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Multi-Parametric Programming & Explicit Model Predictive Control

Stratos Pistikopoulos

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Multi-Parametric Programming & Model Predictive Control – *are they meant for each other?*

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Multi-Parametric Programming & Model Predictive Control – *are they meant for each other?*

YES!

in many cases (but not for all)

Outline

- Key concepts & historical overview
- Multi-parametric Programming Theory
  - Recent Developments & future directions
- Explicit Model Predictive Control Theory
  - Recent Developments & future directions
- A framework for multi-parametric programming & MPC
- MPC-on-a-Chip Applications
  - Recent Developments & future directions

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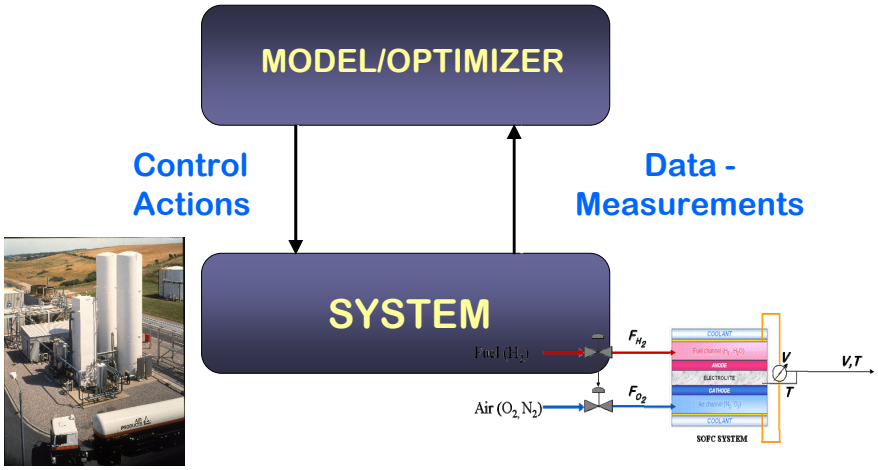
What is On-line Optimization?



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What is Multi-parametric Programming?

- Given:
  - a performance criterion to minimize/maximize
  - a vector of constraints
  - a vector of parameters

$$z(x) = \min_{u} f(u,x)$$
$$\text{s.t. } g(u,x) \le 0$$
$$x \in \mathbb{R}^n$$
$$u \in \mathbb{R}^s$$

What is Multi-parametric Programming?

- Given:
  - a performance criterion to minimize/maximize
  - a vector of constraints
  - a vector of parameters
- Obtain:
  - the performance criterion and the optimisation variables as a function of the parameters
  - the regions in the space of parameters where these functions remain valid

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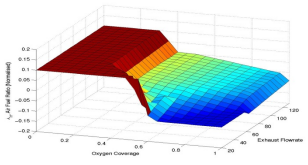
Multi-parametric programming

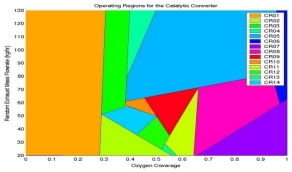
$$z(x) = \min_{u} f(u,x)$$
$$\text{s.t. } g(u,x) \le 0$$
$$x \in \mathbb{R}^n$$
$$u \in \mathbb{R}^s$$

$u(x)$

(1) Optimal look-up function



(2) Critical Regions



Obtain optimal solution $u(x)$ as a function of the parameters x

Multi-parametric programming

Problem Formulation

$$\min_{\mathbf{u}_1,\mathbf{u}_2} \left(-3\mathbf{u}_1 - 8\mathbf{u}_2\right)$$

$$st.$$

$$\begin{bmatrix} 1 & 1 \\ 5 & -4 \\ -8 & 22 \\ -4 & -1 \end{bmatrix} \cdot \begin{bmatrix} \mathbf{u}_1 \\ \mathbf{u}_2 \end{bmatrix} + \begin{bmatrix} -1 & 0 \\ 0 & 0 \\ 0 & -1 \\ 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \end{bmatrix} + \begin{bmatrix} -13 \\ -20 \\ -121 \\ 8 \end{bmatrix} \leq \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$-10 \leq \mathbf{x}_1 \leq 10 \quad -100 \leq \mathbf{x}_2 \leq 100$$

