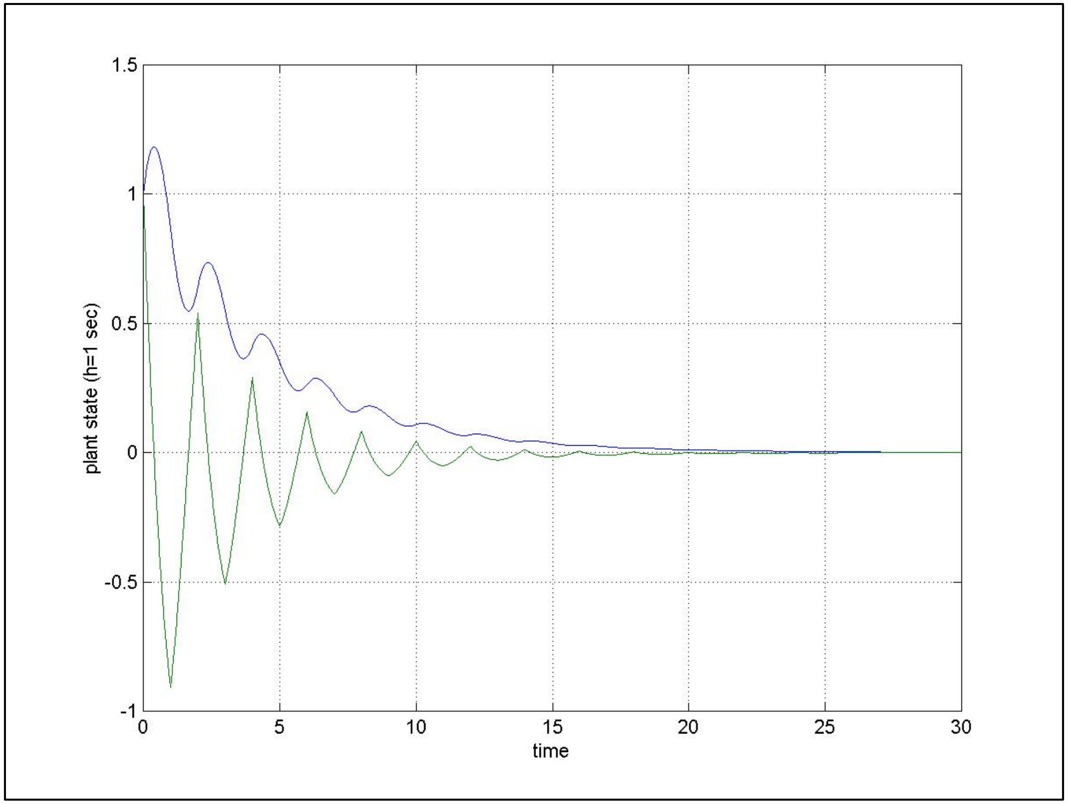
Maximum eigenvalue magnitude versus the update time.



System response with different update times.

Now using our setup, we will use a plant model that has a similar structure to the actual plant. We will use the randomly perturbed plant model:

$$\hat{A} = \begin{bmatrix} -0.5395 & 1.7990 \\ -0.7126 & -0.4972 \end{bmatrix}, \ \hat{B} = \begin{bmatrix} 0.3030 \\ 0.0096 \end{bmatrix}$$



System response with improved model and *h*=1s.

Example - Applicability

model: $\hat{A} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, \hat{B} = \begin{bmatrix} 0 \\ 1 \end{bmatrix};$

