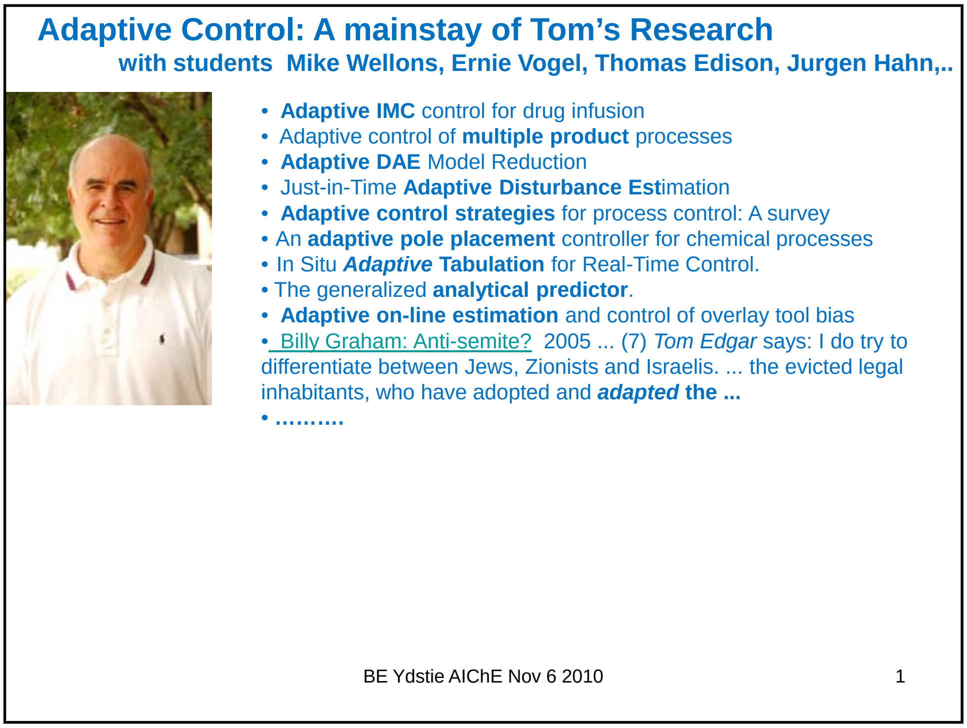

Adaptive Control: A mainstay of Tom's Research

with students Mike Wellons, Ernie Vogel, Thomas Edison, Jurgen Hahn,..

- **Adaptive IMC** control for drug infusion
- Adaptive control of **multiple product** processes
- **Adaptive DAE** Model Reduction
- Just-in-Time **Adaptive Disturbance Est**imation
- **Adaptive control strategies** for process control: A survey
- An **adaptive pole placement** controller for chemical processes
- In Situ ***Adaptive*** **Tabulation** for Real-Time Control.
- The generalized **analytical predictor**.
- **Adaptive on-line estimation** and control of overlay tool bias
- Billy Graham: Anti-semite? 2005 ... (7) *Tom Edgar* says: I do try to differentiate between Jews, Zionists and Israelis. ... the evicted legal inhabitants, who have adopted and ***adapted*** **the ...**
- **……….**

Adaptive Control: A mainstay of Tom's Research

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- …………

"Has anything New Happened since we (Seborg, Edgar, Shah) wrote our review article in 1986?"

(CAST Lecture)

Critical Review of 30 years of Adaptive Control

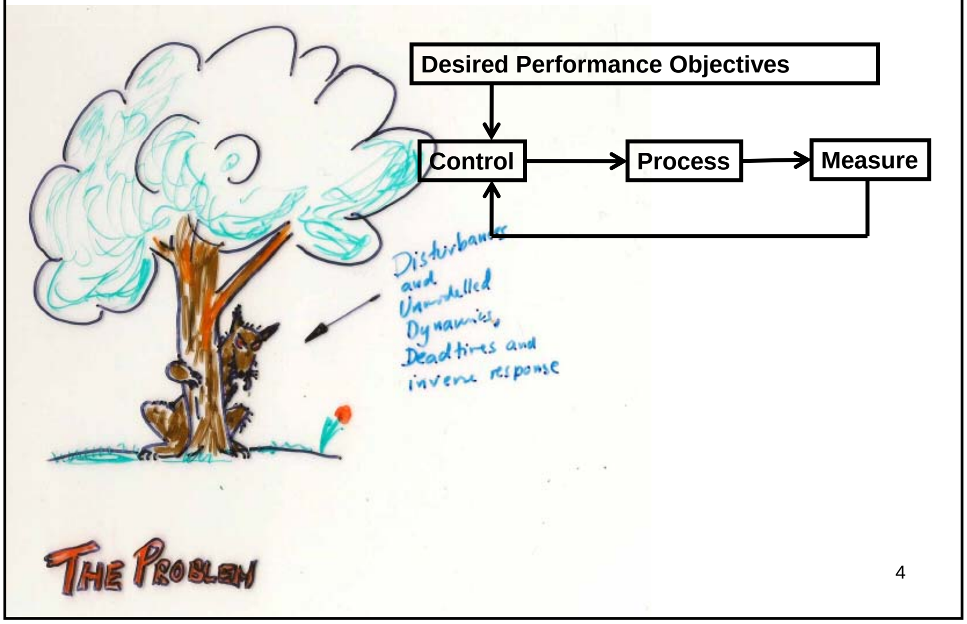
(Was it a Crash?)