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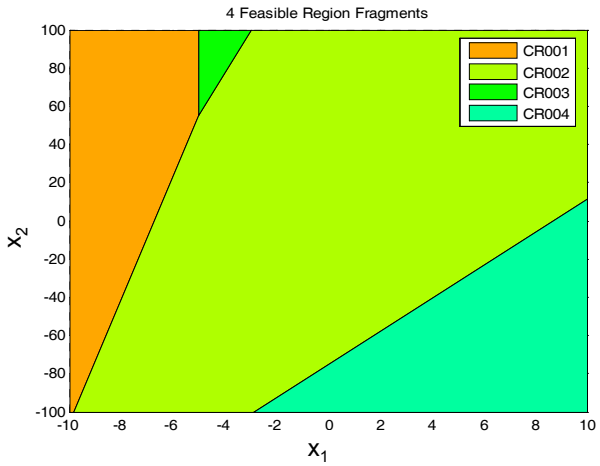
Multi-parametric programming

Critical Regions



Multi-parametric programming

Multi-parametric Solution

$$\mathbf{U} = \begin{cases} \begin{bmatrix} -0.33 & 0 \\ 1.33 & 0 \end{bmatrix} \cdot \begin{bmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \end{bmatrix} + \begin{bmatrix} -1.67 \\ 14.67 \end{bmatrix} & \textbf{if} \begin{bmatrix} 1 & -0.031 \\ 1 & 0 \\ -1 & 0 \\ 0 & -1 \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \end{bmatrix} \le \begin{bmatrix} -6.71 \\ -5 \\ 10 \\ 100 \\ 100 \end{bmatrix} \\ \begin{bmatrix} 0.73 & -0.03 \\ 0.26 & 0.03 \end{bmatrix} \cdot \begin{bmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \end{bmatrix} + \begin{bmatrix} 5.5 \\ 7.5 \end{bmatrix} & \textbf{if} \begin{bmatrix} 1 & -0.115 \\ -1 & 0.031 \\ -1 & 0.045 \\ 1 & 0 \\ 0 & -1 \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \end{bmatrix} \le \begin{bmatrix} 8.65 \\ 6.71 \\ 7.5 \\ 10 \\ 100 \\ 100 \end{bmatrix} \\ \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 13 \end{bmatrix} & \textbf{if} \begin{bmatrix} 1 & -0.045 \\ -1 & 0 \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \end{bmatrix} \le \begin{bmatrix} -7.5 \\ 5 \\ 100 \end{bmatrix} \\ \begin{bmatrix} 0 & 0.05 \\ 0 & 0.06 \end{bmatrix} \cdot \begin{bmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \end{bmatrix} + \begin{bmatrix} 11.8 \\ 9.8 \end{bmatrix} & \textbf{if} \begin{bmatrix} -1 & 0.11 \\ 1 & 0 \\ 0 & -1 \end{bmatrix} \cdot \begin{bmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \end{bmatrix} \le \begin{bmatrix} -8.65 \\ 10 \\ 100 \end{bmatrix} \end{cases}$$

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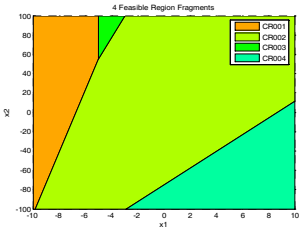
Multi-parametric programming

$$\min_u (-3u_1 - 8u_2)$$

$$st.$$

$$\begin{bmatrix} 1 & 1 \\ 5 & -4 \\ -8 & 22 \\ -4 & -1 \end{bmatrix} \cdot \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} + \begin{bmatrix} -1 & 0 \\ 0 & 0 \\ 0 & -1 \\ 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} -13 \\ -20 \\ -121 \\ 8 \end{bmatrix} \le \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

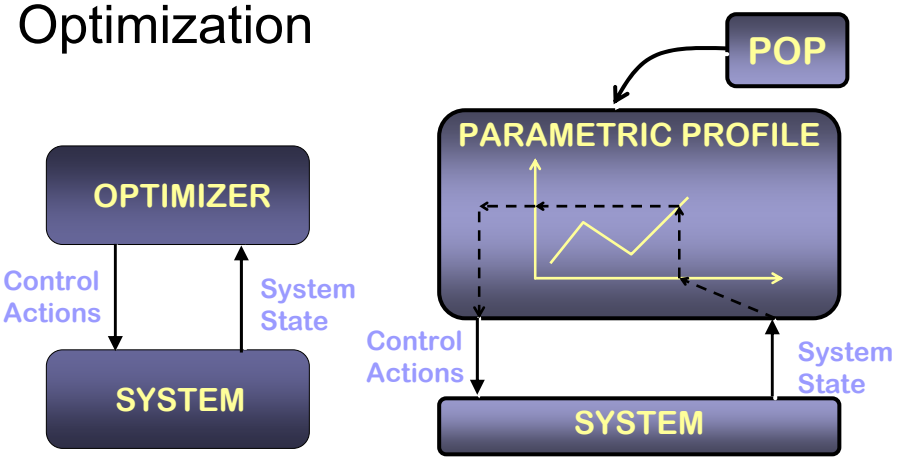
$$-10 \le x_1 \le 10, -100 \le x_2 \le 100$$



