MIT Symposium
2040 Visions of Process Systems Engineering

George’s Impact

Manfred Morari
Electrical & Systems Engineering
University of Pennsylvania

June 1, 2017
George’s Formative Years

1965

1974

1977
MIT Symposium
2040 Visions of Process Systems Engineering

George’s Impact

Manfred Morari
Electrical & Systems Engineering
University of Pennsylvania

June 1, 2017
Outline

• My Time with George at U of MN
• Past Attempts to Predict the Future
• Predicting the Future
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• My Time with George at U of MN
• Past Attempts to Predict the Future
• Predicting the Future
My advisors at the U of Minnesota 1975-77

George Stephanopoulos

Rutherford "Gus" Aris 1929-2005
Manfred,
Do you have this photo?
Wow, I had forgotten how better certain things looked 25 years ago.
Best regards to all
George
Technology: Digital Control Computer

IBM 1800 (introduced 1964)
Computer Control ~1968
Standard Oil of California

Courtesy: Chevron
Advanced Process Control Textbooks with Origins at U of Minnesota

1969

1981
Critique of (Process) Control

1973
Critique of Chemical Process Control Theory

1976
Advanced Control Practice in the Chemical Process Industry: A View from Industry

1976
Design Concepts for Process Control

1975
Superiority of Transfer Function Over State-Variable Methods in Linear Time-Invariant Feedback System Design

ISAAC M. HOROWITZ, FELLOW, IEEE, AND URI SHAKED
Theory-Practice Gap

Main theme of CPC I in 1976

Explosive development of theory had taken place

- Industry did not understand theory
- Academia had no clue about real controller design

Exceptions: Åström, Gilles, Balchen,…
George’s Research Theme in the 1970s

“The research community is studying the wrong problems”
Importance of Timing and a Good Start

If you are to do important work then you must work on the right problem at the right time and in the right way. Without any one of the three, you may do good work but you will almost certainly miss real greatness.

An important aspect of any problem is that you have a good attack, a good starting place, some reasonable idea of how to begin.

*A Stroke of Genius: Striving for Greatness in All You Do*
R. W. Hamming October 1993
Socratic Method: Learning by Debate

Success is a journey, not a destination. The doing is often more important than the outcome.

Arthur Ashe
Major Themes of George’s Research Program in the 1970s

“The research community is studying the wrong problem”

• Architectures
  – Control Structure
  – Decomposition for optimization
• Design for Control
Decomposition

Studies in the Synthesis of Control Structures for Chemical Processes


March, 1980

Figure 1. Multilayer decomposition of the control tasks.

Figure 2. Multiechelon decomposition of the control tasks.
George Arguing about Decomposition
The Use of Hestenes’ Method of Multipliers to Resolve Dual Gaps in Engineering System Optimization

G. Stephanopoulos and A. W. Westerberg

- Lagrangian decomposition
- Method to resolve the dual gap destroying the separability of separable systems
Literature from the 1970s
Decomposition and Optimization

Current revival because

- Suitable hardware has become available
- Problems have become too large, e.g. machine learning
Control Structures

Part II: Structural Aspects and the Synthesis of Alternative Feasible Control Schemes

March, 1980

AICHE Journal (Vol. 26, No. 2)

Figure 1. The double effect evaporator.

Figure 2. The digraph for the double effect evaporator.
Survey Paper

A review of methods for input/output selection

Marc van de Wal\textsuperscript{a,1}, Bram de Jager\textsuperscript{b,*}

Control structure design for complete chemical plants

Sigurd Skogestad \textsuperscript{*}

\textit{Department of Chemical Engineering, Norwegian University of Science and Technology (NTNU), 7491 Trondheim, Norway}
Major Themes of
George’s Research Program in the 1970s

“The Research Community is studying the wrong problem”

• Architectures
  – Control Structure
  – Decomposition for optimization

• Design for Control
Process Lags in Automatic-Control Circuits

By J. G. Ziegler and N. B. Nichols, Rochester, N. Y.

Transactions of the A.S.M.E.

JULY, 1943

Methods are given for quantitative determination of time lags in automatically controlled processes. The area under recovery curves is taken as a direct measure of process difficulty, and this area is shown to vary as the second power of the time lag. A "recovery-factor" term, part of a complete expression for controllability, is introduced which makes possible a classification of processes in dimensions of the process itself, regardless of controller or valve mechanism used. Values of this recovery factor from various industrial applications are given in tabular form.
A PRACTICAL PROBLEM IN DYNAMIC HEAT TRANSFER

By J. S. ANDERSON, B.Sc.*

Fig. 1.—Heat exchange system as originally designed

Fig. 8.—New design of heat exchangers
Design for Control
Outline

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• Predicting the Future
Predicting the future in 1990
Digital Equipment Corp. (DEC) and DuPont

Voice Control
Finger Print ID
Video Phone
Operator Screen
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Voice Control
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Status Assessment and Trends