B. Erik Ydstie

Chemical Engineering

CMU

General Structure of Control Problem



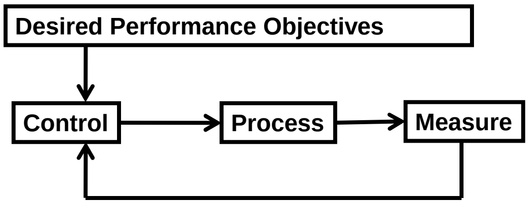
Desired Performance Objectives

Control

Process

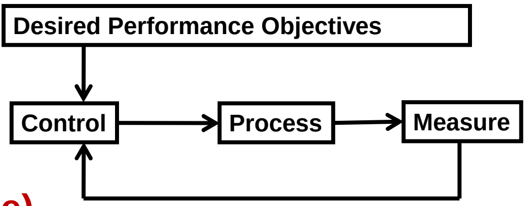
Measure

General Structure of Control Problem



NEED A REALLY GOOD THEORY!

General Structure of Control Problem

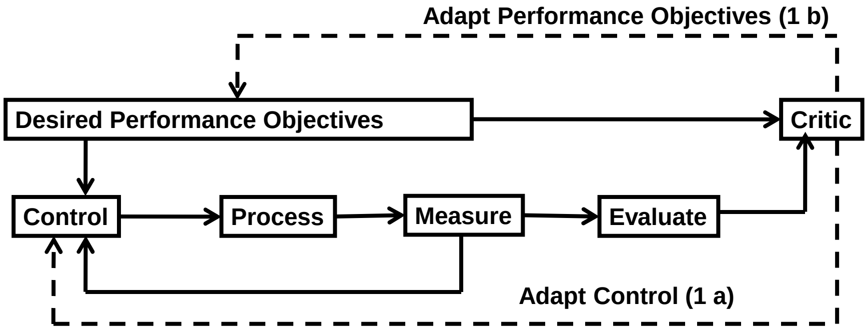


Robert McNamara,
(US Secretary of State)
on Business Management (1995)

1. Defining clear business objectives (Performance Model)
2. Developing plans to achieve the objectives (Control)
3. Systematically monitoring progress against the plan (Gap analysis)
4. Adapt the objectives and the plans as new needs and opportunities

Adaptive Control!!!

The McNamara Structure of Adaptive Control



Adapt Performance Objectives (1 b)

Desired Performance Objectives

Critic

Control

Process

Measure

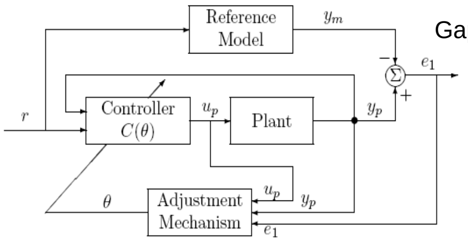
Evaluate

Adapt Control (1 a)

1. Measure, evaluate and critique (Gap analysis)
2. Control strategies (pole assignment, LQR, MPC, …..
3. Adaptation
    a) Adapt Controllers
    b) Adapt Performance Objectives (closed loop time constant, Q,R)

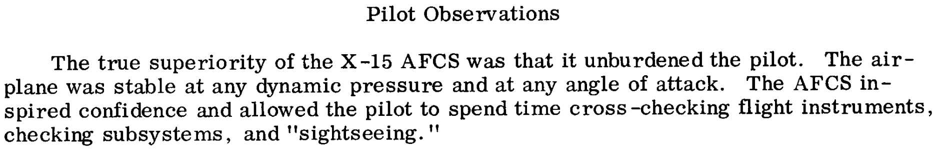
The MIT Rule for Adaptive Control: Adaptive Flight Control System – X15

Performance model (not adapted)



Gap

Feedforward control



Pilot Observations

The true superiority of the X-15 AFCS was that it unburdened the pilot. The airplane was stable at any dynamic pressure and at any angle of attack. The AFCS inspired confidence and allowed the pilot to spend time cross-checking flight instruments, checking subsystems, and "sightseeing."

