Systems Engineering and Innovation in Control—an Industry Perspective and an Application to Automotive Powertrains

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Honeywell

In collaboration with Greg Stewart, Honeywell

College Park, Maryland, 28 Oct. 2013

Outline

- Honeywell and controls
- Advanced control applications in the industrial context
- Trends in automotive powertrain control
- Advanced control for powertrains—initial “successes”
- Advanced control for powertrains—Honeywell OnRAMP
- Summary and conclusions

Honeywell's Businesses

- $37.5 billion in revenues, about 55% of sales outside of U.S.
- More than 130,000 employees, operating in more than 100 countries

Automation and Control Solutions

Aerospace

Performance Materials and Technologies

Transportation Systems

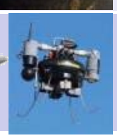
A Brief History of Honeywell Controls

- Albert Butz invents “damper flapper”, forms company, 1885
- Minneapolis-Honeywell Regulator Company formed, 1927
- Acquisition of Brown Instrument Co., entry into process control, 1934
- Minneapolis-Honeywell C-1 Automatic Pilot put into production, 1943
- T-86 “Round™” thermostat introduced, 1953
- Honeywell Research Center established: “Research must always be relevant to the field of automatic control,” 1958
- First computer-based control system for a process plant, 1961
- Delta 2500, computer control system for buildings, introduced in 1971
- Honeywell introduces TDC 2000, first distributed control system (DCS) in 1975
- First flight management system introduced (B757, Sperry acquisition), 1982
- Foundational developments in robust control, early 1980s
- Allied-Signal merger, 2000—automotive, engines, and specialty materials businesses
- New MPC developments, 2000s: nonlinear, explicit, embedded, distributed
- New applications for advanced control, 2000s: microgrids, automotive, supply-chain management, water distribution networks
- Controls-related acquisitions: Invensys Sensors, PAS, Akuacom, Matrikon, others

Honeywell
Helping You Control Your World

J.L. Rodengen, *The Legend of Honeywell*, Write Stuff Syndicate, 1995

Honeywell Presence in Advanced Controls

Industry	Example Applications	Realized Benefits
Oil Refining Petrochemicals Oil and Gas  	Refinery, Ethylene Plant, Aromatics, Xylene, Gas Processing, LNG/LPG	• 2-15% higher production • Refinery: ~$1/Barrel for advanced control • 5-20% less energy/unit product
Pulp & Paper 	Cross/Machine Directional Control	• Up to 50% higher performance • 50-80% lower calibration time
Building Control 	HVAC adaptive control	• 7-33% energy cost savings • Low setup costs
Commercial Aircraft 	B787, C919 EPIC, APEX	• Stabilization of unstable aircraft • Level 1 handling qualities
Aero Engines 	AS907-1 HTF 7500E HPW3000	• 99.7% fault coverage • Optimized engine start • Improved engine life with power assurance
Space 	Orion Multi-Purpose Crew Vehicle	• reduced propellant requirements by 20% • optimal steering of Control Moment Gyro
Military & Unmanned Aircraft  	Reusable Launch Vehicle, T-Hawk	• Stabilization, Vehicle Utility & Operability • 4X less development time • Missions completed after component failures

- **Problem dimensions up to 1000s of measurement points, 100s of actuators**
- **Dynamics from milliseconds to minutes**

30+ years of advanced control leadership and successful products

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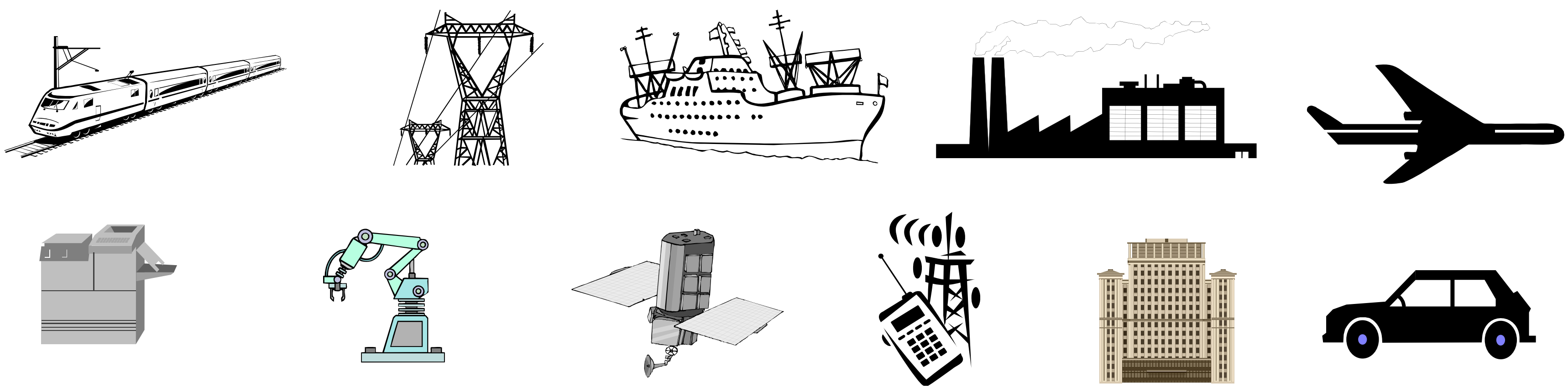
Advanced Control – Industry-specific Considerations

- Value chain: who does the control design, software development, integration?
- How many identical copies of a controller will be deployed (one to millions)?
- How easy or difficult is it to “adjust” a fielded control algorithm?
- What variety of conditions will be encountered in practice?
- Is the application safety critical?
- What is the expected lifetime of the application?
- What regulatory and certification requirements must be addressed?



Advanced Control – End-to-End, Systems Engineering Perspective

- In the business context, advanced control isn't just about the algorithm . . .

- Numerous other factors are relevant
  - technical
  - industry sector
  - work process and environment—including people involved
  - benefits—vis-à-vis application-specific requirements

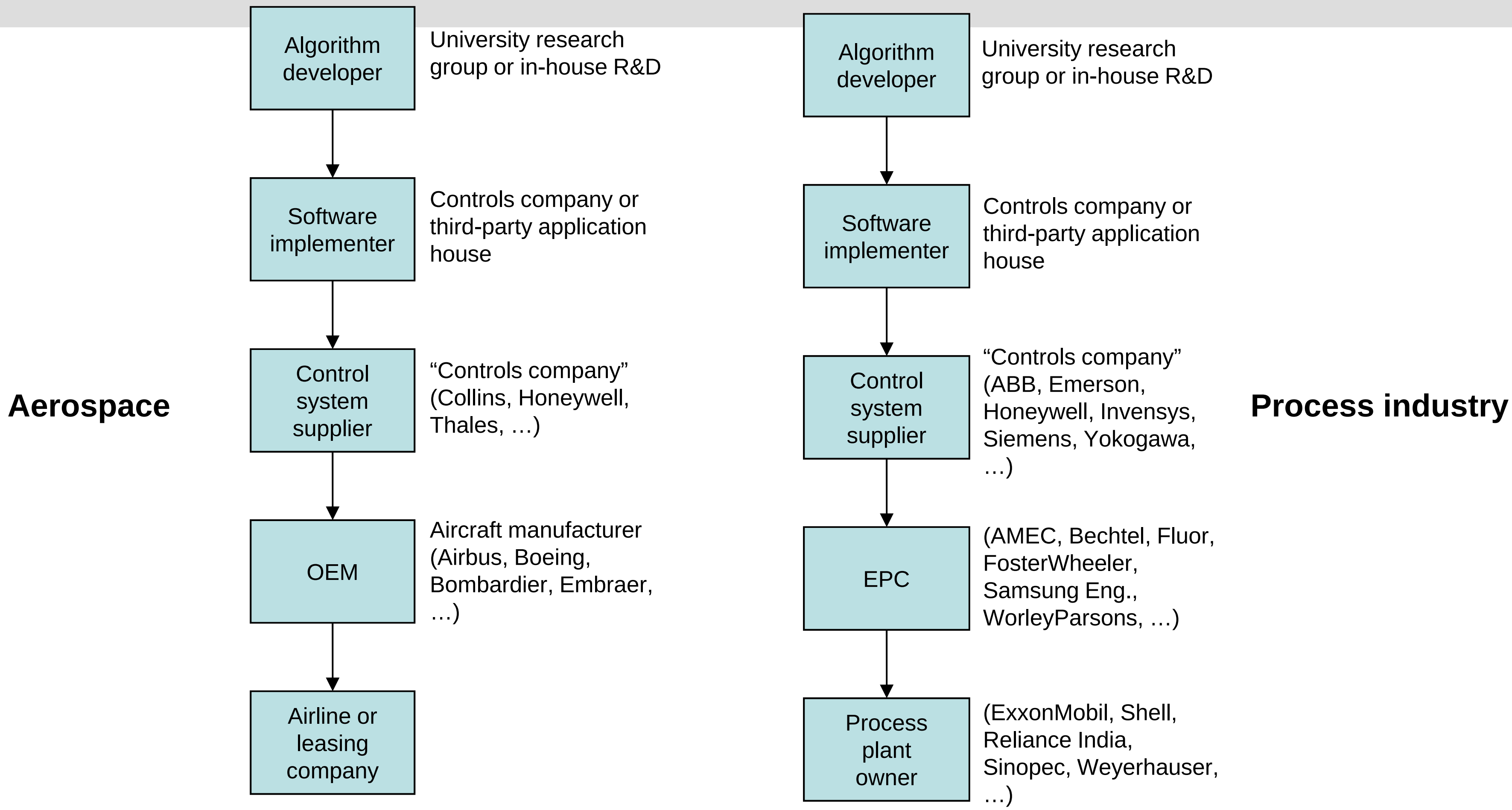
- Understanding the "big picture" is crucial when considering new control technology

T. Samad and G. Stewart, "Perspectives on innovation in control systems technology: Compatibility with industry practices," *IEEE Trans. on Control Sys. Tech.*, Mar. 2013.

Advanced Control – Technical Considerations

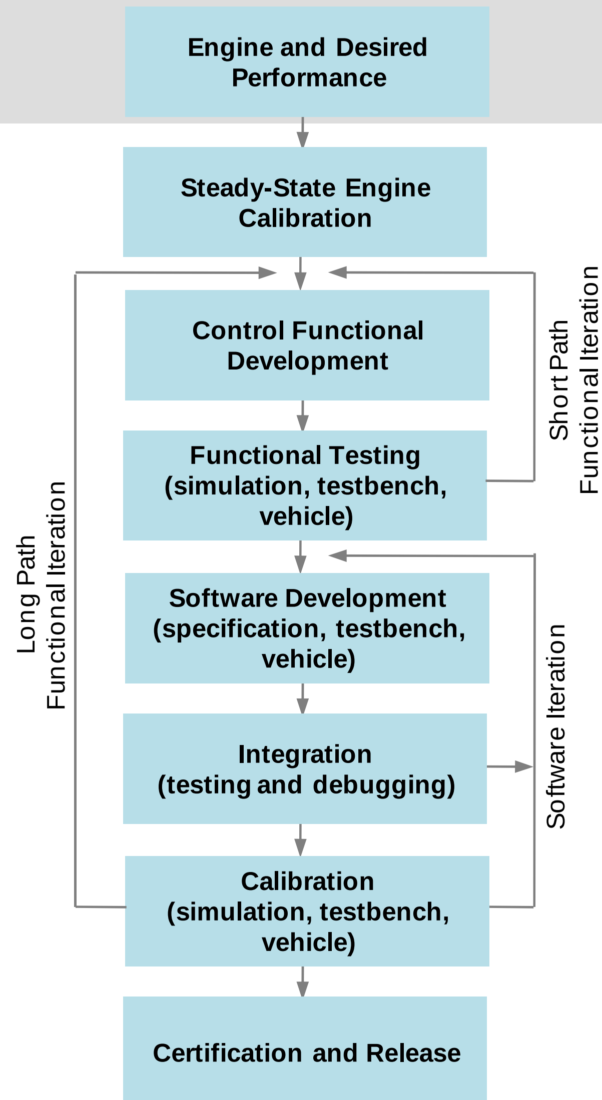
- **Plant**: nonlinear, multivariable, constraints, dynamics, uncertain, time-varying
- **Sensors and actuators**: presence, performance, reliability
- **Computing and communications platform**: memory (RAM, ROM), processor power (clock rate, floating/fixed point, DSP), networks (wireless, wired, protocols)
- **SW structure and processes**: legacy control code, software development methodology
- **Control tuning**: objective versus subjective
- **Tooling:** application software for designers, developers, operators, engineers

Simplified value chains for control algorithms

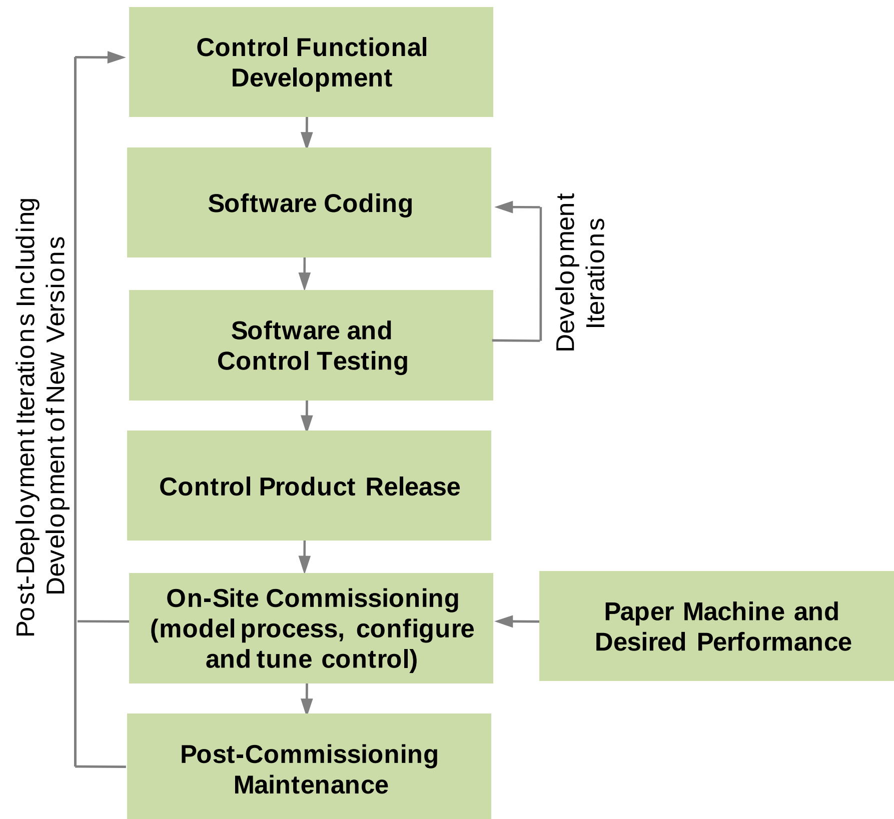


Complexities not considered include retrofit applications, the roles of other organizations such as suppliers of other systems, standards and regulatory bodies, and financiers. Value chains for other controls technology developments, such as control design tools, will be different.