$$U = \begin{cases} \begin{bmatrix} -0.333 & 0 \\ 1.333 & 0 \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} -1.6667 \\ 14.6667 \end{bmatrix} & \textbf{if} \begin{bmatrix} 1 & -0.03125 \\ 1 & 0 \\ -1 & 0 \\ 0 & -1 \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \le \begin{bmatrix} -6.71875 \\ -5 \\ 10 \\ 100 \\ 100 \end{bmatrix} \\ \begin{bmatrix} 0.7333 & -0.0333 \\ 0.26667 & 0.03333 \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 5.5 \\ 7.5 \end{bmatrix} & \textbf{if} \begin{bmatrix} 1 & -0.115385 \\ -1 & 0.03125 \\ -1 & 0.0454545 \\ 1 & 0 \\ 0 & -1 \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \le \begin{bmatrix} 8.65385 \\ 6.71875 \\ 7.5 \\ 10 \\ 100 \\ 100 \end{bmatrix} \\ \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 13 \end{bmatrix} & \textbf{if} \begin{bmatrix} 1 & -0.0454545 \\ -1 & 0 \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \le \begin{bmatrix} -7.5 \\ 5 \\ 100 \end{bmatrix} \\ \begin{bmatrix} 0 & 0.05128 \\ 0 & 0.0641 \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 11.8462 \\ 9.80769 \end{bmatrix} & \textbf{if} \begin{bmatrix} -1 & 0.115385 \\ 1 & 0 \\ 0 & -1 \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \le \begin{bmatrix} -8.65385 \\ 10 \\ 100 \end{bmatrix} \end{cases}$$

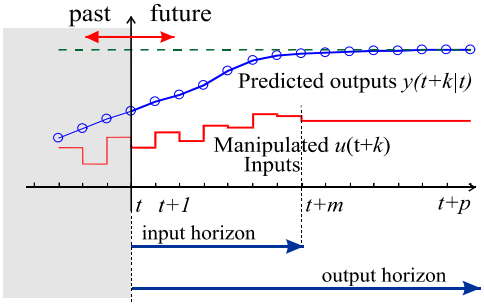
Only 4 optimization problems solved!

On-line Optimization via off-line Optimization



Function Evaluation!

Multi-parametric/Explicit Model Predictive Control



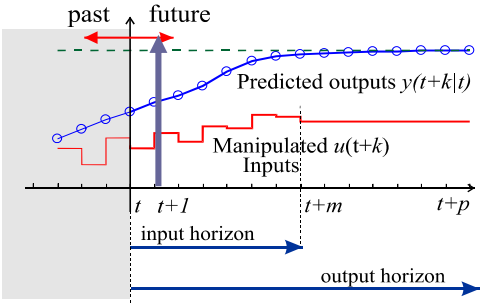
- Compute the optimal sequence of manipulated inputs which minimizes

tracking error = output – reference

subject to constraints on inputs and outputs

- On-line re-planning: Receding Horizon Control

Multi-parametric/Explicit Model Predictive Control



- Compute the optimal sequence of manipulated inputs which minimizes

Solve a QP at each time interval

- On-line re-planning: Receding Horizon Control

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Multi-parametric Programming Approach

- State variables → Parameters
- Control variables → Optimization variables

- MPC → Multi-Parametric Programming problem
- Control variables → F(State variables)

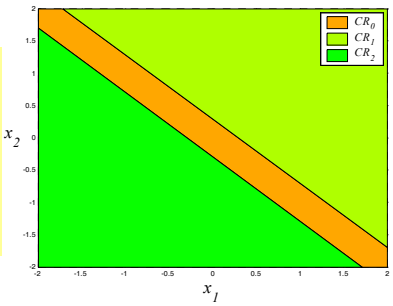
Multi-parametric Quadratic Program

Explicit Control Law

$$J(x(t)) = \min_{u_{t|t},\ldots,u_{t+1|t}} \sum_{j=0}^{1} \left\{ \mathbf{x}_{t+j|t}^T \mathbf{x}_{t+j|t} + 0.01\, \mathbf{u}_{t+j|t}^2 \right\} + \mathbf{x}_{t+2|t}^T P \mathbf{x}_{t+2|t}$$