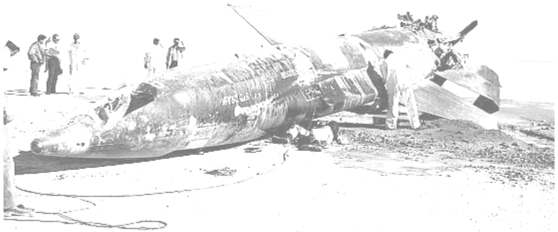
EXPERIENCE WITH THE X-15 ADAPTIVE FLIGHT CONTROL SYSTEM

By Staff of the Flight Research Center

Several disadvantages associated with the system were also disclosed: Additional design analysis was required because of the high-gain values; commands by the pilot and other spurious inputs caused gain reduction and degraded performance at undesirable times; filters were required to prevent sustained resonance of the structural modes; and supercritical gain operation existed in flight which, because of mechanical nonlinearities and electrical saturation, resulted in divergent airplane motions.

---

operation in the other axis. Saturation in one axis resulted in complete loss of control in the other axis. This problem occurred immediately following recovery from a high-altitude spin in the last flight of the X-15 airplane with the AFCS. The resulting loss of damping and effective control allowed the post spin aircraft motions in pitch, roll, and yaw to persist until the associated acceleration forces exceeded the aircraft's structural limits.



$$u_c = \mu\underbrace{\int_0^t y_m y_r e}_{\text{integral control}}$$

operation in the other axis. Saturation in one axis resulted in complete loss of control in the other axis. This problem occurred immediately following recovery from a high-altitude spin in the last flight of the X-15 airplane with the AFCS. The resulting loss of damping and effective control allowed the post spin aircraft motions in pitch, roll, and yaw to persist until the associated acceleration forces exceeded the aircraft's structural limits.

You Forgot Integral Wind-up!

Criticism # 1

Must include modifications used in normal PID control

- Anti reset wind-up
- Filters
- Bump-less transfer
- Variable scaling
- Nonlinear compensation (nonlinear adaptive control)

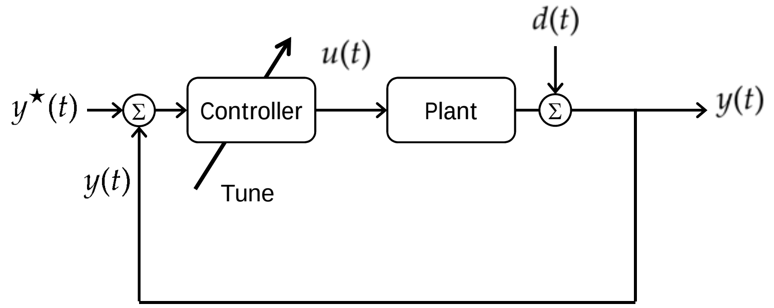
KJ Astrom IFAC World Congress 1984

Brief History of Adaptive Control

Analog Circuits and Direct Adaptive Control		**(1960-1970)**
MIT Rule (X-15)	Direct gain adaptation	(hope for the best)
Stability theory	Based on positive real	(unrealistic)
Direct Adaptive Control -	**Ideal Case**	**(1970-1980)**
Self tuning regulator	Optimal if parameters converge	
d-step ahead control	Stable if plant stably invertible	
Some applications	ship steering, ore crushing	
Indirect Adaptive Control - Robustness		**(1980-1990)**
Pole assignment	Admissibility	(important !!!)
Predictive control	EHC, STC, GPC, MPC	
Recursive estimators	VFF, deadzone, normalization,….	
Robustness	Bounded chaos, transients	(important !!!)
Many applications	process control, cars, metallurgy	
Slow adaptation	Iterative control, averaging,…	(red herring)
Commercialization of Adaptive Control		**(1990-2010)**
Fast adaptation	Cybocon, direct adaptive control	(model free)
MPC with stable filter	Brainwave, iLS	(admissibility solved)
MPC with ARMAX	TaiJi	(identification/control)
PID	iLS	(non-convex optimization