Differentiating Control Applications—Examples



Engine Control Development Process



Papermaking Control Development Process

Stewart and Samad, in *Impact of Control Technology*, ieeecss.org/main/IoCT-report

The “So what?” of advanced control

- Benefits typically a combination of
  - accelerated development time—design, development, calibration, testing, . . .
  - enhanced insight or simplified development process
  - system performance in normal operating conditions
  - robust performance to product variations and in off-nominal conditions
  - reliability and fault tolerance
  - reduced cost of hardware
- And these must all be considered in context
  - *. . . relative to current solutions and alternatives*
  - *. . . given the current business and technical environment*

Notable Advantages of PID Controllers

- Modeling not required
- PhD’s not required
- Easy to install and commission
- Easy to adjust the controller during operation
- Familiar to control engineers and operators
- Design and implementation processes already established
- Computationally and algorithmically simple

Advanced control benefits must be sufficient to overcome these advantages . . . And there are many such successes!

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Large-scale vs Embedded Systems Engineering

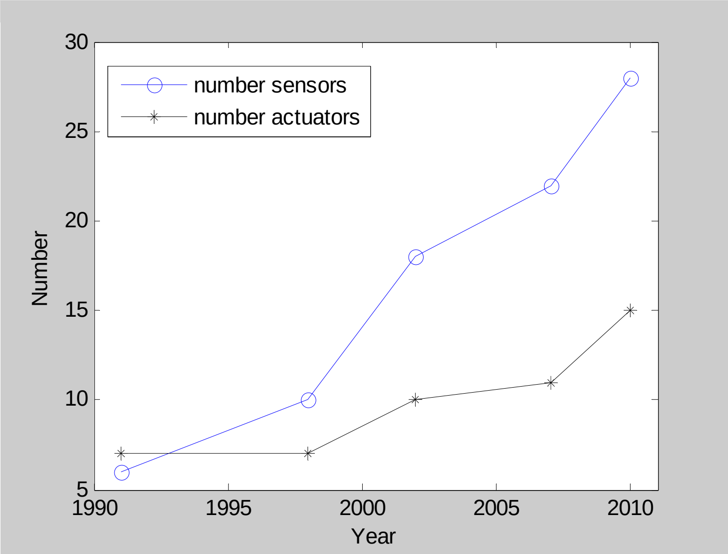
- Much academic research in SE focused on large-scale programs (e.g., aerospace and defense platforms)
- Many control applications in commercial and industrial applications and devices
- Iterative, agile product development

Challenges Facing the Transportation Industry

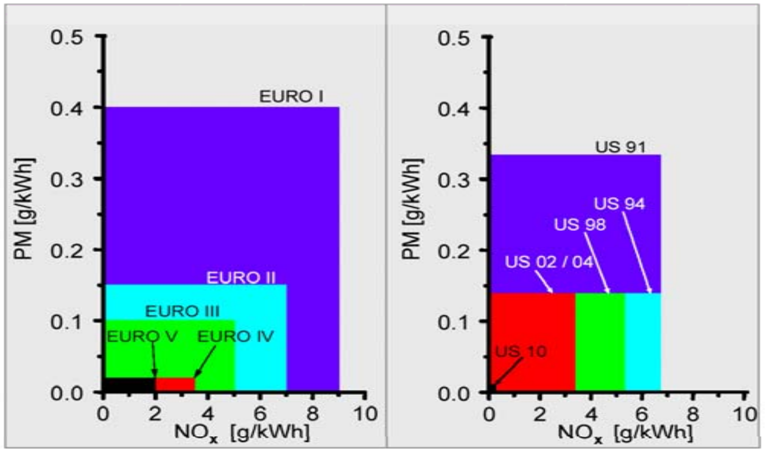
- Industry Spent >$1B on Control Design & Calibration in 2011
- Lines of Control Code are Increasing by Factor of 10 every 8 Years
- Development Cost for Software will Exceed Hardware before 2020
- Controls are being Developed using a Non-Systematic Approach

Global Trends Necessitating Advanced Controls

- Increasing complexity of engines
  - more components, more actuators and sensors – increasing development cost
  - control scope increase: emerging sophisticated combustion technologies and subsystem interaction
  - complexity brings new combinations of operating conditions and failure modes



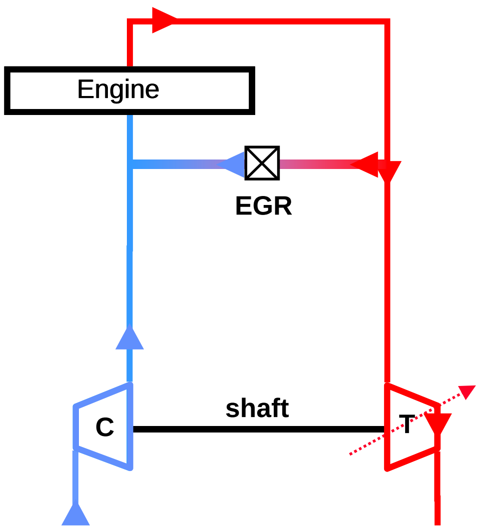
- Increasingly tighter requirements
  - emissions legislation
  - fuel efficiency
  - performance
  - reliability
  - cost

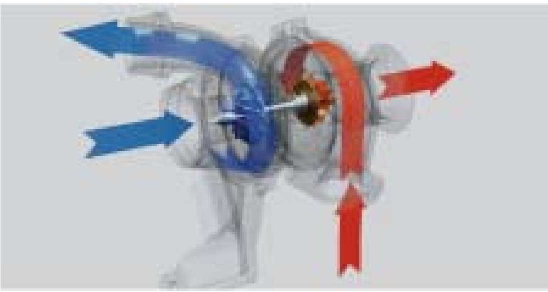


Europe **U.S.**

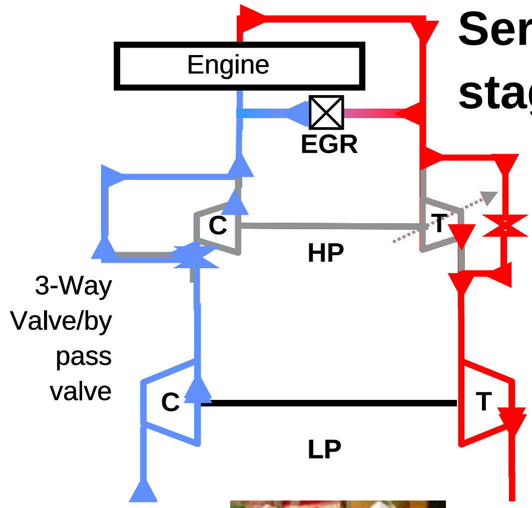
Turbocharged engines

Single stage

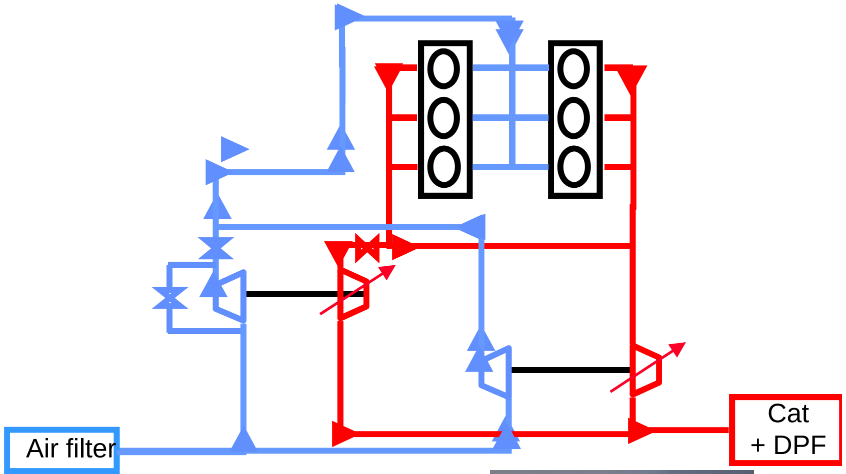




Serial dual-stage



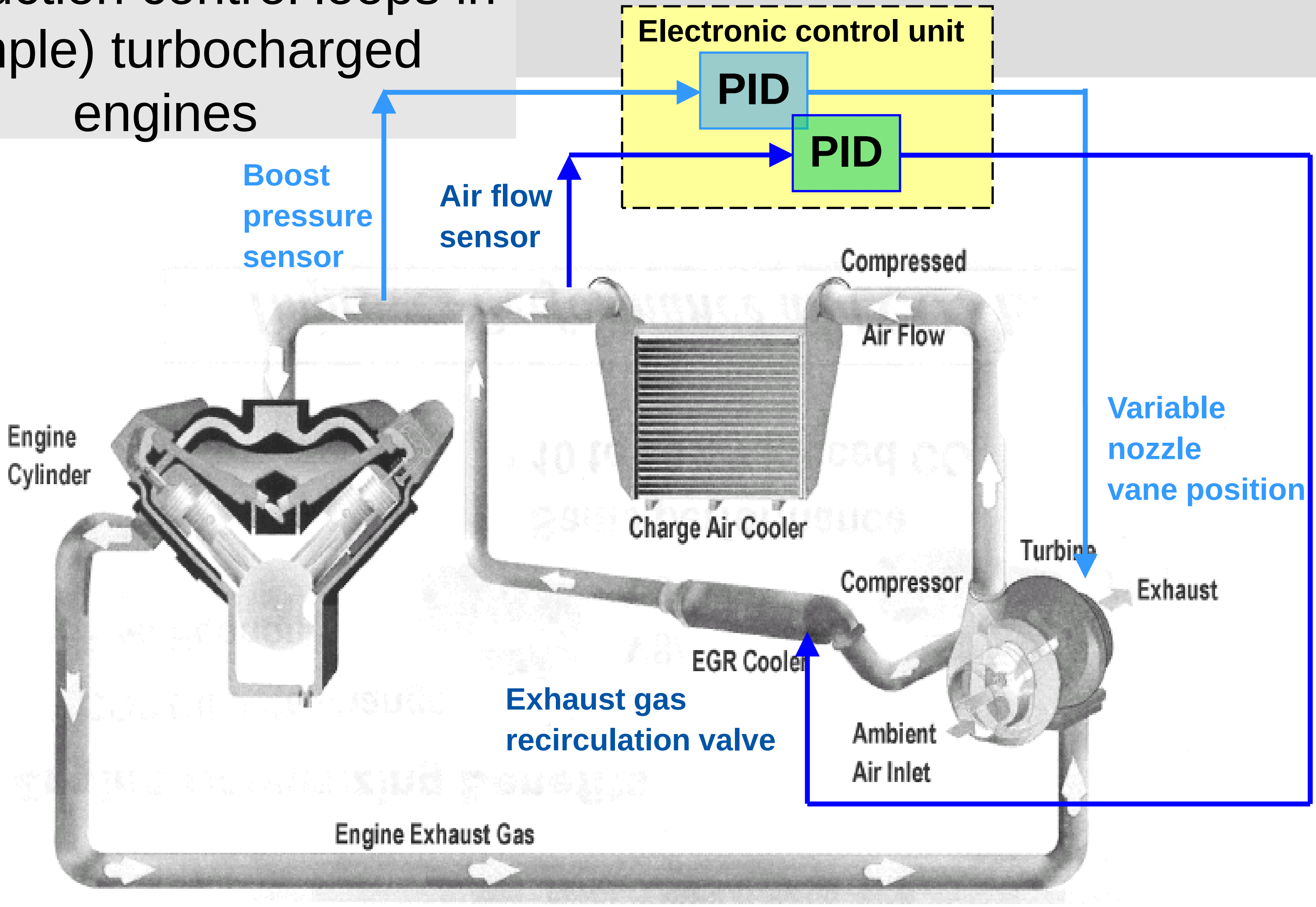
Parallel dual-stage*



* EGR not illustrated

- Many configurations; all MIMO, all nonlinear
- Even the simple engine structure is well known to pose control challenges.