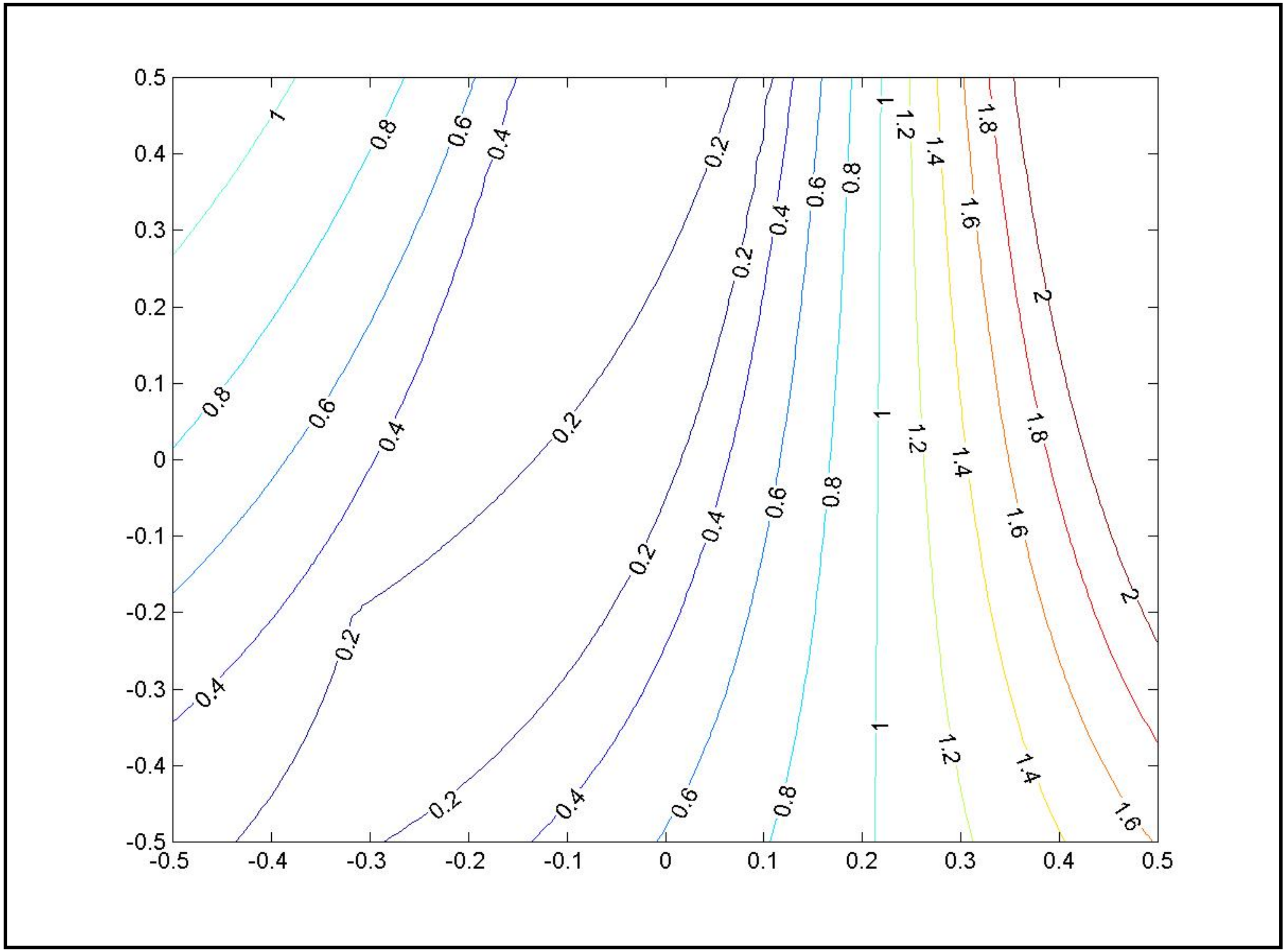
plant: $A = \begin{bmatrix} 0 & 1+\tilde{a}_{12} \\ 0+\tilde{a}_{21} & 0 \end{bmatrix}, B = \begin{bmatrix} 0 \\ 1 \end{bmatrix};$

with $\tilde{a}_{12} = [-0.5, 0.5]$, $\tilde{a}_{21} = [-0.5, 0.5]$

controller: $K = [-1, -2];$

Update time: $h = 2.5$ sec.

