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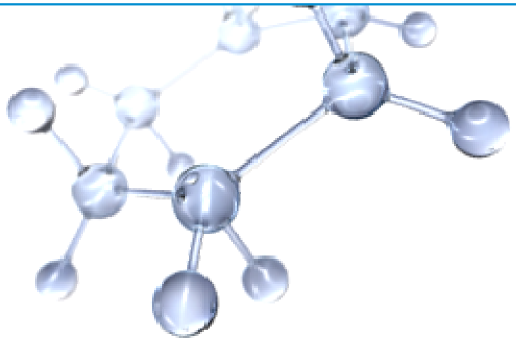
Estimation of $\tilde{x}_{MPC}$

(The state of Model Predictive Control)



Thomas A. Badgwell, Ph.D., P.E.

Session 10B01: In Honor of Tom Edgar’s 65 Birthday II

2010 AIChE Annual Meeting
Salt Lake City, UT
November 7-12, 2010

Outline

- Origins
- Progress in Research
- Progress in Applications
- Current State: What is Model Predictive Control?
- Remaining Opportunities
- EMPC (Edgar MPC)
- Conclusions

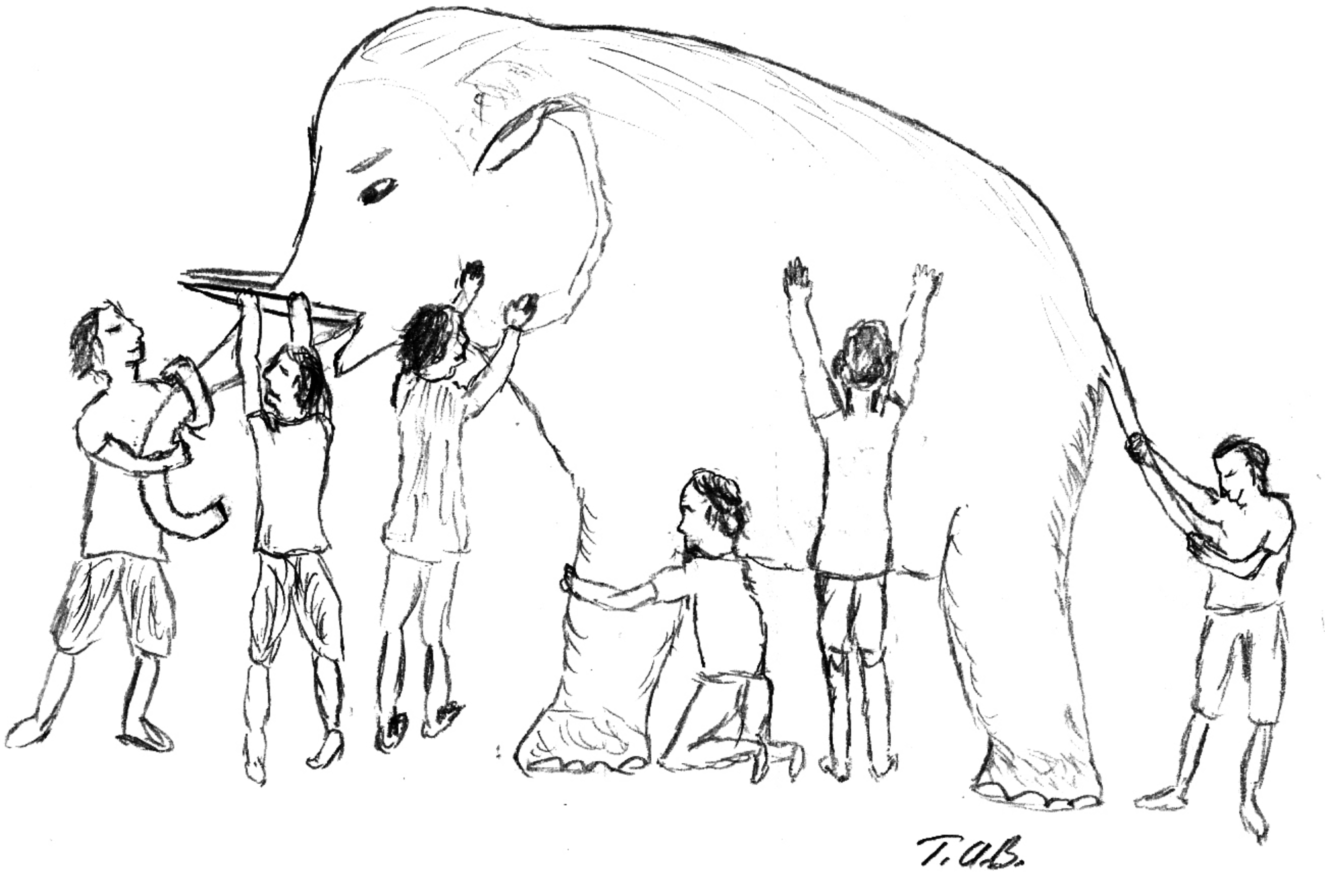
Origins

- *Lee and Markus (1967):* One technique … is to measure the current control process state and then compute very rapidly for the open-loop control function. The first portion of this function is then used during a short time interval, after which a new measurement of the process state is made and a new control function is computed for this new measurement. The procedure is then repeated.
- Not much progress implementing this idea in the process industries until the infrastructure became available in the 1970's
- IDCOM – Identification and Command *(Richalet, et al.,1978)*
- DMC – Dynamic Matrix Control *(Cutler and Ramaker, 1979)*

Origins, cont.

- IDCOM and DMC represent a **1st generation** of MPC technology:
  - Linear convolution models (step or impulse)
  - Simple step testing to generate data for model identification
  - Heuristic numerical solution to handle input and output constraints
  - Bias feedback to correct model predictions
- QDMC - Quadratic Dynamic Matrix Control *(Garcia and Morshedi 1986)* represents a **2nd generation** of MPC algorithms that provide a systematic way to implement input and output constraints through the use of a constrained optimization.