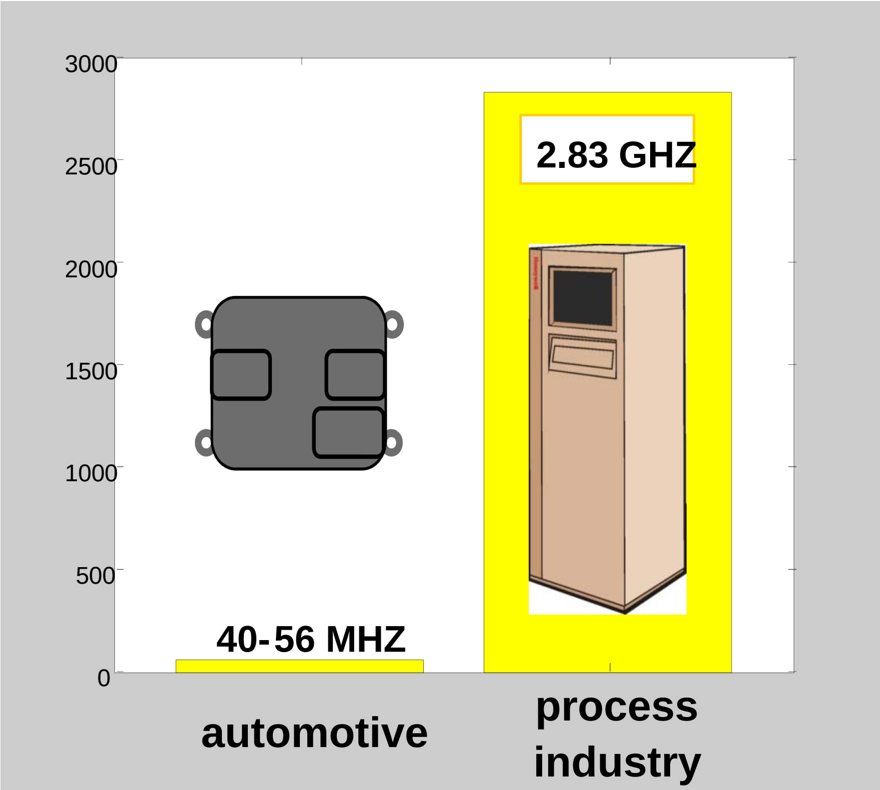
Air induction control loops in (simple) turbocharged engines



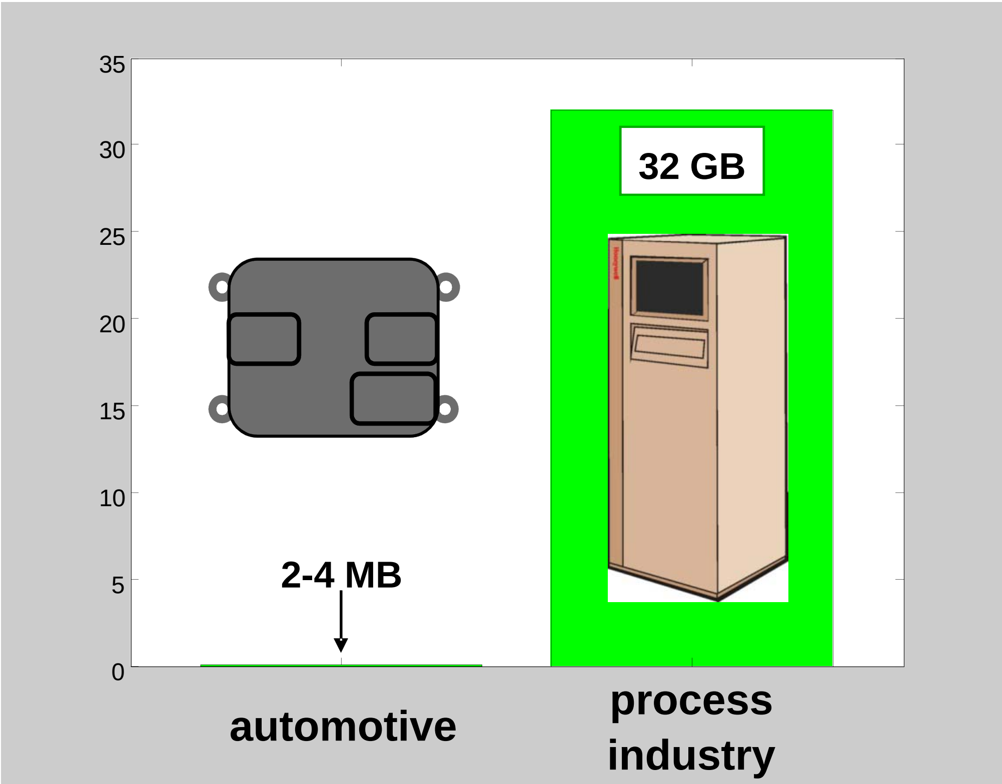
Highly nonlinear engine often controlled by combination of lookup tables and PID controllers

Automotive versus process control

Processor Speed



Memory



Control algorithm must have small CPU and memory footprint . . . a challenge for model-based control?

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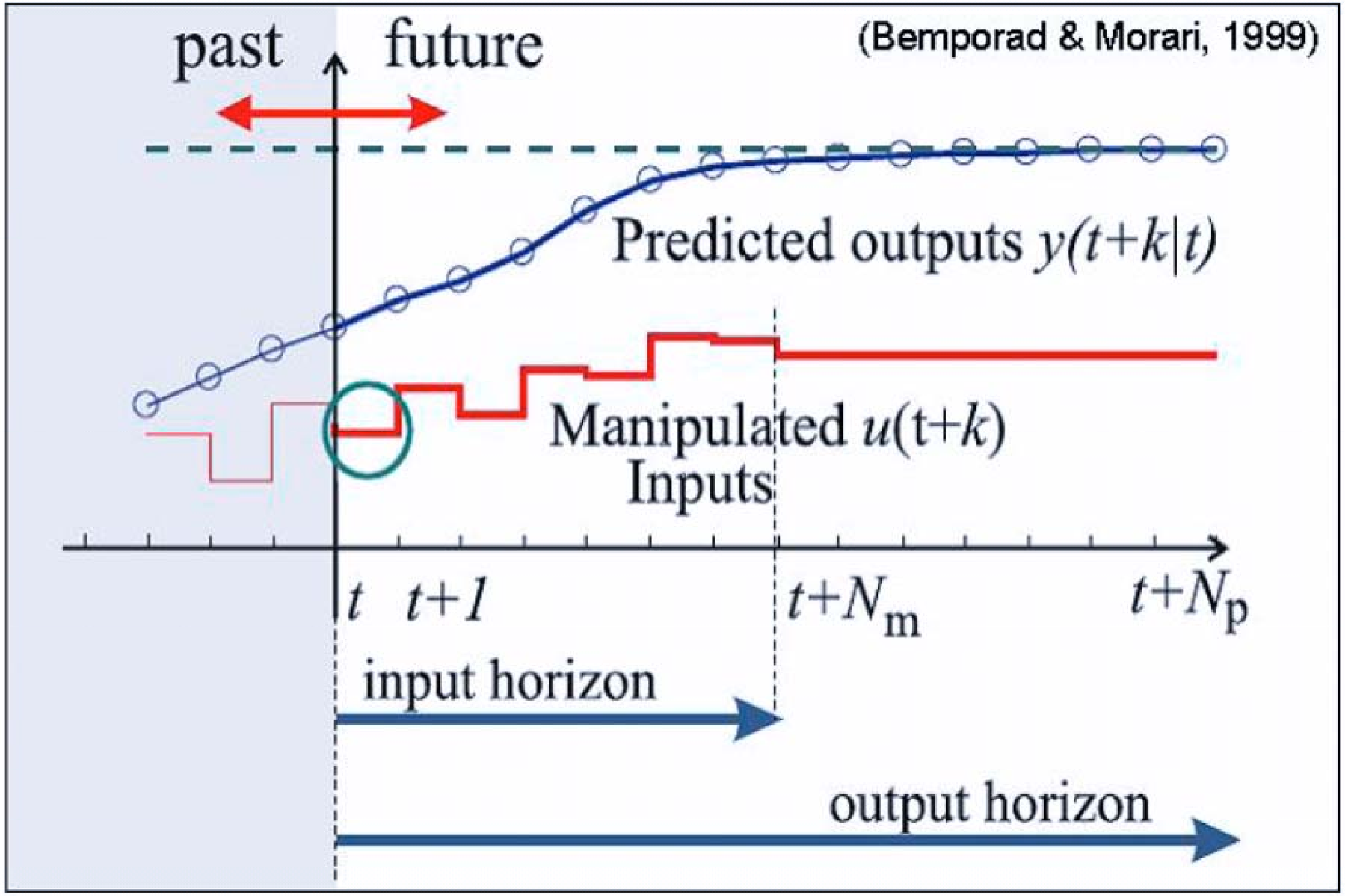
Linear Model Predictive Control



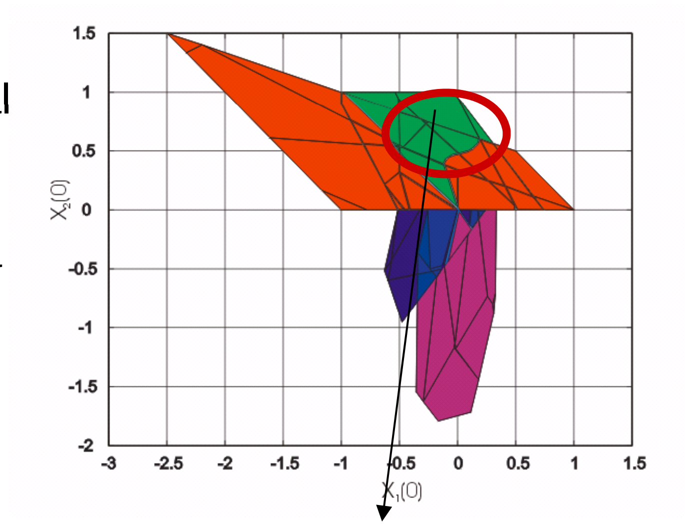
Fast MPC (Borrelli, 2003)

Multiparametric technology: Recent developments in advanced control allow dramatic reduction in computational complexity; control is much easier to verify and implement

Solution of a constrained optimization problem for finding a series of control moves:

$$\min_U J\big(U, x(0)\big)$$

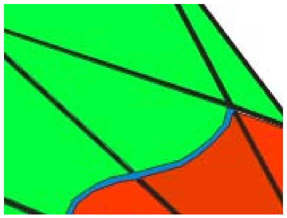
$$\text{subject to } g(U, x(0)) \le 0$$



where cost function ***J*** and constraints ***g*** are determined from a model of the system and control requirements. Constraints and criteria are specified during control design.

The optimization is solved *offline* with a math program solver, generating a simple *online* implementation:

$$U^* = f_0\big(x(0)\big) = F_i x(0) + G_i \text{ if } x(0) \in \mathfrak{D}_i$$

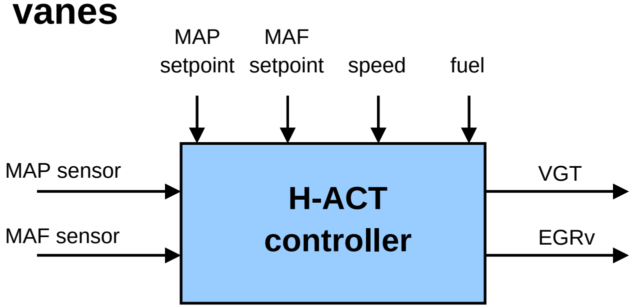


Several extensions, including for multi-mode systems (colors: modes, segments: different $\mathfrak{D}_i$)

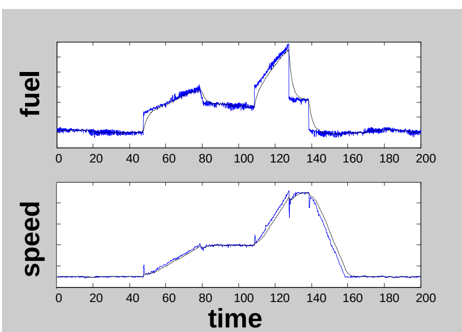
Engine: small engine with single turbo and EGR
Experiment: simultaneous tracking of setpoints through changing engine speed and load transients.