Applicability Example (cont.)

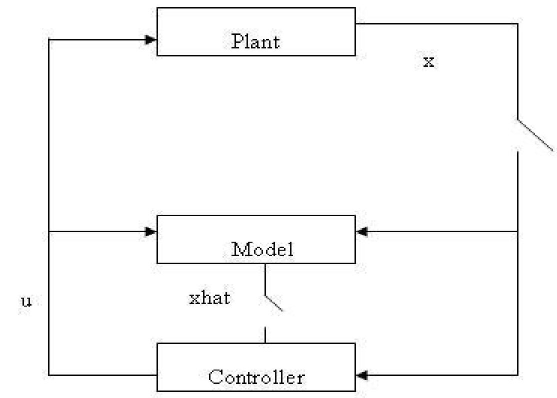


MB-NCS with Intermittent Feedback Problem formulation

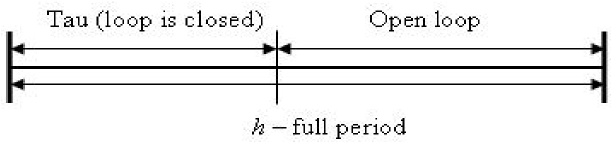
Similar to MB-NCS setup

Closed loop: $[t_k, t_k + \tau)$

Open loop: $[t_k + \tau, t_{k+1})$



Basic setup



Closed and open loop in one cycle of intermittent feedback

Intermittent feedback: Related work

Concept also appears in:

Psychology (learning process, reinforcement) (Skinner; Salzberg et al),
Chemical engineering (chlorine disinfection, distillation) (Kim; Oldroyd),
Mechanical engineering (Koay, Bugmann), etc.
Robotics: visual feedback designed after biological system (Ronco)

- R. Brockett and D. Liberzon, "Quantized feedback stabilization of linear systems." (uses a related idea, minimum attention control)

- G. Conte and A. Perdon – MB used in control of underwater vehicles

Problem formulation

Control law: $u = K\hat{x}$

Plant: $\dot{x} = Ax + Bu$

Model: $\dot{\hat{x}} = \hat{A}\hat{x} + \hat{B}u$

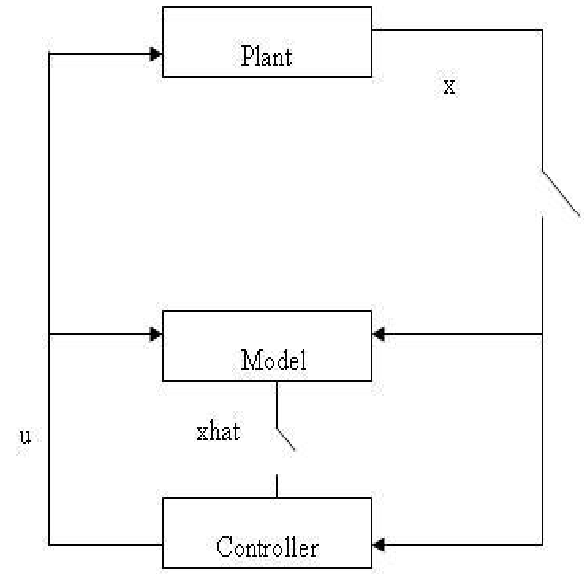
Error matrices:

$$\tilde{A} = A - \hat{A}$$

$$\tilde{B} = B - \hat{B}$$

Error: $e = x - \hat{x}$

Also: $z(t) = \begin{bmatrix} x(t) \\ e(t) \end{bmatrix}$



Basic setup for MB-NCS with IF

State Response of the System-1

Open loop: $t \in [t_k + \tau, t_{k+1})$ $\quad u = K\hat{x}$

$$\begin{bmatrix} \dot{x} \\ \dot{\hat{x}} \end{bmatrix} = \begin{bmatrix} A & BK \\ 0 & \hat{A} + \hat{B}K \end{bmatrix} \begin{bmatrix} x(t) \\ \hat{x}(t) \end{bmatrix}$$

with initial conditions $\hat{x}(t_k + \tau) = x(t_k + \tau)$.