Progress in Research



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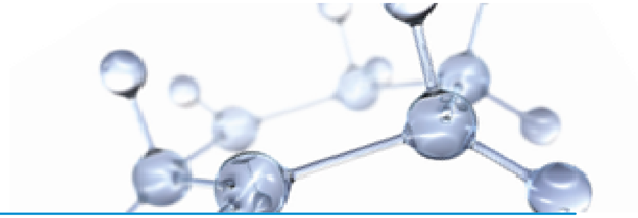
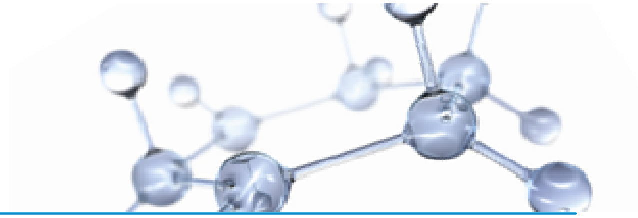
Progress in Research, cont.



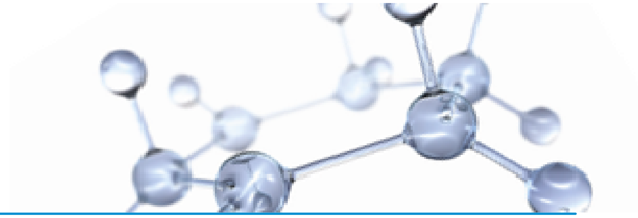
- Limitations of 1st and 2nd generation methods identified:
  - Restrictive model forms – difficulty with integrating, unstable plants
  - Primitive model identification methods – long tests, poor models
  - Sub-optimal bias feedback – poor model predictions
  - Lack of nominal stability – can go unstable with perfect model
  - Inefficient numerical solution methods – limits scope of applications
- New formulations developed using general linear, nonlinear models, hybrid integer/continuous models
- New class of model ID algorithms developed – Subspace ID
- State estimation techniques developed for improved feedback
- Nominal stability addressed with infinite prediction horizon
- More efficient numerical solution methods developed

Progress in Applications



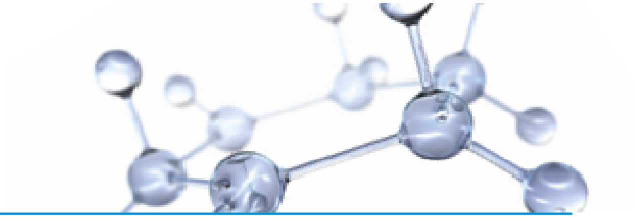
- Many model types and control formulations tried
- Methods established for training implementers, estimating benefits, executing projects, and sustaining benefits
- Size and scope of MPC applications increased with time; representative medium size is now around 30x50
- Link established to Real-Time Optimization technology, enabling significant increase in benefits
- Applications spread among a wide range of process types, from refining and petrochemical processes to polymers, specialty chemicals, pulp and paper, air separation, food processing, etc.