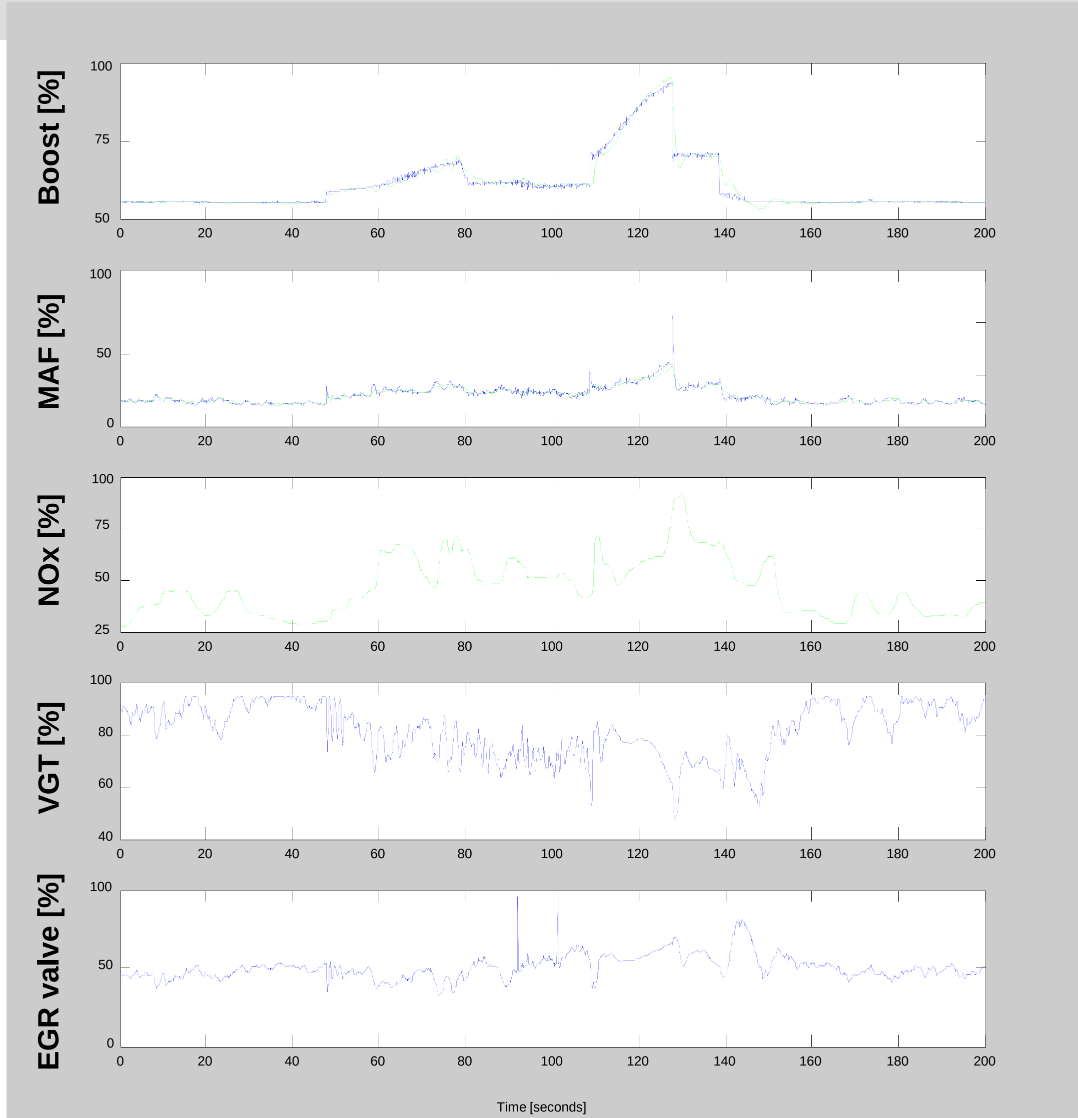
Multivariable Control over NEDC-like cycle

Setpoints: Boost and MAF
Actuators: EGR valve and VGT vanes



Transient: NEDC-like



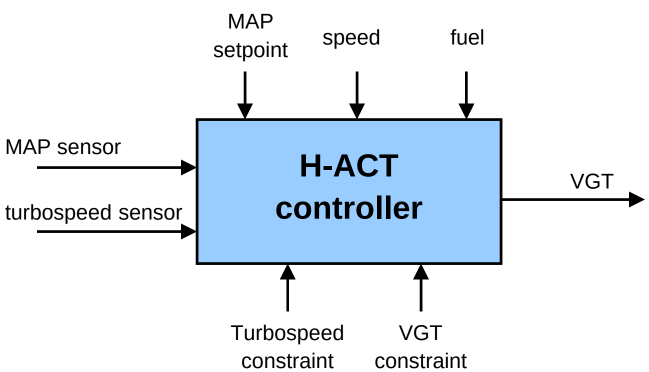


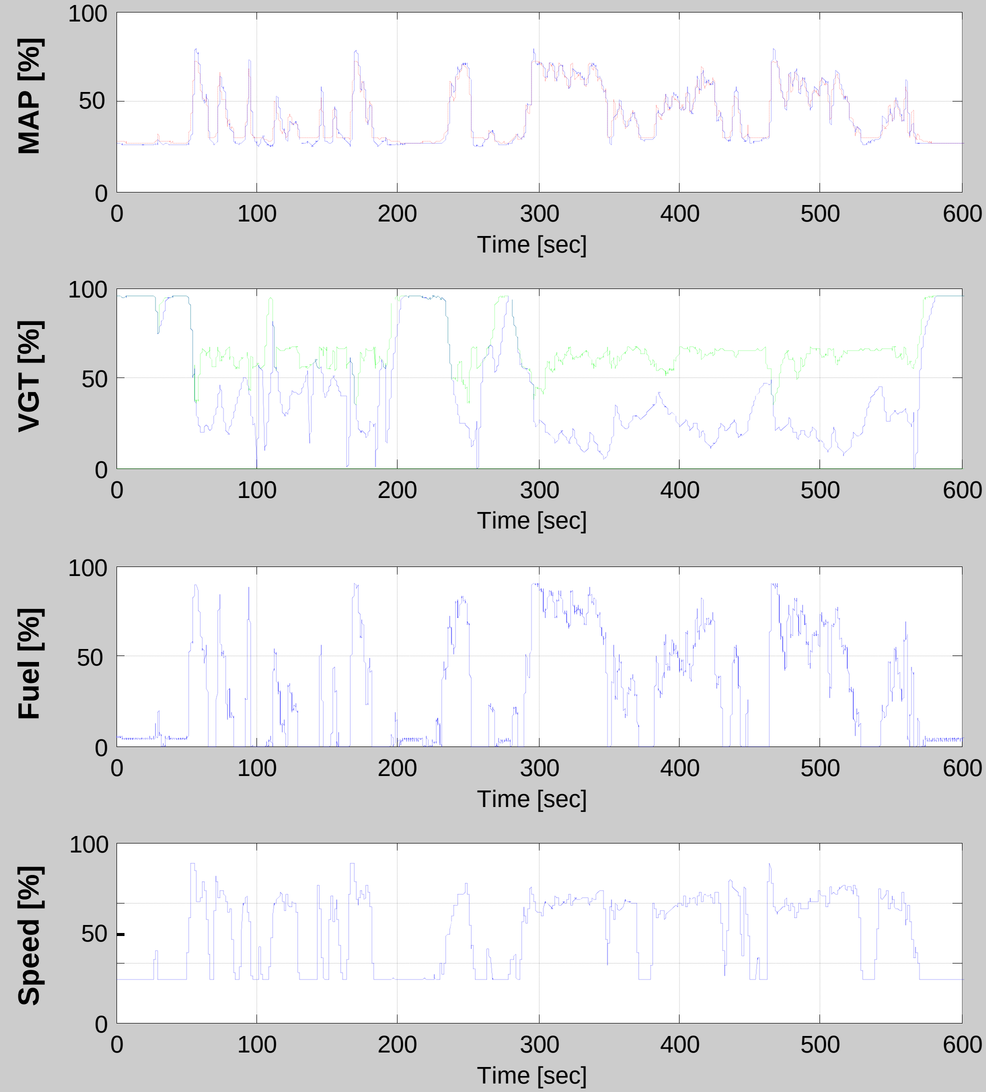
Implemented on a production ECU on a production engine

Control Over Highly Transient Part Of FTP Cycle

Engine: Medium size engine with single turbo and EGR
Experiment: Modes 2 and 3 of FTP cycle

Controller: MAP control with time-varying turbospeed and VGT constraints, using VGT actuator



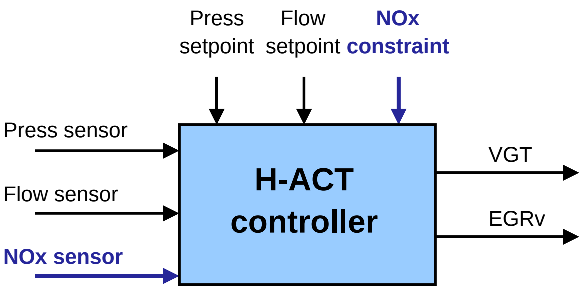


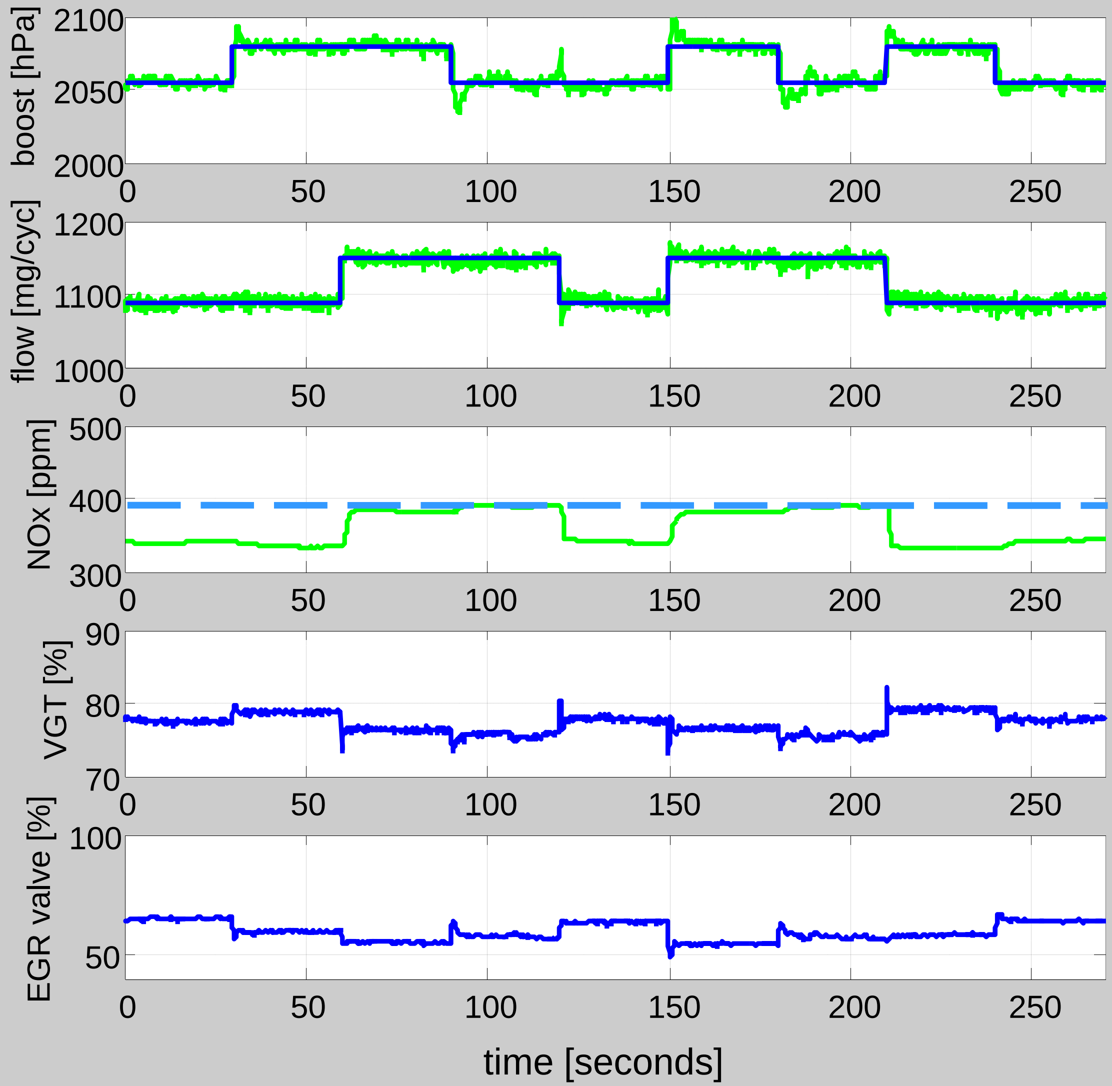
Control with time-varying actuator constraints

Engine Control Within Emissions Constraint

- **Augmented with constraint on engine-out NO_x**

<u>Setpoints</u>: Pressure and Flow
<u>Actuators</u>: EGR valve and VGT vanes
<u>Constraint</u>: engine-out NOx





Model-based control: flexibility in problem formulation

We thought we were done, but . . .

- Customers very impressed with our controls expertise and test cell demonstrations!
  - not just the performance achieved, but the speed of controller development
- But then questions started to come up . . .
  - what does this really mean for us?
  - how will it fit within our processes?

. . . our learning experience was just starting.