$$\dot{z}(t) = \begin{bmatrix} \dot{x}(t) \\ \dot{e}(t) \end{bmatrix} = \begin{bmatrix} A + BK & -BK \\ \tilde{A} + \tilde{B}K & \hat{A} - \tilde{B}K \end{bmatrix} \begin{bmatrix} x(t) \\ e(t) \end{bmatrix}$$

$$z(t_k + \tau) = \begin{bmatrix} x(t_k + \tau) \\ e(t_k + \tau) \end{bmatrix} = \begin{bmatrix} x(t_k + \tau^-) \\ 0 \end{bmatrix}$$

for all $t \in [t_k + \tau, t_{k+1})$.

State Response of the System-2

Thus, we have

$$\dot{z} = \Lambda_o z, \text{ where } \Lambda_o = \begin{bmatrix} A + BK & -BK \\ \tilde{A} + \tilde{B}K & \hat{A} - \tilde{B}K \end{bmatrix}$$

for all $t \in [t_k + \tau, t_{k+1})$.

Closed loop: $t \in [t_k, t_k + \tau)$

$$\dot{z} = \Lambda_c z, \text{ where } \Lambda_c = \begin{bmatrix} A + BK & -BK \\ 0 & 0 \end{bmatrix}$$

State Response of the System-3

Initial condition: $z(t=0)=z_0$

Then: $$z(t)=e^{\Lambda_c(t)}z_0\,,\ t\in[0,\tau)$$

Opening the loop:

$$z(t)=e^{\Lambda_o(t-\tau)}z(\tau)=e^{\Lambda_o(t-\tau)}e^{\Lambda_c(\tau)}z_0\,,\ t\in[\tau,t_1).$$

After time *h*: $$z\left(t_1^-\right)=e^{\Lambda_o(h-\tau)}e^{\Lambda_c(\tau)}z_0$$

State Response of the System-4

Complete description of the output:

$$z(t) = \begin{cases} e^{\Lambda_c(t-t_k)} \left(\begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} \Sigma \begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} \right)^k z_0 \\ \qquad \text{for } t \in [t_k, t_k + \tau) \\ e^{\Lambda_o(t-(t_k+\tau))} e^{\Lambda_c(\tau)} \left(\begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} \Sigma \begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} \right)^k z_0 \\ \qquad \text{for } t \in [t_k + \tau, t_{k+1}) \end{cases}$$

where

$$\Sigma = e^{\Lambda_o(h-\tau)} e^{\Lambda_c(\tau)},$$

$$\Lambda_o = \begin{bmatrix} A + BK & -BK \\ \tilde{A} + \tilde{B}K & \hat{A} - \tilde{B}K \end{bmatrix},$$

$$\Lambda_c = \begin{bmatrix} A + BK & -BK \\ 0 & 0 \end{bmatrix},$$

and $t_{k+1} - t_k = h$.

Stability Condition

System is globally exponentially stable if and only if the eigenvalues of

$$\begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} \Sigma \begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix}$$

$$\Sigma = e^{\Lambda_o(h-\tau)} e^{\Lambda_c(\tau)}$$

are strictly inside the unit circle.

Example

Plant:

$$A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, \; B = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