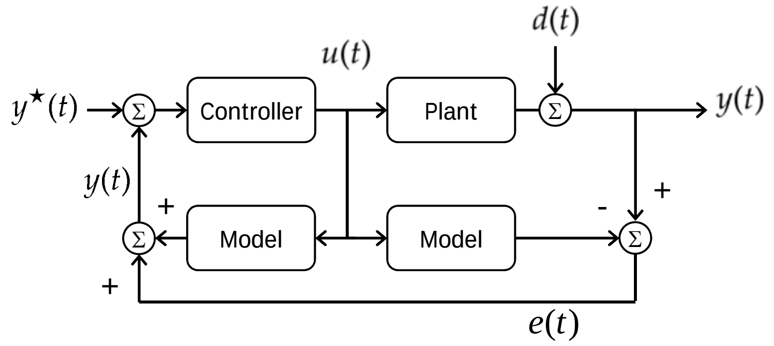
Architecture for Certainty Equivalence Adaptive Control

Classical Feedback Control (PID, MPC)



Closed Loop: $$e = -\frac{1}{1+G_pG_c}y^*$$

Architecture for Certainty Equivalence Adaptive Control



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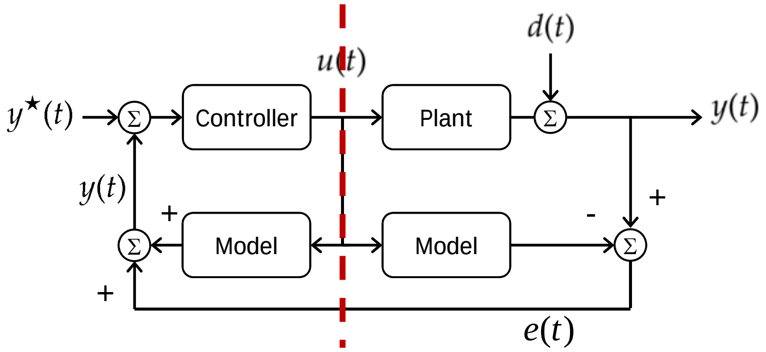
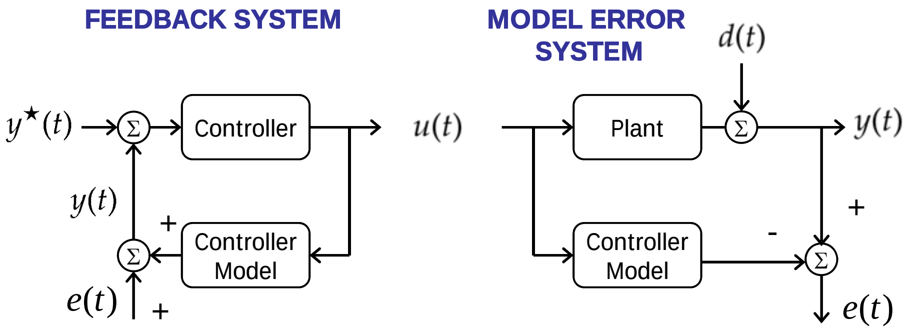
Architecture for Certainty Equivalence Adaptive Control



$$\text{Closed Loop:} \quad e = -\frac{1}{1+G_pG_c} y^*$$

Architecture for Certainty Equivalence Adaptive Control


FEEDBACK SYSTEM

MODEL ERROR SYSTEM

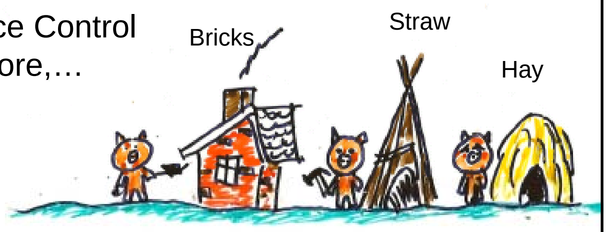
Certainty Equivalence: design controller as if model gives a true representation of the plant.