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Overview of Standard Control Development Process

Engine and steady-state calibration

↓

Control development

↓

Software development

↓

Calibration (tuning) of controllers

↓

Certification

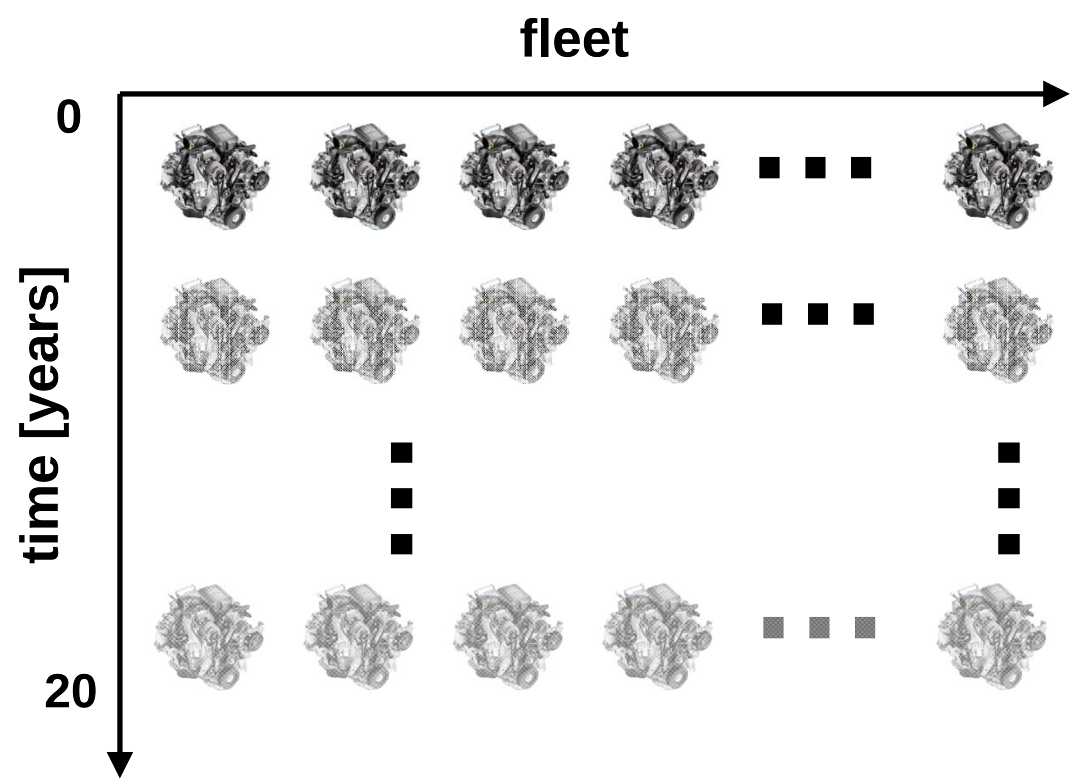
↓

Release

↓

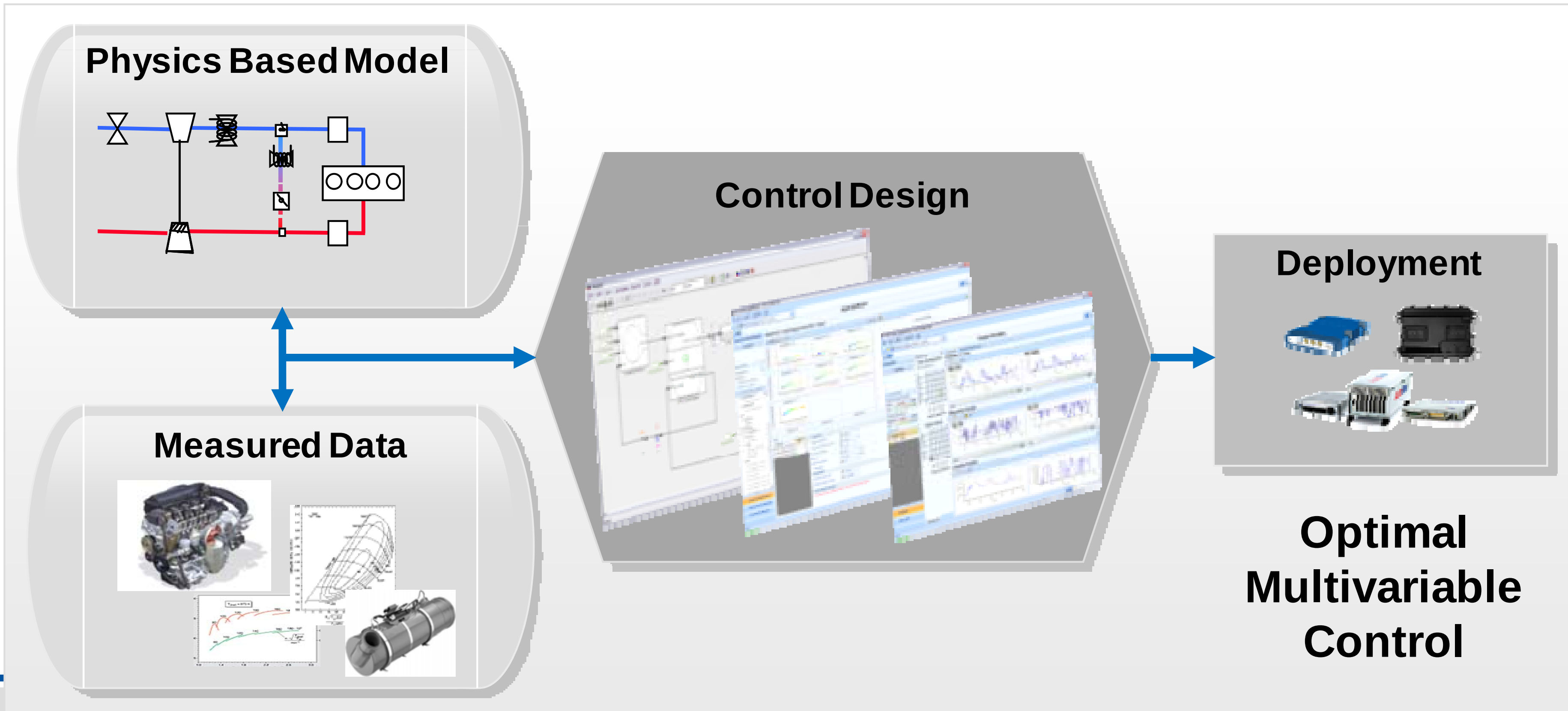
Post-release support

Resulting controller must perform well for all engines and over lifetime of fleet.



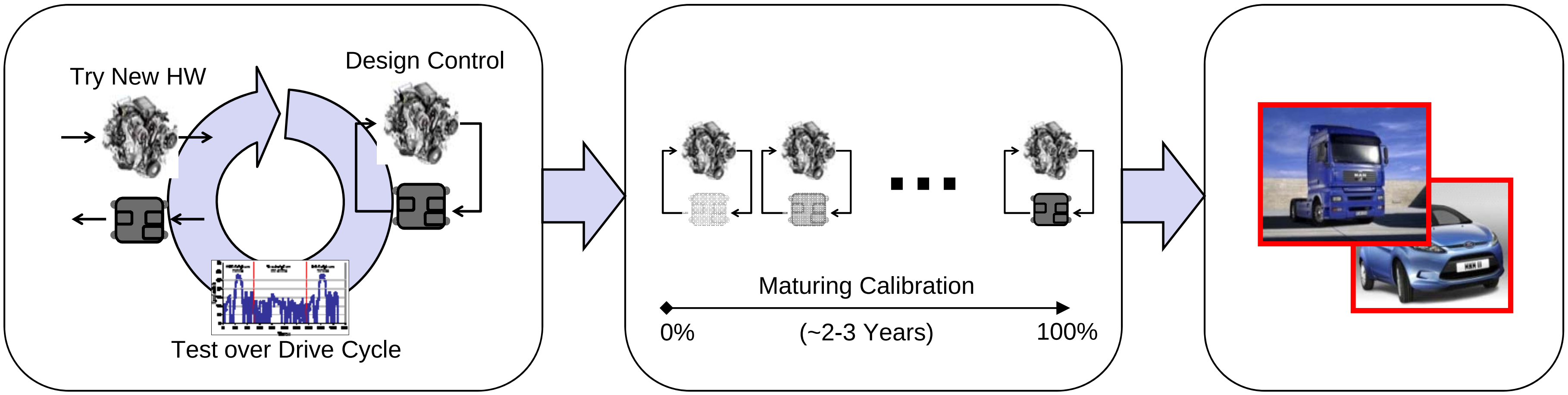
OnRAMP – Optimized, Model-Based Design

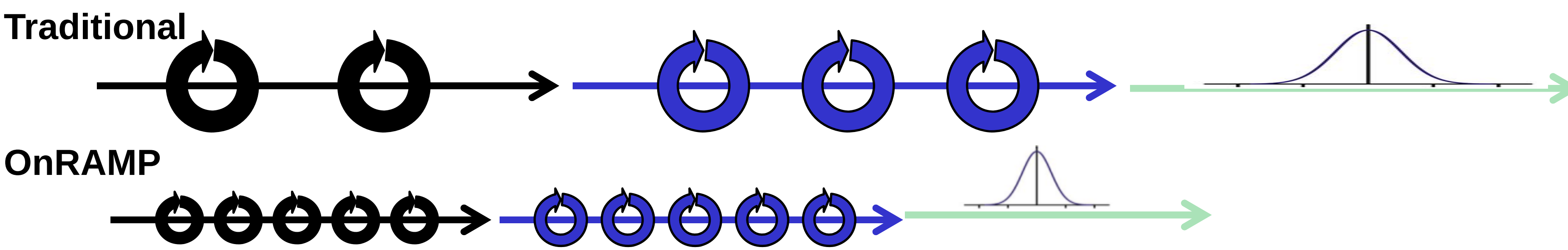
Modeling → Control Design → Controller Deployment



Engine Development w/ OnRAMP

Hardware Selection | **Production Software & Emissions Cal** | **OBD Software & Cal**





More Chances to Get Hardware Right in Less Time
- Faster Iterations
- Coordinated AFT Controls

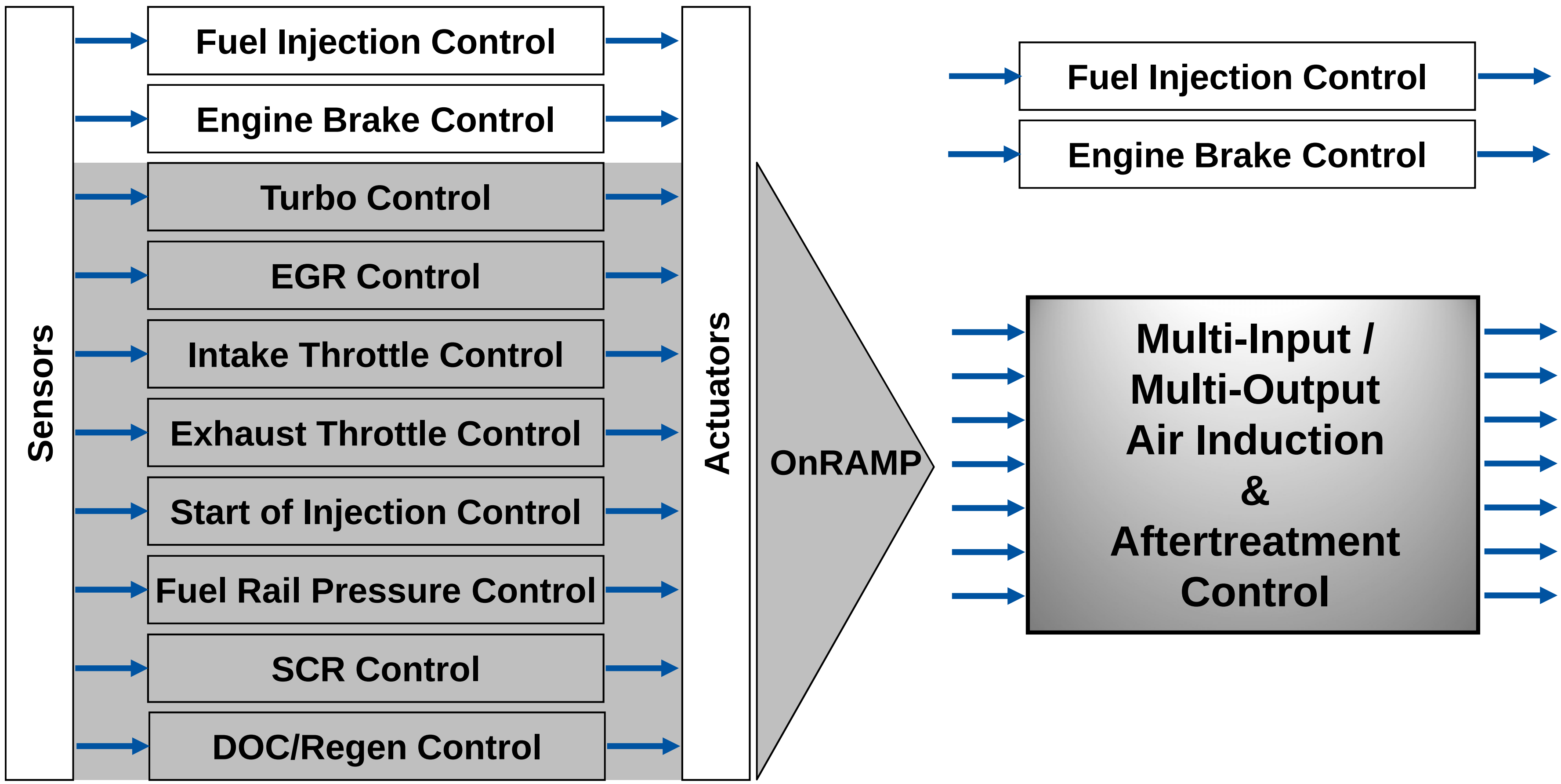
Intuitive Tradeoffs Between Driveability and Emissions/Fuel Economy → More Mature Cal in Same Time, or Launch Early and Earn Credits