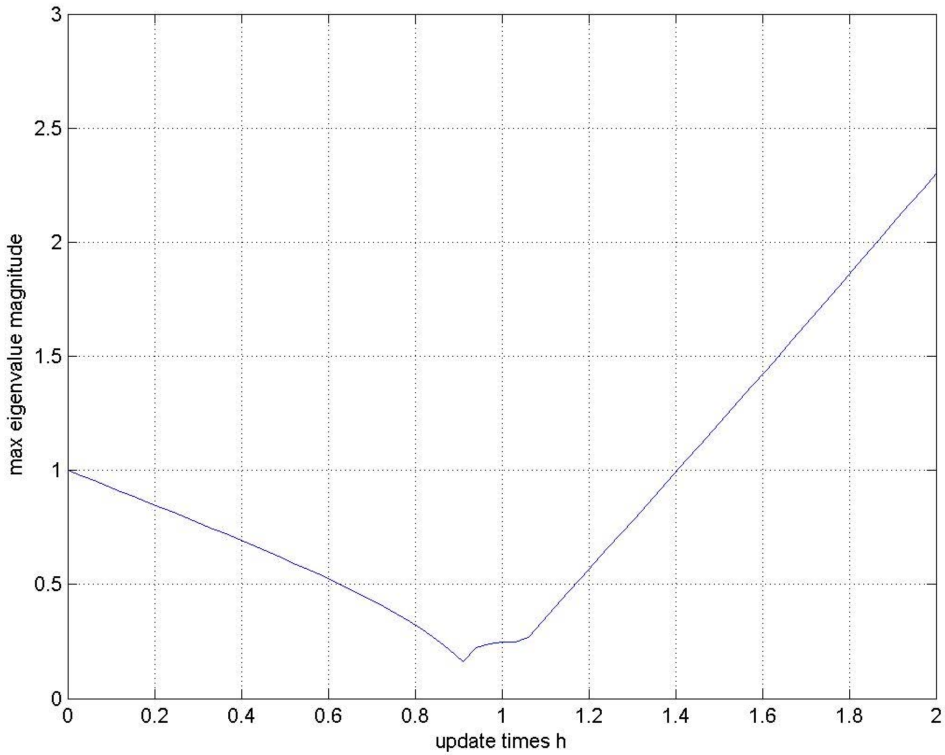
Controller:

$$k = [-1, -1.5]$$

Model:

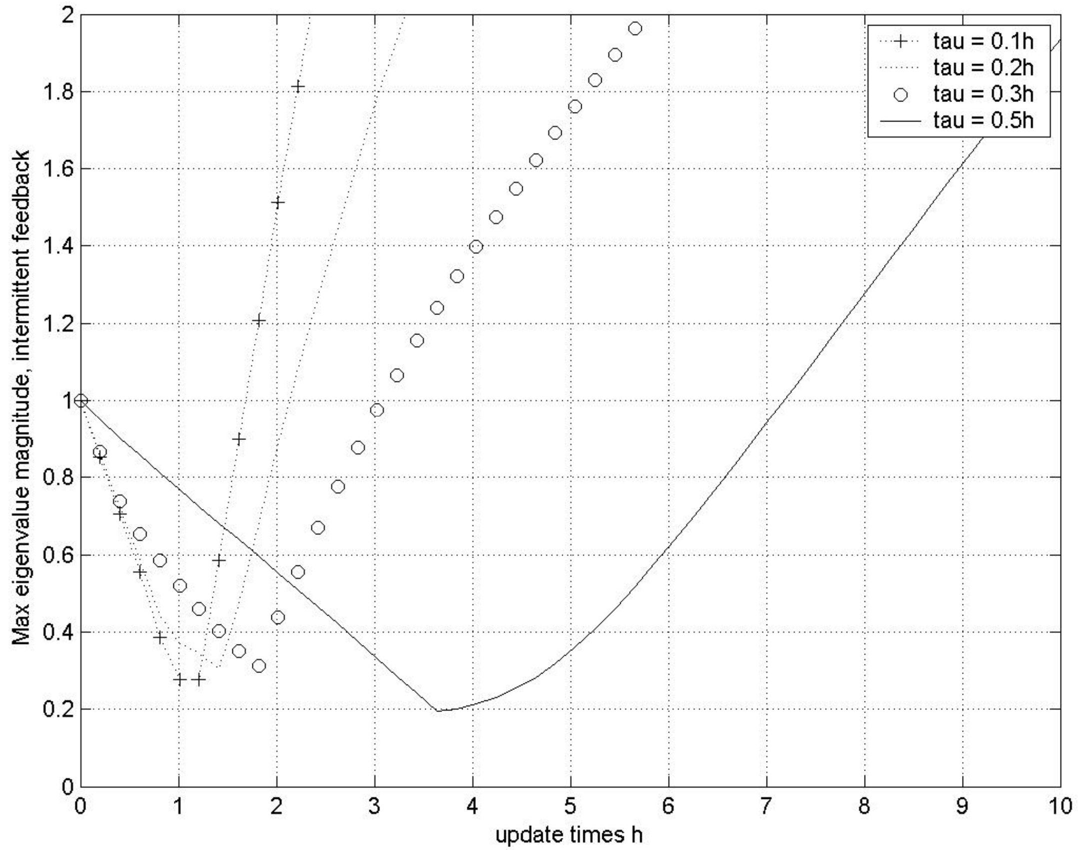
$$\hat{A} = \begin{bmatrix} 0 & 0.5 \\ 0 & 0 \end{bmatrix} \qquad \hat{B} = \begin{bmatrix} 0 \\ 0.25 \end{bmatrix}$$