Feed Forward System – Many possibilities

1. Gradient/Projection Algorithms
2. Recursive least squares with modifications
    a) Covariance Reset
    b) Forgetting Factors
    c) Deadzone
    d) Leakage
3. Moving Horizon Estimation
4. Non-convex optimization
5. Sub-space identification
6. + Many, many more,… (check identification toolbox)

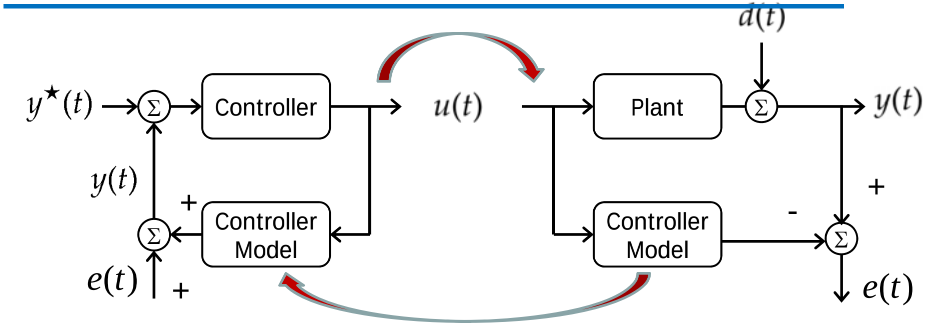
Feedback System: Even more

1. Pole Assignement
2. Linear Quadratic Control with Kalman filter
3. PID with Feedforward
4. Model Predictive Control
5. Model Reference Control
6. Minimum Variance Control
7. + Many, many more,…



Very, very large number of papers
Which is which? Brick, Straw, Hay

Criticism # 2: CE Glosses over Real Issue



Closed Loop: $u = -\dfrac{G_c}{1+G_m G_c} e$

Error: $e = (G_0 - G_m)_\theta u + \Delta u + d$

Controller must not excite un-modelled dynamics!

Estimated Model must be Robustly Stabilizable!

Criticism # 3: Irrational Exuberance

Very Few (if any?) Practical Implementations use parameterizations and estimators which provide stabilizable models. *(We simply estimate and hope for the best.)*

process

$$e(t) = A(q^{-1})y(t) - B(q^{-1})u(t)$$

controller

$$R(q^{-1})u(t) = T(q^{-1})y^\star(t) - S(q^{-1})y(t)$$

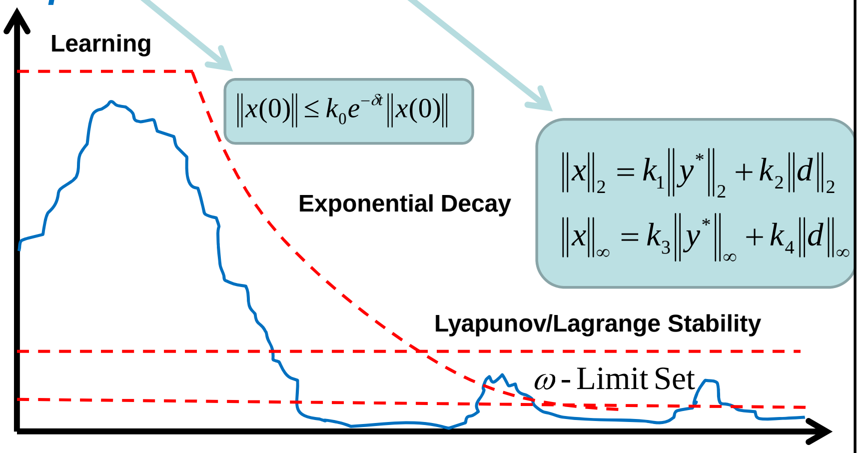
closed loop characteristic eqn. $P(q^{-1}) = A(q^{-1})R(q^{-1}) + B(q^{-1})S(q^{-1})$

$$\begin{pmatrix} 1 & 0 & \cdots & \cdots & \cdots & 0 \\ a_1 & \ddots & & b_1 & & \vdots \\ \vdots & \ddots & 1 & \vdots & \ddots & 0 \\ a_n & & a_1 & b_n & & b_1 \\ & \ddots & \vdots & & \ddots & b_1 \\ 0 & & a_n & 0 & & b_n \end{pmatrix} \begin{pmatrix} 1 \\ r_1 \\ \vdots \\ r_{n-1} \\ s_0 \\ \vdots \\ s_{n-1} \end{pmatrix} = \begin{pmatrix} 1 \\ p_1 \\ \vdots \\ p_{n-1} \\ p_n \\ \vdots \\ p_{2n-1} \end{pmatrix}$$

Diophantus *(AD284 and 298)*
Aryabhatta's *(AD 476 – 550)*
Bezout's *identity (AD 1730-1783)*

$A(q^{-1})$ and $B(q^{-1})$ must belong to the admissible set

Transient and Steady State Response when Adaptive Controller is Robust



$$\|x(0)\| \le k_0 e^{-\delta t}\|x(0)\|$$

$$\|x\|_2 = k_1\|y^*\|_2 + k_2\|d\|_2$$

$$\|x\|_\infty = k_3\|y^*\|_\infty + k_4\|d\|_\infty$$

Small Amplitude Chaos (turned off with a deadzone)