Reduce Variation
- Faster OBD Val
- Fewer Returns from Field

A New Approach to Powertrain Control

Today's Control

Tomorrow with OnRAMP



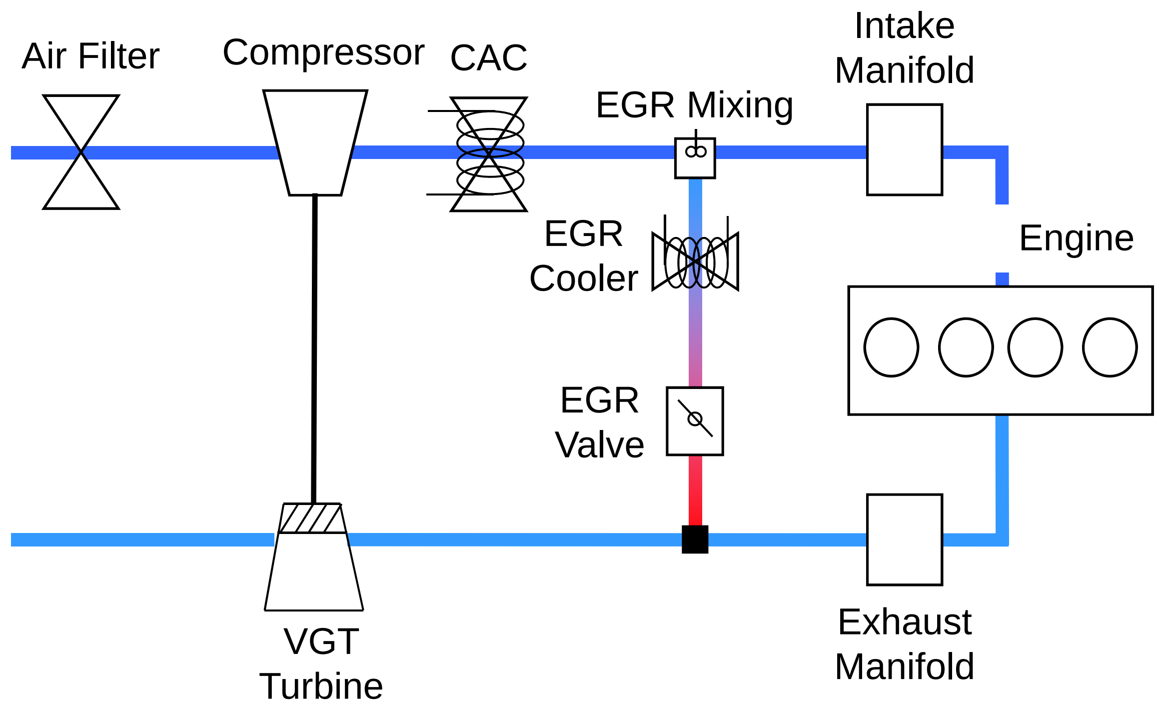
Complex, Labor Intensive → **Simplified, Streamlined**

OnRAMP: Model Setup

Modeling

Control Design

Controller Deployment



- Engine Layout Constructed Piece-by-Piece from a Library of Components

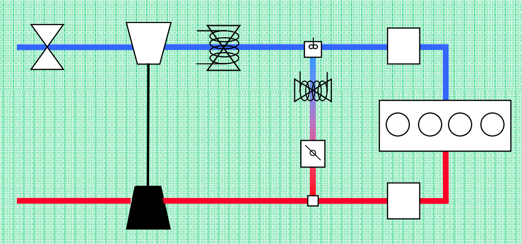
Control Oriented Modeling (COM)

Modeling

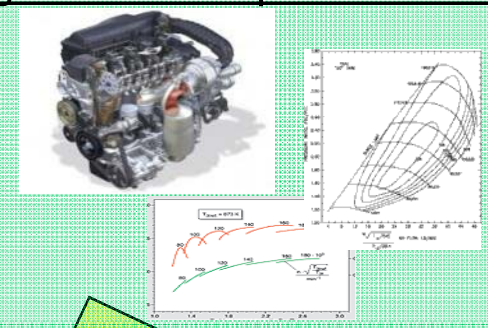
Control Design

Controller Deployment

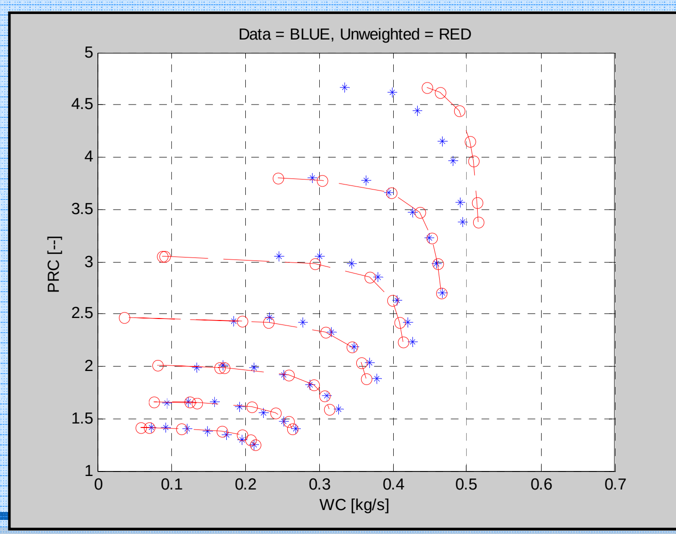
Model Structure



Engine and Component Data



Automatic Model Fit



Component Level Fit

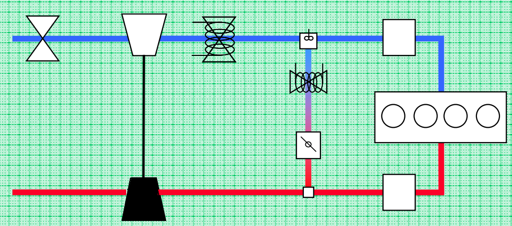
Control Oriented Modeling (COM)

Modeling

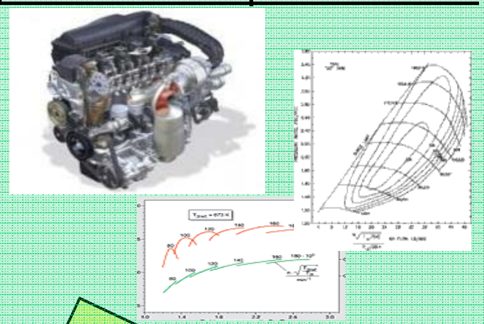
Control Design

Controller Deployment

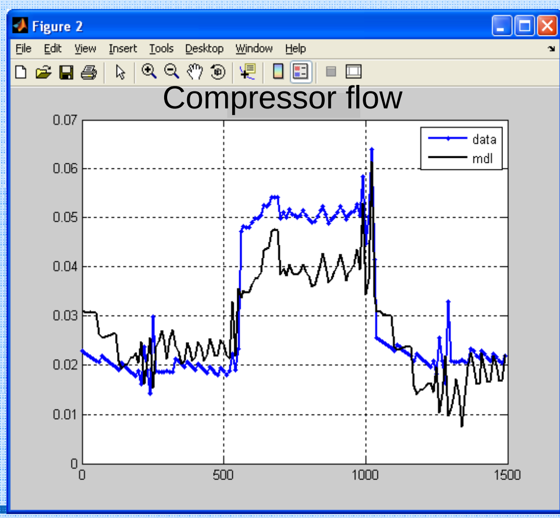
Model Structure



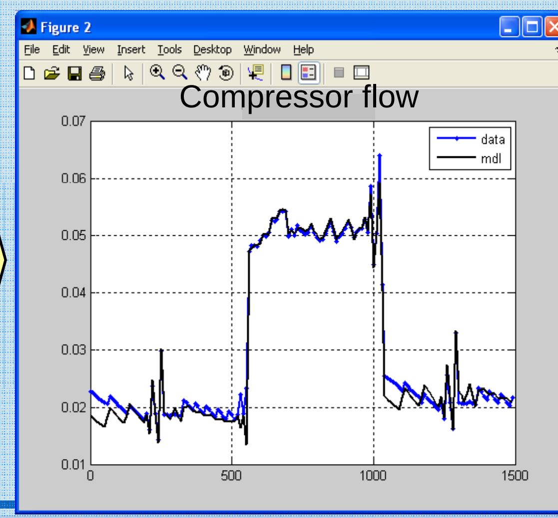
Engine and Component Data



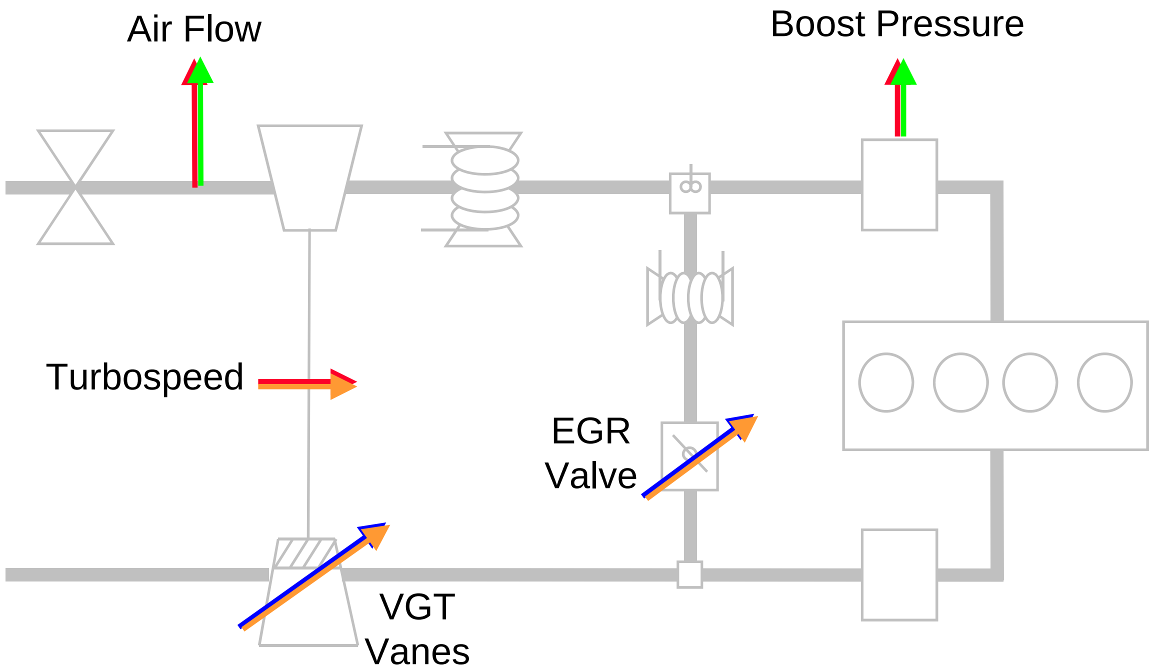
Automatic Model Fit



Global Model Fit



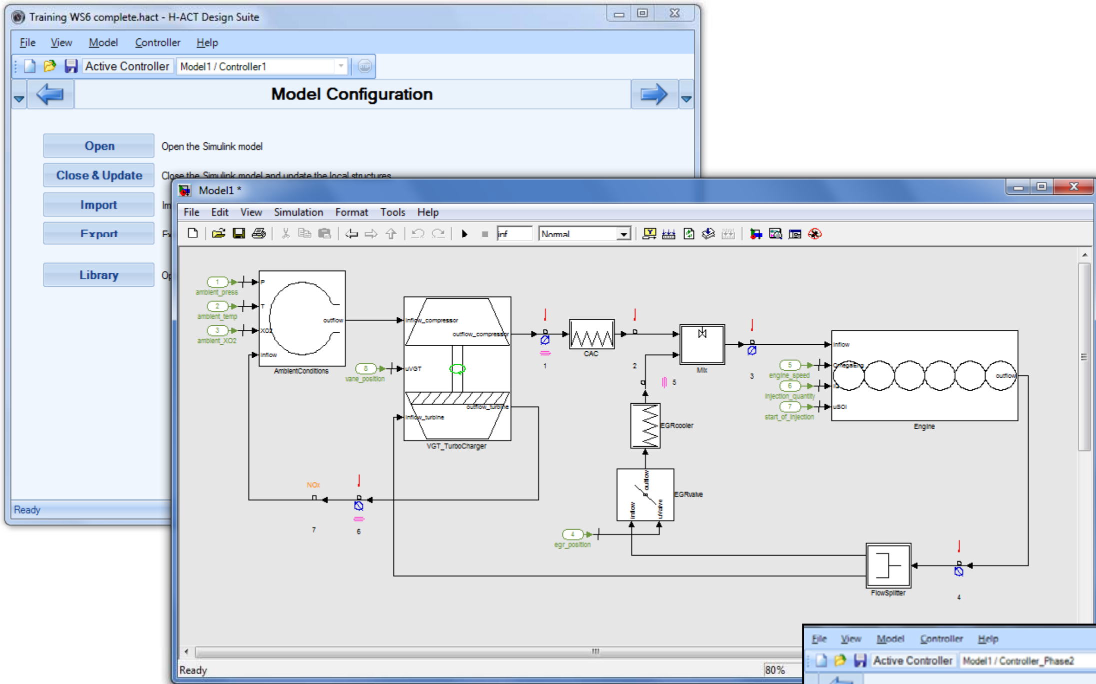
OnRAMP: Control Design



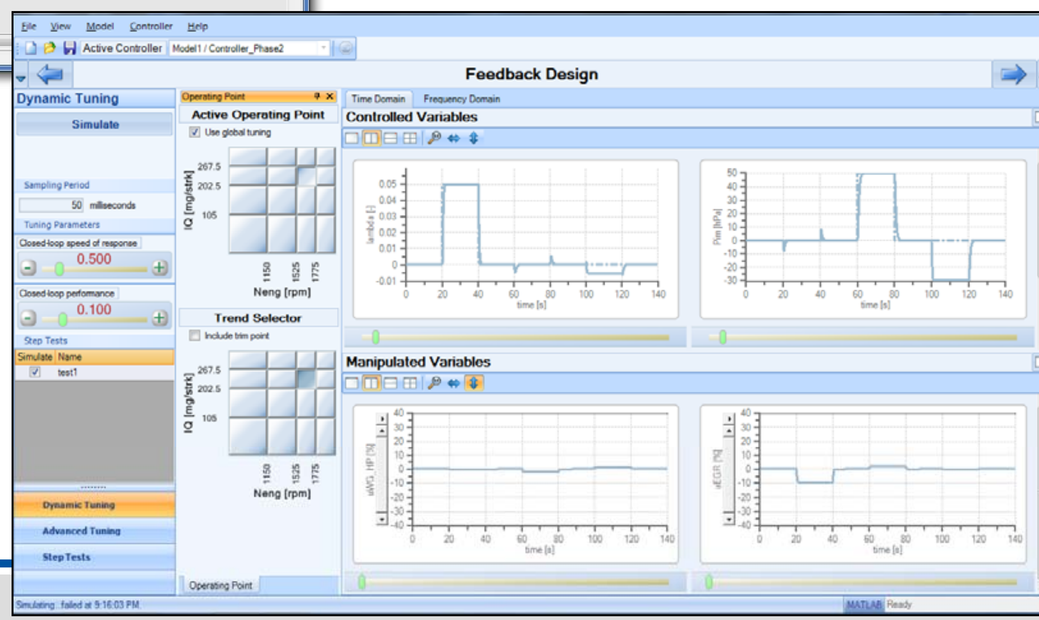
User Specifies:

- Actuators
- Sensors
- Setpoints
- Constraints

OnRAMP tools

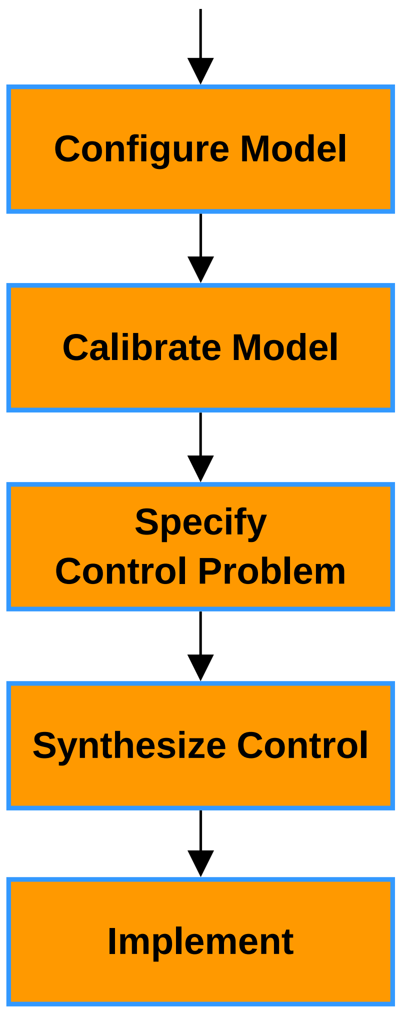


- Ordinarily configuring an engine model in Simulink takes around a week and is error prone
- With OnRAMP, the user can drag and drop engine components and a patented routine automatically generates the wiring. This requires 10-30 minutes and significantly reduces the opportunity for model configuration errors.



- Developed for users without multivariable control background
- Slider bars allow MIMO tradeoffs
- Automatic tuning algorithm determines MPC and observer weights to satisfy small-gain robust stability condition

OnRAMP: Systematic procedure for advanced control design and implementation



- Component libraries for developing control-oriented models
  - low-order models that capture the essential physics
  - nonlinear ODEs generated for control synthesis
  - modeling tool must be robust for all users and engines
- Model calibration as nonlinear identification
- Feedforward and feedback control derived from model
- General ECU template permits many controller configurations
  - no software structure changes
- MIMO controller integrates into production software hierarchy

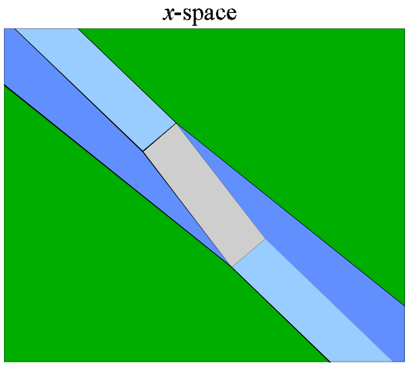
Controller Synthesis

$$\min_U \; J(U; x(t)) = \sum_{k=0}^{N_y} \left\| \hat{y}(t+k \mid t) \right\|_Q^2 + \left\| u(t+k) \right\|_R^2$$

$$\text{subject to} \quad u_{\min} \le u(t+k) \le u_{\max}$$

$$y_{\min} \le \hat{y}(t+k \mid t) \le y_{\max}$$

$$u(x) = \begin{cases} F_1 x + G_1 & \text{if } H_1 x \le K_1 \\ \vdots & \vdots \\ F_N x + G_N & \text{if } H_N x \le K_N \end{cases}$$

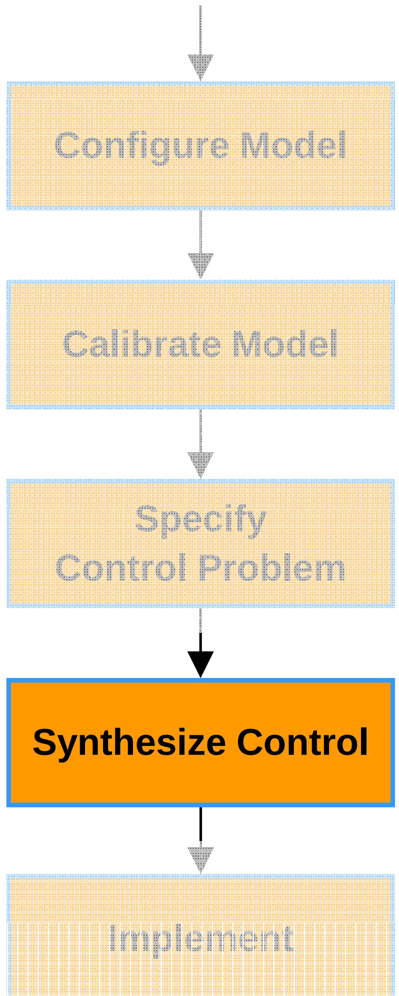


Resulting real time controller:

- **<u>Calibration</u> data {F_j, G_j, H_j, K_j} are problem specific, but**
- **<u>Algorithm</u> structure *does not change***

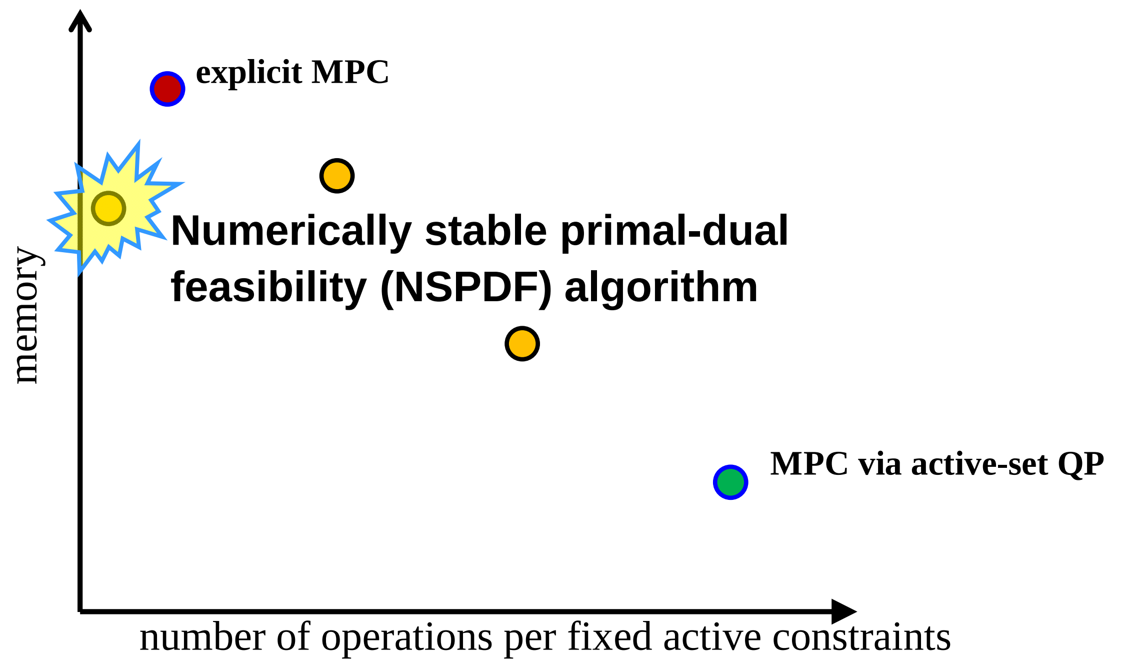
Behind the scenes for the user: fast MPC with patented extensions

H-ACT: Design Steps



Trading off CPU Time and Memory in MPC

[Borrelli, Baotic, Pekar, Stewart, ECC09]



OnRAMP – Modeling, Control & Calibration

Cycle Time Reduction

- Transient Control on Engine in < 2 weeks
- Ability to Reconfigure Structure in < 1 Day
- > 1 FTE Annual Savings per License

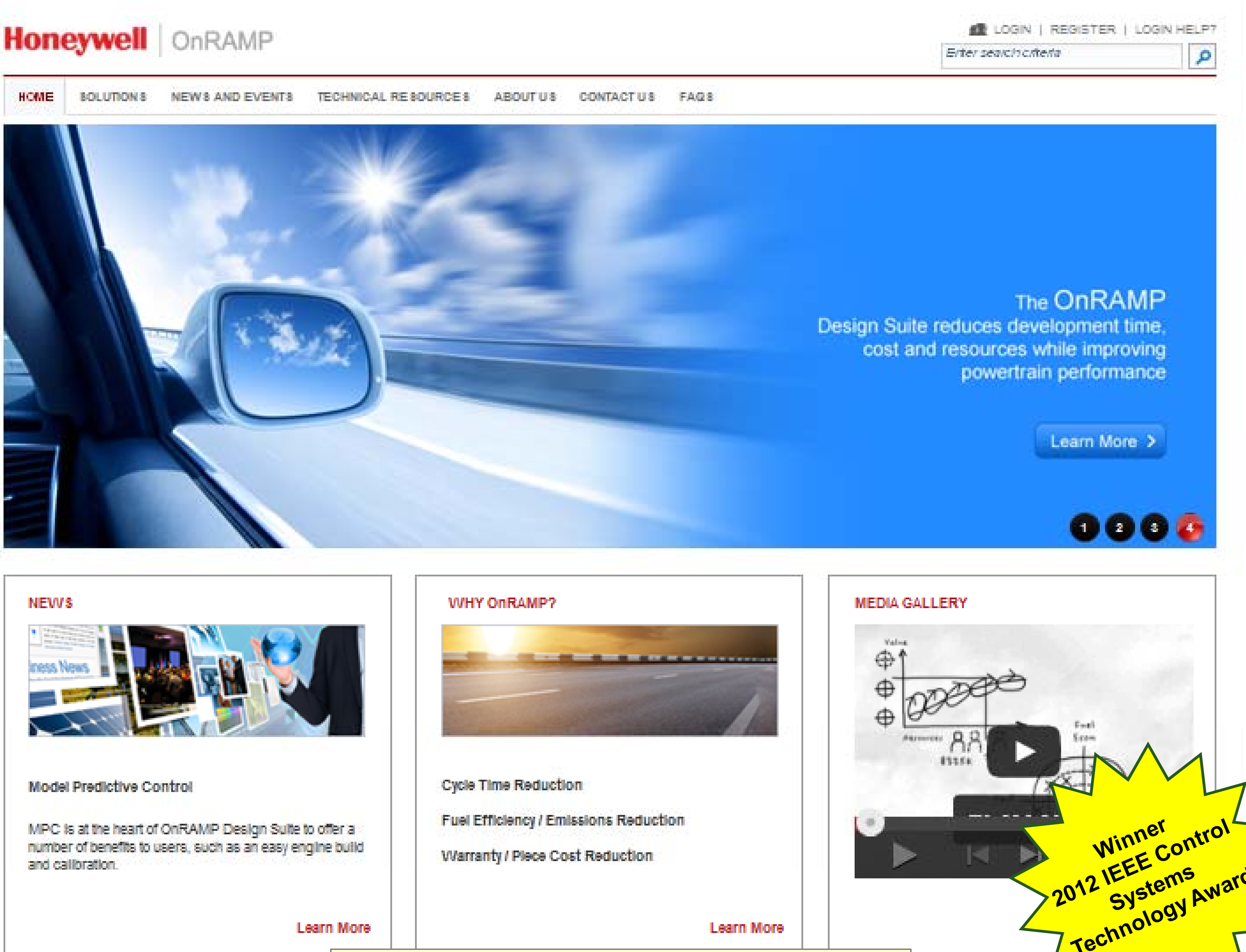
Fuel Efficiency / Emissions

- > 2% Fuel Efficiency Improvement Projected*
- Up to 70% Reduction in Engine Out Smoke
- Robust to Engine / Aftertreatment Ageing

Warranty Reduction

- > 50% Reduction in Actuator Activity
- Remove Potential for Actuator "Fighting"
- Potential to reduce # of Sensors on Engine

Several applications by engine manufacturers . . . clean-sheet development time for transient control reduced in most cases from several months to a few weeks.