Example – max eigenvalue search



h = 1.4 in MB-NCS case

Examples – max eigenvalue search



Maximum eigenvalue for MB-NCS with Intermittent Feedback, for various tau.

Ongoing work

- Robustness
- Filtering
- Optimal control, performance issues
- Stability of MB-NCS with IF: time-varying tau and h, discrete-time plants, disturbances
- System identification
- Multi-rate problems
- Hybrid

Outline

- *A glimpse at* ***Feedback Fundamentals***
- *The* ***Quest for Autonomy*** *leads to* ***DES and Hybrid***
- ***Networked Control Systems****-A different approach.* ***Model-Based and Intermittent Feedback****.*

- **Cyber-Physical Systems**: What are they? Are there any design principles, general concepts that may be helpful here with the cyber, physical, human-in-the loop (feedback) network interconnections? **Passivity** appears promising.

- ***In Closing****-A call to join the* ***Quest for Autonomy***

Cyber-Physical Systems

CPS Opportunities

are

Technological and Economic Drivers

- The decreasing cost of computation, networking, and sensing.
- A variety of social and economic forces will require us to use national infrastructures more efficiently.
- Environmental pressures will mandate the rapid introduction of technologies to improve energy efficiency and reduce pollution.
- As the national population ages, we will need to make more efficient use of our health care systems, ranging from facilities to medical data and information.

CPS Workshops

· National Workshop on "High Confidence Medical Device Software and Systems (HCMDSS)", June 2 - 3, 2005, Philadelphia, PA.
· National Workshop on "Aviation Software Systems: Design for Certifiably Dependable Systems", October 5-6, 2006, Alexandria, TX.

· NSF Workshop on "Cyber-Physical Systems", October 16-17, 2006, Austin,TX.
· National Meeting on "Beyond SCADA: Networked Embedded Control for Cyber Physical Systems", November 8-9, 2006, Pittsburgh, PA.
· National Workshop on "High-Confidence Automotive Cyber-Physical Systems," April 3-4, 2008, Troy, MI
· National Workshop on "High-Confidence Transportation Cyber-Physical Systems: Automotive, Aviation & Rail," November 18-20, 2008, Tyson's Corner, VA

· CPS Week, CPS Summit, April 24-25, 2008, St. Louis, MO
· CPS Week, CPS Forum, April 13-17, 2009, San Francisco, CA
· CPS Week, CPS Forum, April 12-16, 2010, Stockholm, Sweden

UNIVERSITY OF NOTRE DAME

PCAST Report

Leadership Under Challenge:
Information Technology R&D in a Competitive World
An Assessment of the Federal Networking and Information Technology R&D Program
President's Council of Advisors on Science and Technology
August 2007