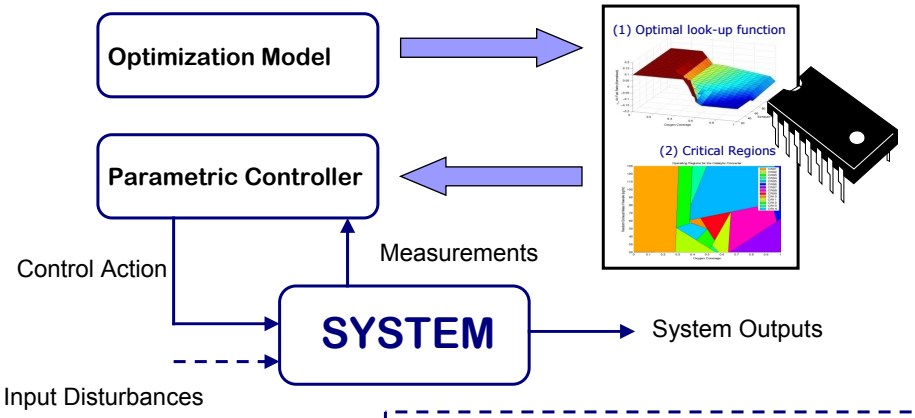
$$\text{s.t} \quad \mathbf{x}_{t+j+1|t} = \begin{bmatrix} 0.7326 & -0.0861 \\ 0.1722 & 0.9909 \end{bmatrix} \mathbf{x}_{t+j|t} + \begin{bmatrix} 0.0609 \\ 0.0064 \end{bmatrix} \mathbf{u}_{t+j|t}$$

$$-2 \le \mathbf{u}_{t+j|t} \le 2 \quad j = 1,2 \quad \mathbf{x}_{t|t} = \mathbf{x}(t)$$



$$\mathbf{u}(t) = \begin{cases} \begin{bmatrix} -6.8355 & -6.8585 \end{bmatrix} \mathbf{x}(t) & \text{if} \quad \begin{bmatrix} 0.7059 & 0.7083 \\ -0.7059 & -0.7083 \end{bmatrix} \mathbf{x}(t) \le \begin{bmatrix} 0.2065 \\ 0.2065 \end{bmatrix} \\ -2 & \text{if} \quad \begin{bmatrix} -0.7059 & -0.7083 \end{bmatrix} \mathbf{x}(t) \le -0.2065 \\ 2 & \text{if} \quad \begin{bmatrix} 0.7059 & 0.7083 \end{bmatrix} \mathbf{x}(t) \le -0.2065 \end{cases}$$

Multi-parametric Controllers



MPC-on-a-chip!

- Explicit Control Law
- Eliminate expensive, on-line computations
- Valuable insights !

Key milestones-Historical Overview

AIChE J.,Perspective (2009)

- Number of publications

	Multi-Parametric Programming	Multi-Parametric MPC & applications
Pre-1999	>100	0
Post-1999	~50	~120

- 2002 Automatica paper ~ 420 citations
- Multi-parametric programming – until 1992 mostly analysis & linear models
- Multi-parametric/explicit MPC – post-2000 much wider attention

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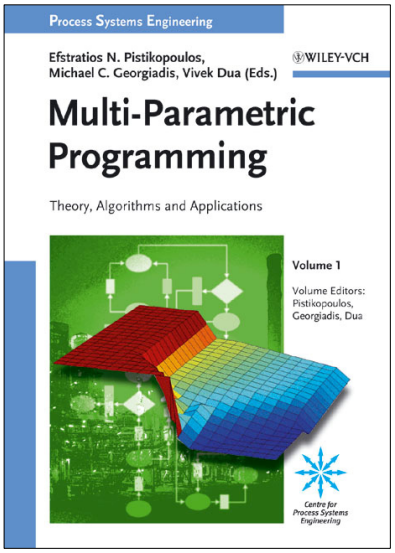

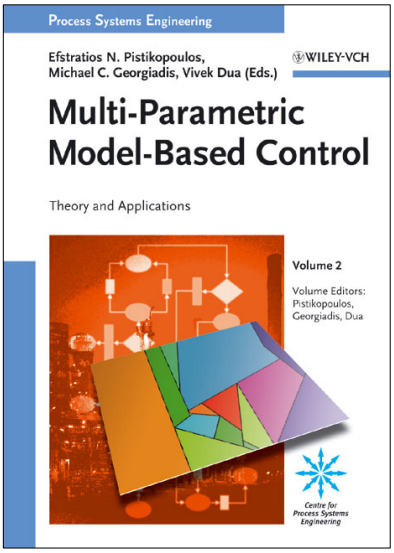

Patented Technology

- Improved Process Control, European Patent No EP1399784, 2004
- Process Control Using Co-ordinate Space, United States Patent No US7433743, 2008

PAROS
Advanced control technology on a chip

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Multi-Parametric Programming & Model Predictive Control – *are they meant for each other?*

YES!