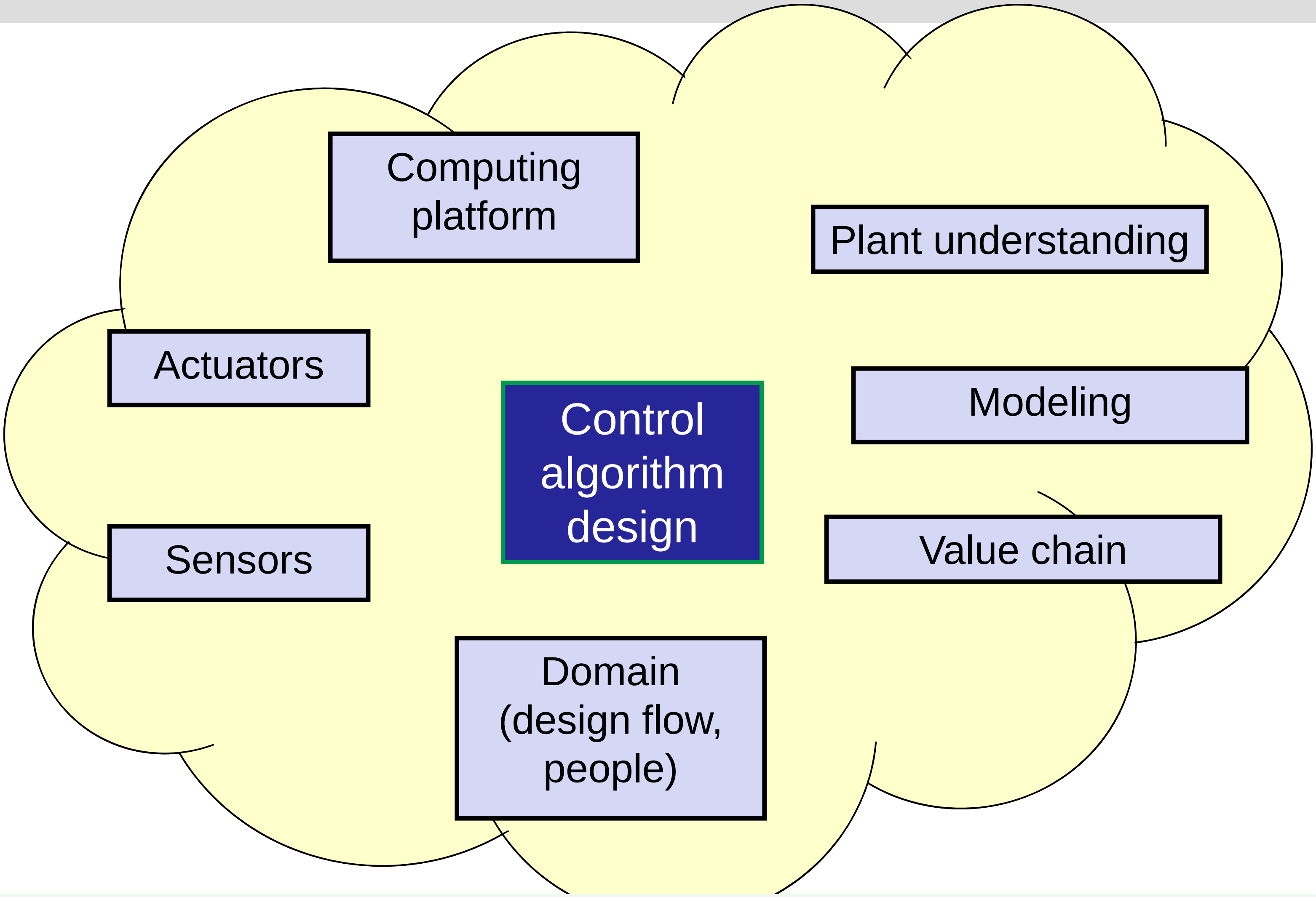
Winner 2012 IEEE Control Systems Technology Award

http://www.honeywellonramp.com

Outline

- Honeywell and controls
- Advanced control applications in the industrial context
- Trends in automotive powertrain control
- Advanced control for powertrains—initial “successes”
- Advanced control for powertrains—Honeywell OnRAMP
- Summary and conclusions

Advanced control in context



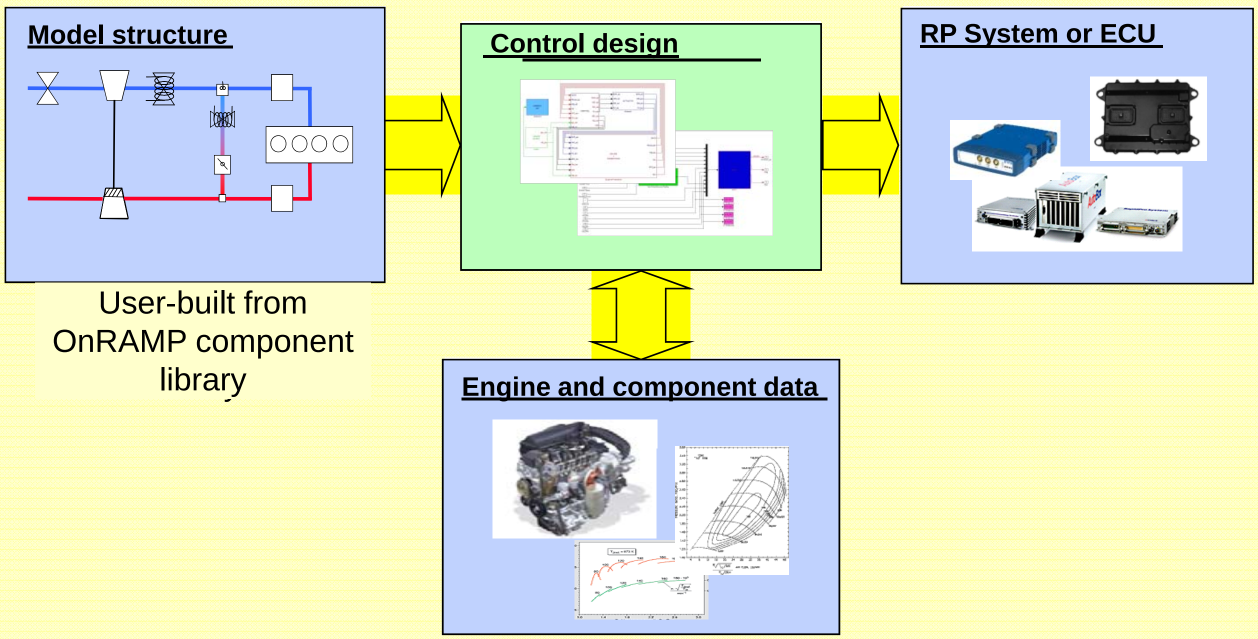
Control algorithm design cannot be isolated from its intended environment

OnRAMP—Advanced Control for Powertrains

Honeywell

Overview:

a development process and software tool for automatic generation of models and optimal control algorithms for a wide range of engine applications

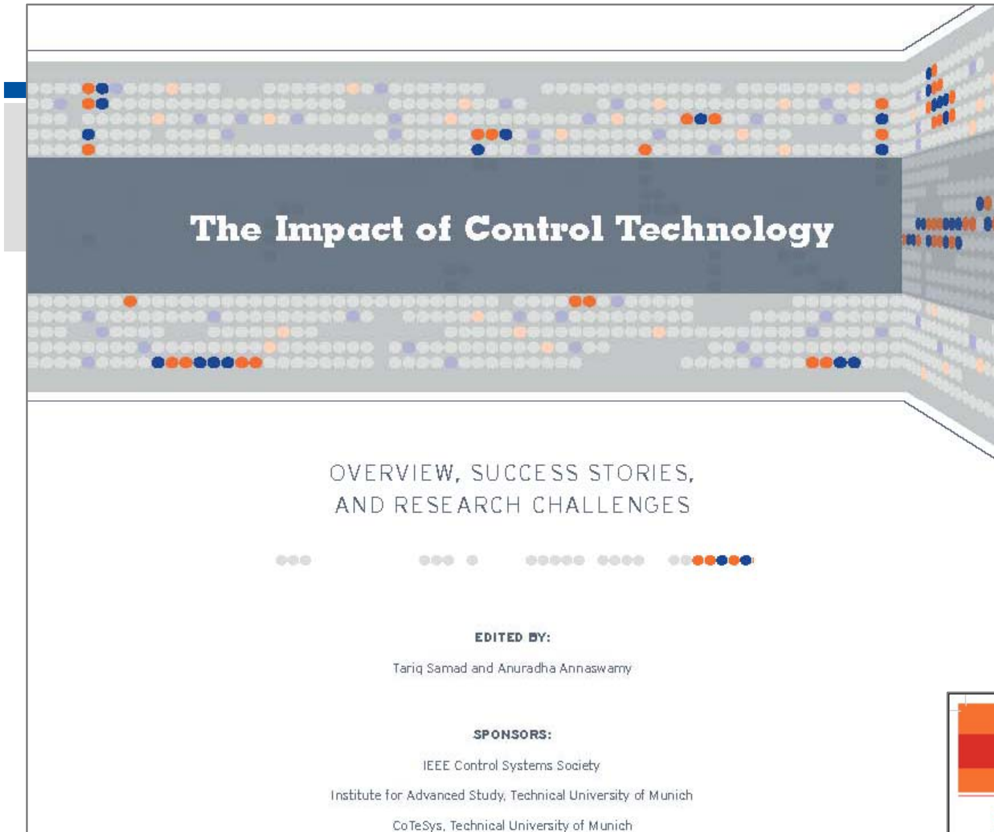


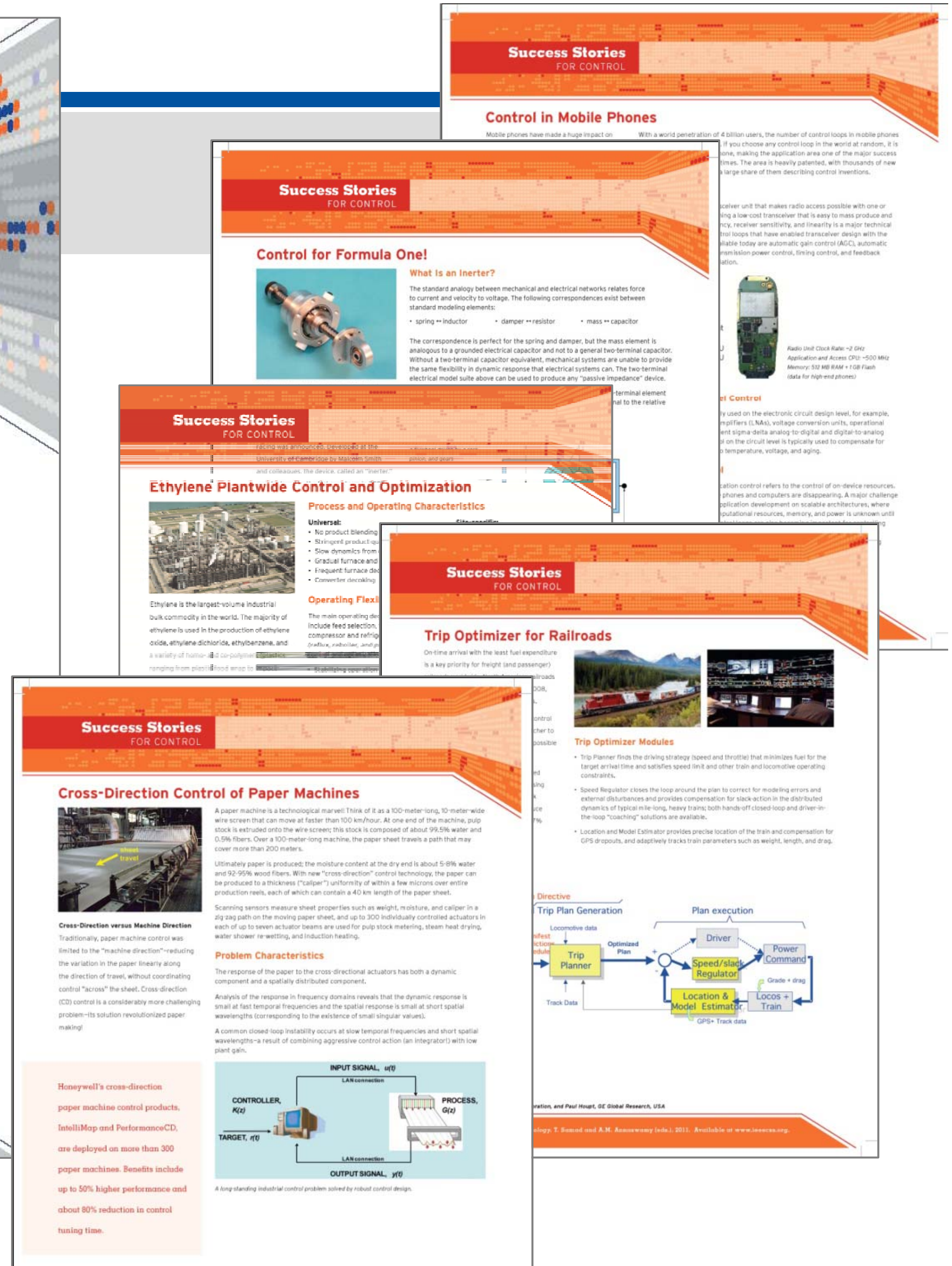
- Modeling: tool for configuration and automated robust identification of nonlinear grey box engine model to fit input-output data.
- Control: “explicit MPC” technique tailored for implementing nonlinear MPC in a production ECU environment.

Advanced Control Applications as Systems Engineering

- Understanding the domain and the industry
  – how are the problems addressed today?
  – how is control performed in the industry and by whom?
- Understanding requirements and the reasons for them
  – what's the "so what?"—from the end user to the immediate customer?
- Understanding if/how advanced control can be a solution
  – what are the barriers to change that must be overcome?
  – what are the costs and benefits versus the "next-best alternative"?
- Tools for modeling, control design, deployment, and support
  – how can advanced control be systematic, replicable, scalable?

Requirements-driven, model-based, agile control design !





- www.ieeecss.org/main/IoCT-report (T. Samad & A. Annaswamy, eds., 2011)
- 40+ two-page flyers
  - "Success stories for control"
  - "Grand challenges for control"
- 2nd edition in preparation (2014)
  - 70 – 80+ flyers expected
  - solicitations welcome through end of year

Highlighting real-world accomplishments and opportunities in our field!

Questions?

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