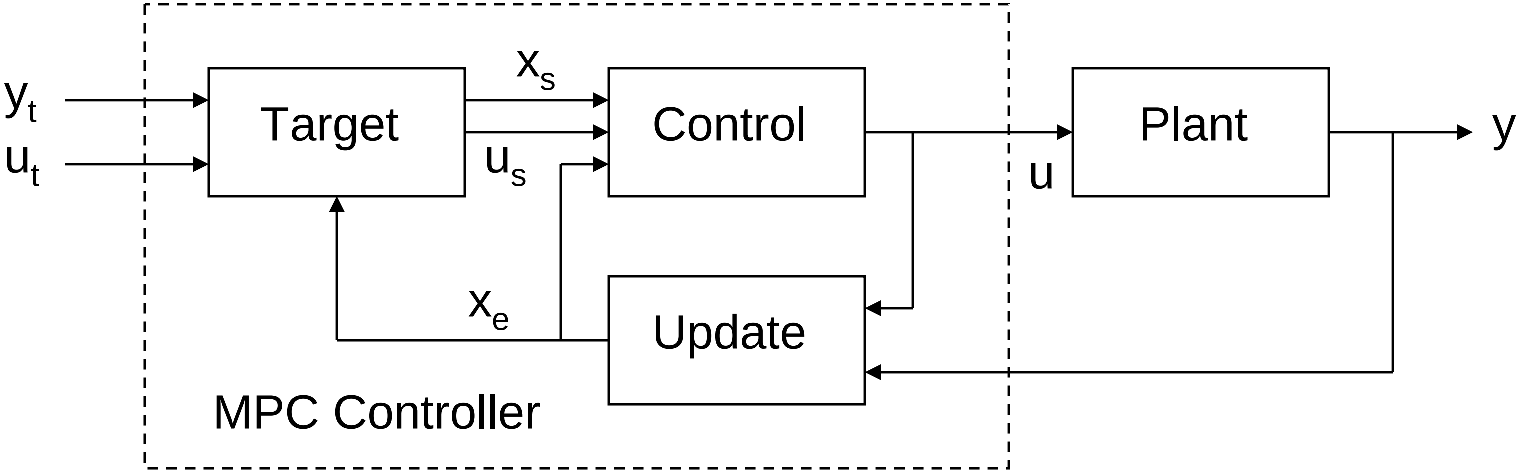
Progress in Applications, cont.



- 3^{rd} and 4^{th} Generation technologies developed (DMCplus®, SMOC, SSC) with input from academic researchers
- Total number of applications in the process industries now $5\text{-}10 \times 10^3$ with estimated benefits of $1\text{-}2 \times 10^9$\$/yr
- Equally important is the intellectual impact; practitioners today equate advanced control with MPC

Current State: What is MPC?

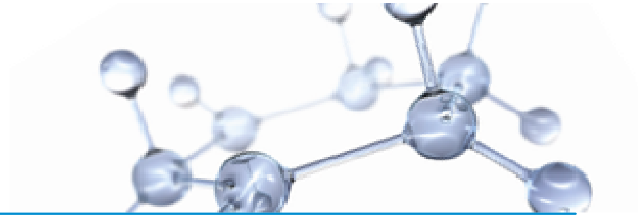




At each control interval, the MPC algorithm answers three questions:

1. Update: *Where is the process going?*
2. Target: *Where should the process go?*
3. Control: *How do you get it there?*

Current State: What is MPC?



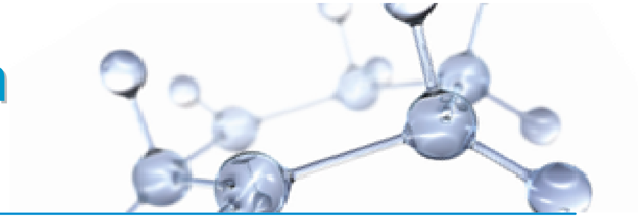
- *Undergraduate Student (Wikipedia):* MPC is an advanced method of process control that has been in use in the process industries such as chemical plants and oil refineries since the 1980s. Model predictive controllers rely on dynamic models of the process, most often linear empirical models obtained by system identification.

- *Professor:* Model predictive control (MPC) is a form of control in which the current control action is obtained by solving *on-line, at each* sampling instant, a finite horizon open-loop optimal control problem, using the current state of the plant as the initial state; the optimization yields an optimal control sequence and the first control in this sequence is applied to the plant.

- *Refinery Control Engineer (B.S., M.S.)*: I don't care what you call it, but I'm going to use DMCplus®.