The John Lennon Principle:

With every mistake we must surely be learning

John Lennon : While my Guitar Gently Weeps

Stop estimation here (deadzone)

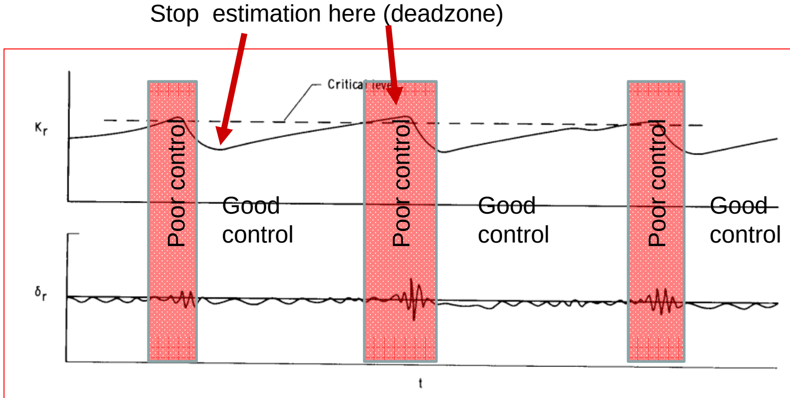
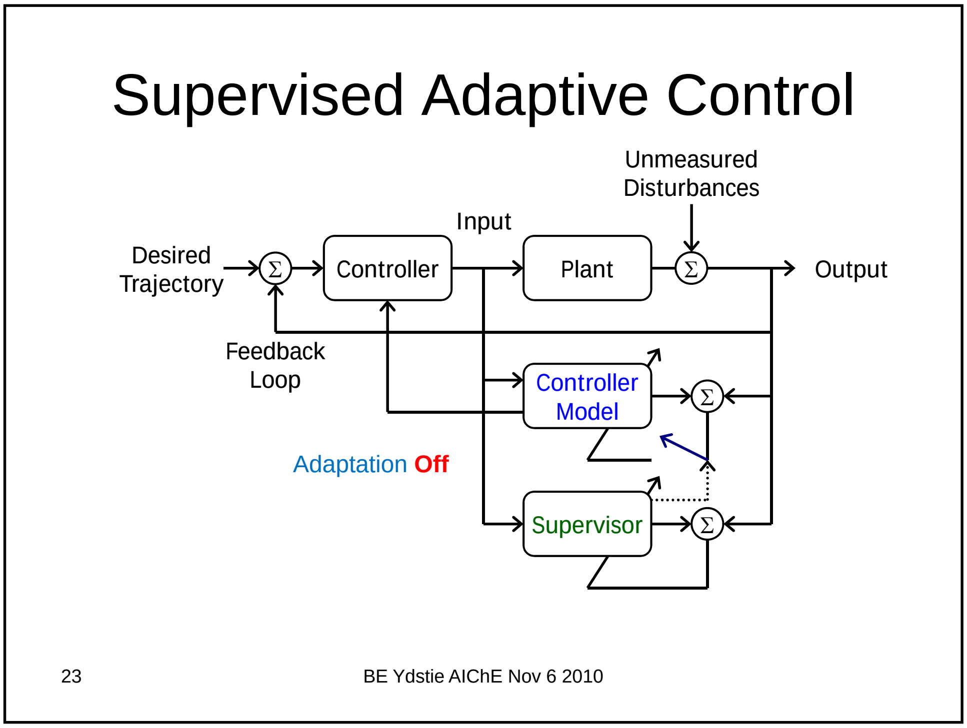


Figure 7. AFCS gain operation and surface activity.

Issue: How to turn estimation on and off so we don't forget?