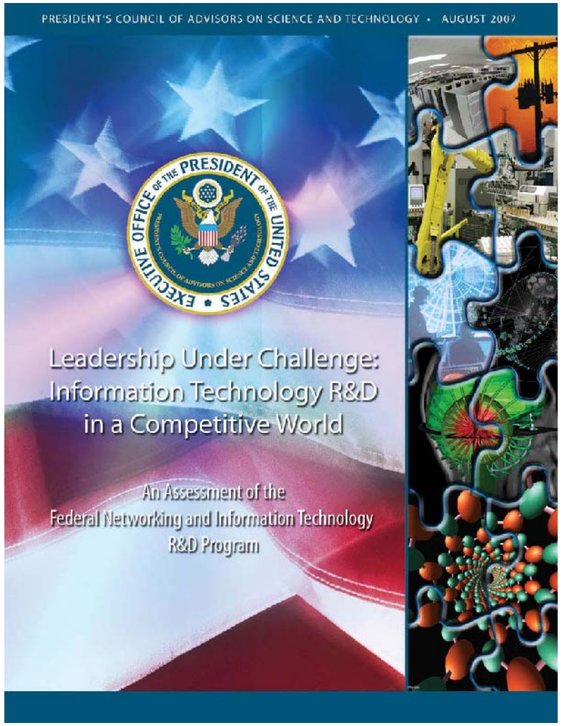
New Directions in Networking and Information Technology (NIT)

Recommendation: No 1 Funding Priority:
NIT Systems Connected with the Physical World

PCAST Report

Chapter 4 in Report –Technical Priorities for NIT R&D

1. NIT Systems Connected with the Physical World
2. Software
3. Data, Data Stores, and Data Streams
4. Networking
5. High End Computing
6. Cyber Security and Information Assurance
7. Human-Computer Interaction
8. NIT and the Social Sciences



CPS Characteristics

What cyber physical systems have as defining characteristics:

- Cyber capability (i.e. networking and computational capability) in every physical component
- They are networked at multiple and extreme scales
- They are complex at multiple temporal and spatial scales.
- They are dynamically reorganizing and reconfiguring
- Control loops are closed at each spatial and temporal scale. Maybe human in the loop.
- Operation needs to be dependable and certifiable in certain cases
- Computation/information processing and physical processes are so tightly integrated that it is not possible to identify whether behavioral attributes are the result of computations (computer programs), physical laws, or both working together.

CPS Issues

There is a set of pervasive underlying problems for CPS not solved by current technologies:

• How to build predictable real time, networked CPS at all scales?

• How to build and manage high-confidence, dynamically-configured systems?

• How to organize and assure interoperability?

• How to avoid cascading failure?

• How to formulate an evidential (synthetic and analytic) basis for trusted systems? Certified.

Research Challenges

- We need systems that are compositional, scalable, and evolvable
  - Big and small components
  - One component to billions of components
  - New and old technology co-exist
- We need ways to measure and certify the "performance" of cyber-physical systems
  - Time and space, but multiple degrees of resolution
  - New metrics, e.g., energy use
  - New properties, e.g., security, privacy-preserving
- We need new engineering processes for developing, maintaining, and monitoring CPS
  - Traditional methods will not work or are too costly

Source: NSF

Passivity and CPS

-In real world CPS-automotive, medical-overall system dynamics emerge from the interaction of physical dynamics, computational dynamics and communication network

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

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

-Controlling robot over a wireless network (with Vanderbilt). **NSF**

Passive Hybrid Systems

Definition of Passivity (1)

- A system is *passive* if there exists a positive semi-definite storage function *V(x)* and a specific supply rate $\omega(u,y) = u^T y$ such that the following inequality holds

$$u^T y \geq \frac{dV}{dt}$$

- It should be noted that the input *u* and output *y* must have the same dimension.