• Interest in control is at an all-time high
# Graduate Course Enrollments ETH

<table>
<thead>
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<th>Course</th>
<th>2008</th>
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<th>2010</th>
<th>2015/16</th>
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<td>44</td>
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<td>Dynamic Programming</td>
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Status Assessment and Trends

- Interest in control is at an all-time high
- Interest in computer science is at an all-time high
CS Majors at Caltech

CS majors & minors 217 (projected)
CS majors 170

CS is almost as big as the next 3 combined
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- Interest in control is at an all-time high
- Interest in computer science is at an all-time high
- Interest in traditional positions in “hot” areas is low
Raff D’Andrea
PhD students & Post-Docs since moving to ETH

Federico Augugliaro               startup
Mark Muller                       assistant professor (Berkeley)
Philipp Reist                     startup
Luca Gherardi                     startup
Gajamohan Mohanarajah             startup (founder)
Markus Waibel                     startup (founder)
Markus Hehn                       startup (founder)
Sergei Lupashin                   startup (founder)
Raymond Oung                      startup
Sebastian Trimpe                  group leader (Max Planck)
Angela Schoellig                  assistant professor (U. of Toronto)
Michael Sherback                  startup
Frederic Bourgault                startup
Guillaume Ducard                  assistant professor (U. of Nice)
Oliver Purwin                     startup
Status Assessment and Trends

• Interest in control is at an all-time high
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• Interest in predictive control is at an all-time high
• 65 / 900 papers on MPC
Example problem

- Hit back a thrown ball
- Implicit feedback law updated at 20ms
  - Try 10’000 trajectories
    - Sample different ways to hit the ball
  - Apply first 20ms of the best one
Evaluation

- Algorithm evaluated in the Flying Machine Arena

- System limits
  \[ c_{\text{min}} = 5 \text{m/s}^2 \]
  \[ c_{\text{max}} = 20 \text{m/s}^2 \]
  \[ \omega_{\text{max}} = 25 \text{rad/s} \]
Rapid trajectory generation for quadrocopters
Motivation
Prove feasibility of online optimization@MHz sampling rate

Setup
- Algorithms: first-order methods (FGM, ADMM)
- Implementation: hand-crafted fixed-point VHDL design on high-end FPGA (Xilinx Vertex 7)

Case study
Control of Piezo-electric plate actuator in high-speed AFM (provided by IBM Zurich)

Objective: Maintain constant loading force
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- Interest in predictive control is at an all-time high
- Trends in software and hardware
  - Optimization software
  - Data and Connectivity
  - Validation and Verification
Speedup of software for MIPs

Calculations

Improvement in MIP Software from 1988-2017

- Algorithms: 147650x
- Machines: 17120x


- NET: (Algorithm × Machine): 2,527,768,000x

What Does This “Mean”??

- A “typical” MILP that would have taken 124 years to solve in 1988 will solve in 1 second now.
- This is amazing, but your mileage may vary
Control and Optimization

Convex and Combinatorial Optimization for Dynamic Robots in the Real World

Russ Tedrake

russt@mit.edu
groups.csail.mit.edu/locomotion
MIT's approach to the DARPA Robotics Challenge

Rules allowed a human operator, but with a degraded network connection

Teleoperation

Our approach:

- Focus on autonomy.
  - Human operator provides high-level "clicks" to seed (nearly) autonomous algorithms
- Almost everything the robot does is formulated as an optimization
  - For me personally, a triumph for optimization-based synthesis
Abundance of Data and Connectivity
The New Opportunity

- 2020: 50 billion devices connected to the internet
- 2020: 800 million smart meters deployed

=> 1 million smart meters generate 1.3 TB data over 90 days.
Why Dinosaurs Will Keep Ruling the Auto Industry

Get ready for the complexity revolution. by John Paul MacDuffie and Takahiro Fujimoto

June 2010
BACK TO THE MANUFACTURER

With more computers controlling functions like braking, annual vehicle recalls related to electrical systems have quadrupled in the U.S. since the 1970s.

100M AVERAGE LUXURY AUTO
20M NAVIGATION S-CLASS MERCEDES
10M AVERAGE 20: FORD AUTO
6.5M BOEING 78 DREAMLINER
5.7M U.S. AIR FOR JUNIOR STRIKERS
1.7M U.S. AIR FOR F-22 RAPTOR

20 11 8 34
1970s 1980s 1990s 2000s

SOURCES BLOOMBERG; NHTSA
Model checking of safety properties for Simulink Models

Avionics distributed control system complexity:
  – 10K-250K simulink blocks
  – 40k-150K binary raw variables
  – Hundred to few thousand bin’s after simplification/abstraction

Automotive single controller complexity:
  – 5K-80K simulink blocks
  – Few thousand bin’s after simplification/abstraction

FormalSpecsVerifier tool environment (NuSMV)

Source: Alberto Ferrari
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  - Validation and Verification
Dear George:

Thank you!
Happy Birthday!
Happy Retirement!