Supervised Adaptive Control

Unmeasured Disturbances

Input

Desired Trajectory

Σ

Controller

Plant

Σ

Output

Feedback Loop

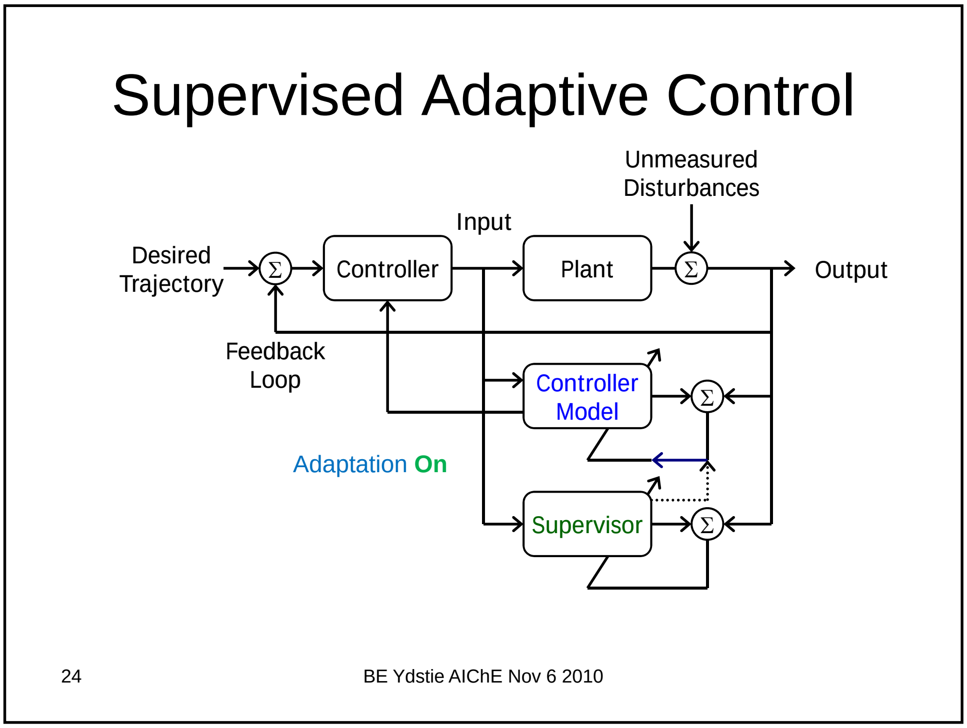
Controller Model

Σ

Adaptation **Off**

Supervisor

Σ



Supervised Adaptive Control

Unmeasured Disturbances

Input

Desired Trajectory

Σ

Controller

Plant

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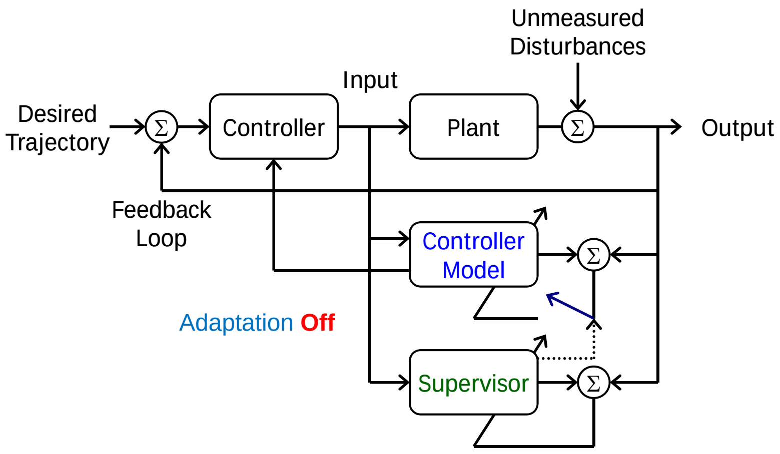
Σ

Adaptation **On**

Supervisor

Σ

Supervised Adaptive Control



Unmeasured Disturbances

Input

Desired Trajectory

Controller

Plant

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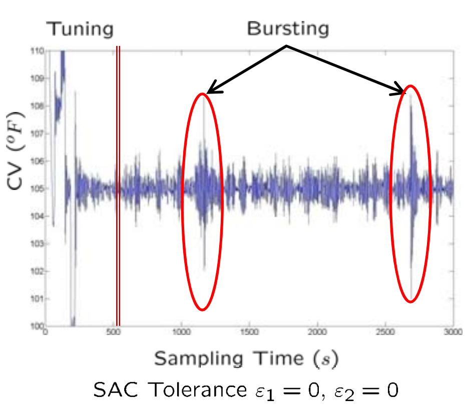
Feedback Loop

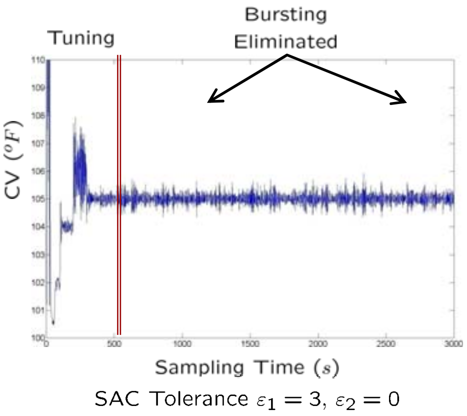
Controller Model

Adaptation **Off**

Supervisor



Steady State Chaotic Performance



With Deadzone

Criticism # 4: Impractical Theory

Methods exist which provide a solution to the admissibility problem (e.g. H- infinity control). They are complex and have not been incorporated into adaptive control theory in a systematic manner. Theoreticians simply point out the problem and leave it at that.