Definition of Passivity (2)

- The previous definition is equivalent to the integral definition of passivity

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

- Once in this form, the integral can be replaced with a sum to define passivity for discrete time systems

$$\sum_{k=k_1}^{k_2} u^T(k)y(k) \geq V(x(k_2)) - V(x(k_1))$$

Definitions for Continuous Time Systems

Passive	$u^T y \ge \dot{V}$
Lossless	$u^T y = \dot{V}$
Strictly Passive	$u^T y \ge \dot{V} + \psi(x)$
Strictly Output Passive	$u^T y \ge \dot{V} + \varepsilon y^T y$
Strictly Input Passive	$u^T y \ge \dot{V} + \delta u^T u$

- Note that *V(x)* and *Ψ(x)* are positive semidefinite and continuously differentiable. These equations hold for all times, inputs, and states.

LMI Formulation (CT)

$$V(x) = \frac{1}{2} x^T P x$$

$$\dot{V}(x) = \frac{1}{2} \dot{x}^T P x + \frac{1}{2} x^T P \dot{x}$$

$$= \frac{1}{2}(Ax + Bu)^T P x + \frac{1}{2} x^T P (Ax + Bu)$$

$$= \frac{1}{2}\left[x^T (A^T P + PA)x + x^T PBu + u^T B^T P x\right]$$

$$\leq u^T y = \frac{1}{2}\left[u^T y + y^T u\right]$$

$$= \frac{1}{2}\left[u^T C x + u^T D u + x^T C^T u + u^T D^T u\right]$$

$$\Leftrightarrow x^T (A^T P + PA)x + x^T (PB - C^T)u + u^T (B^T P - C)x - u^T (D + D^T)u \leq 0$$

- For LTI passive systems, can always assume quadratic storage function with

$$P = P^T > 0$$

- Leads to LMI:

$$\begin{bmatrix} A^T P + PA & PB - C^T \\ B^T P - C & -D - D^T \end{bmatrix} \leq 0$$

Properties of Passive Systems

- The parallel and (negative) feedback interconnection of two passive systems remains passive.
- It may be possible to preserve passivity over a network. Wave variables.
- Stable, minimum-phase of relative degree 0 or 1.

Definition of Passive Hybrid Systems (1)

- This theory applies to hybrid systems that can be represented as general nonlinear switched systems

$$\dot{x} = f_i(x,u)$$
$$y = h_i(x)$$

- Different storage functions for each subsystem *i*.
- Each subsystem has a different energy supply rate when it is off.

Definition of Passive Hybrid Systems (2)

- A *hybrid system* is *passive* if it meets the following conditions

1. Each subsystem *i* is passive when on:

$$u^T y \geq \frac{dV_i}{dt}$$

2. Each subsystem *i* is dissipative when off:

$$\omega_i(u, y) \geq \frac{dV_i}{dt}$$

Passivity and CPS

-Current work includes passivity indices for hybrid dynamical systems (output feedback & input forward) and their use in preserving properties while interconnecting.

-Also using symmetries.

Outline

- *A glimpse at the* ***Feedback Fundamental Mechanism****.*
- *The* ***Quest for Autonomy*** *leads to* ***DES and Hybrid***
- ***Networked Control Systems****-A different approach.* ***Model-Based and Intermittent Feedback****.*
- ***Cyber-Physical Systems****: What are they?*

  Passivity *appears promising.*

- **In Closing**-A call to join the **Quest for Autonomy**

Concluding Remarks

- Main points
  - **New ways of thinking needed to deal effectively with the CPS problems. New ways to determine research directions.**
  - Needs should determine methodology. ODE may not be enough.
  - Need deeper understanding of fundamentals that cut across disciplines.

    CPS, Distributed, Embedded, Networked Systems. Analog-digital, large scale, life cycles, safety critical, end to end high-confidence.

  - Education-Engineering, CS. Book

    ***Structure and Interpretation of Signals & Systems*, by Edward A. Lee and Pravin Varaiya, Addison Wesley, 2003.**

  - **Join the Quest for Higher Degree of Autonomy in Systems**
  - **Need to expand our horizons. Control Systems at the center.**
  - Collaborations with, build bridges to Computer Science, Networks, Biology, Physics. Also Sociology, Psychology…