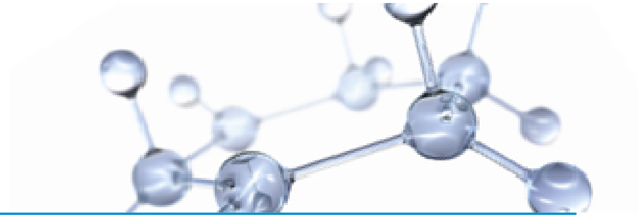
- *Refinery Operator:* Say what you want about Monterrey Peninsula College (The Lobos), but please don't turn off the DMC!

Remaining Opportunities for Research and Development



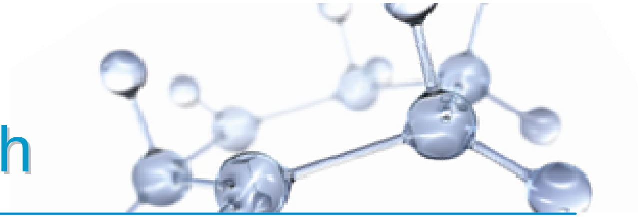
- Better modeling tools (integrate blend first-principles knowledge with test data, nonlinear model reduction, etc.)
- State Estimation and Disturbance Modeling
- Incorporation of Model Uncertainty
- More Efficient Numerical Solution using Offline Computations
- Linking individual unit MPC applications together to improve overall plant control

Edgar MPC (EMPC)



- Tom Edgar's success can be attributed to:
  - Practical Objective – focused on real-world issues
  - Multivariable model – ongoing research on many fronts
  - Good state estimation – sees trends and exploits them successfully
  - Long prediction horizon – visionary
  - Lots of MVs – many students
  - Tight CV tuning – very focused on goals
  - Loose MV tuning – lets students find their way

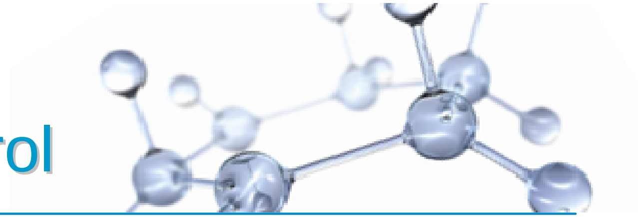
Tom Edgar's Impact on MPC Research



Highlights of Tom Edgar's specific contributions to MPC research:

- Experimental MPC applications on laboratory-scale systems:
  - packed distillation column
  - fixed bed water gas shift reactor
  - single-wafer rapid thermal reactor
  - batch distillation column
- Nonlinear MPC for distributed parameter systems
- Approximate nonlinear MPC with in-situ adaptive tabulation
- Nonlinear model reduction

Tom Edgar's Impact on Process Control



Tom Edgar has been a visionary leader in process control research and education:

- published 250 journal articles
- helped educate and mentor a generation of thought leaders: 64 PhD students, 43 MS students
- helped educate thousands of undergraduates through his classes and textbooks
- strengthened interactions between industry and academia through TWCCC, CAChE, Short Courses, and CPC meetings
- provided leadership for the entire profession through AIChE
- his impact will continue to be felt for years to come

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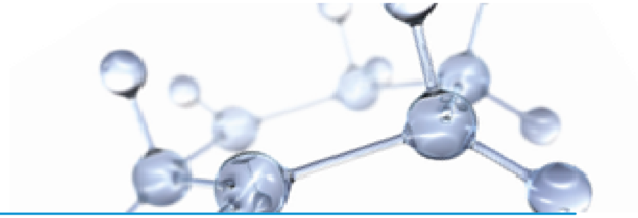
Conclusions



- In the past forty years, Model Predictive Control technology has progressed from textbook theory to its current dominant position in industrial practice
- DMCplus®, lies in the sweet-spot
- At present there are some 5-10x10^3 MPC applications in the process industries with estimated benefits of 1-2x10^9 \$/yr
- Significant opportunities remain for MPC research and development
- The development and application of MPC technology is a major success story for the AIChE CAST10 community.
- Through his leadership, research publications, and educational initiatives, Tom Edgar has played a key role in this story

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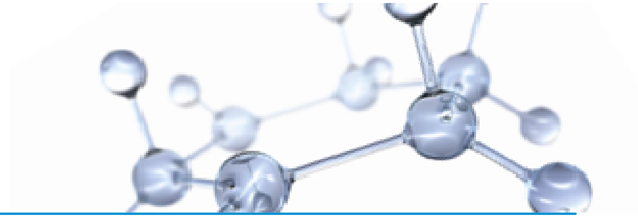

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