Criticism # 5: Fallacy of Slow Adaptation

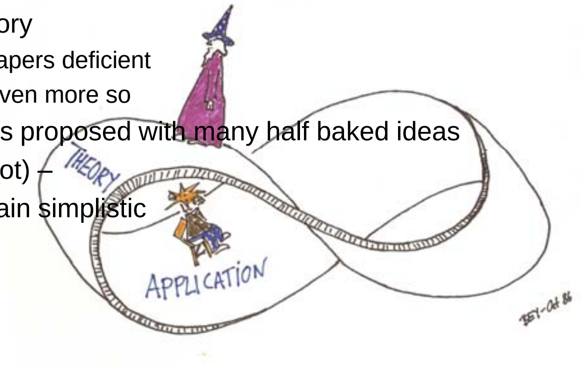
Many papers and books promote the idea that CE adaptive control can be rescued by adapting slowly (iterative learning, averaging). This approach invariably leades to PE. It will work at steady state but it must be combined with deadzones and it does not address transient stability. How to excite is an unresolved question.

It was not a Crash

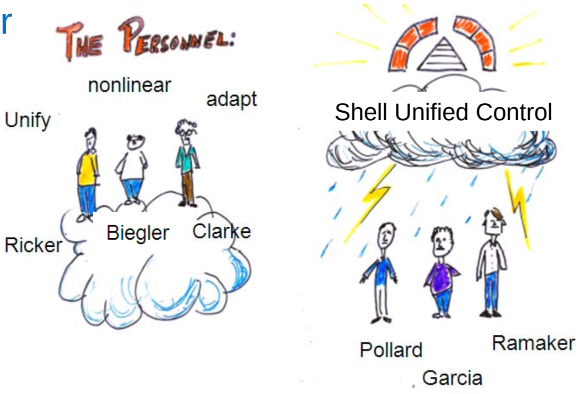
Very good (almost complete) theory for robust adaptive control developed in the 1980ies. Transient and steady state performance well understood by mid 1990ies.

But, during the past 2 decades we forgot Robert's and John's advice and ended up as Nick Cage.

- Theoreticians ignored needs of practitioners
- Practitioners ignored theory
  - Academic application papers deficient
  - Industrial applications even more so
- A mishmash of algorithms proposed with many half baked ideas
- Computers got faster (a lot) –
  while algorithms remain simplistic
- ***Field ran out of steam***



The State of Model Predictive Control at 1986 CPC @ Asilomar

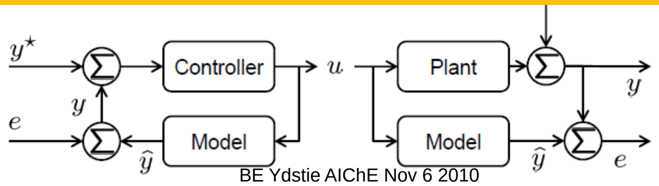


Adaptive Control still has a way to go to achieve the same success MPC did during the past 3 decades

Conclusion: Did Anything Happen?

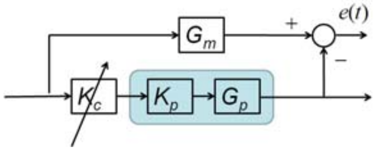
Robust Adaptive Process Control

- Parameterization and identification combined to solve robust admissibility problem
- Design controller robustly stabilize <u>model (H-infinity type design)</u>
- Turn off estimation when signals are not excited
- Adapt fast during transients
- Excite system when needed at steady state
- Filter signals to remove bias
- Take advantage of computational power
  (Non-convex optimization is feasible)



Happy Birthday Tom !

The MIT Rule for Adaptive Control:



$G_p(s) = K_p G_p(s),$ unknown gain

set $G_m \approx G_p$ and adapt K_c to get $K_c\ K_p = 1$

$$\dot{K}_c = \mu y_m e$$

stable if $\left(\dfrac{G_p}{G_m}\right)$ is positive real