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- Key concepts & historical overview
- Multi-parametric Programming Theory
  - Recent Developments & future directions
- Explicit Model Predictive Control Theory
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- A framework for multi-parametric programming & MPC
- MPC-on-a-chip Applications
  - Recent Developments & future directions

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Multi-parametric Programming Theory

mp-LP	Gass & Saaty [**1954**], Gal & Nedoma [**1972**], Propoi [1975], Adler and Monterio [1992], Gal [1995], Acevedo and Pistikopoulos[1997], Dua et al [2002], Pistikopoulos et al [2007]
mp-QP	Townsley [**1972**], Propoi [1978], Best [1995], Dua et al [2002], Pistikopoulos et al [2002,2007]
mp-NLP	Fiacco [**1976**],Kojima [1979], Bank et al [1983], Fiacco [1983], Fiacco & Kyoarisis [1986], Acevedo & Pistikopoulos [1996], Dua and Pistikopoulos [1998], Pistikopoulos et al [2007]
mp-DO	Sakizlis et al.[2002], Bansal [2003], Sakizlis et al [2005], Pistikopoulos et al [2007]
mp-GO	Fiacco [1990], Dua et al [1999,2004], Pistikopoulos et al [2007]
mp-MILP	Marsten & Morin [**1975**], Geoffrion & Nauss [1977], Joseph [1995], Acevedo & Pistikopoulos [1997,1999], Dua & Pistikopoulos[2000]
mp-MINLP	McBride & Yorkmark [**1980**], Chern [1991], Dua & Pistikopoulos [1999], Hene et al [2002], Dua et al [2002]

Multi-parametric Programming Theory – Recent Developments

- Multi-parametric NLP (mp-NLP)
- Dynamic Programming
- Global Optimization
  - Bilevel/Multilevel Programming
  - Multi-parametric MILP

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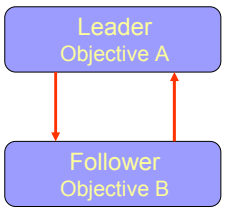
Bilevel/Multilevel Programming



$$\min_{x,y} F(x,y)$$
$$\text{s.t. } G(x,y) \le 0$$

Outer Problem

$$\min_{y} f(x,y)$$
$$\text{s.t. } g(x,y) \le 0$$

Inner Problem

- Even linear case is non-convex
- Multi-parametric Programming approach
  - Follower's problem - Multi-parametric Programming Problem
  - Leader's problem - single optimization problems
- Methodology applies to Multi-level problems
- Applications in Hierarchical Decision Making/Control

Multi-parametric Programming Theory – Future Directions

- Dynamic Systems
  - Multi-parametric Dynamic & Mixed Integer Optimization (mp-DO, mp-MIDO)
  - Valid bounds on number of control laws (Sakizlis et al, 2006) – approximations
- Global Optimization
  - Exploit model structure
  - General classes of nonlinear, mixed integer & dynamic systems
- Revisit fundamentals/basics
  - In search of a new 'breakthrough'
  - Avoid active set strategy

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Multi-parametric/Explicit Model Predictive Control Theory

mp-MPC	Pistikopoulos [**1997, 2000],** Bemporad, Morari, Dua & Pistikopoulos [2000], Sakizlis & Pistikopoulos [2001], Tondel et al [2001], Pistikopoulos et al [2002], Bemporad et al [2002], Johansen and Grancharova [2003], Sakizlis et al [2003], Pistikopoulos et al [2007]
mp-Continuous MPC	Sakizlis et al.[2002], Kojima & Morari[2004], Sakizlis et al [2005], Pistikopoulos et al [2007]
Hybrid mp-MPC	Bemporad et al [2000], Sakizlis & Pistikopoulos [2001], Pistikopoulos et al [2007]
Robust mp-MPC	Kakalis & Pistikopoulos [2001], Bemporad et al [2001], Sakizlis et al [2002], Sakizlis & Pistikopoulos [2002], Sakizlis et al [2004], Olaru et al [2005], Faisca et al [2008]
mp-DP	Nunoz de la Pena et al [2004],Pistikopoulos et al [2007],Faisca et al [2008]
mp-NMPC	Johansen [2002], Bemporad [2003], Sakizlis et al [2007], Dobre et al [2007], Narciso & Pistikopoulos [2009]

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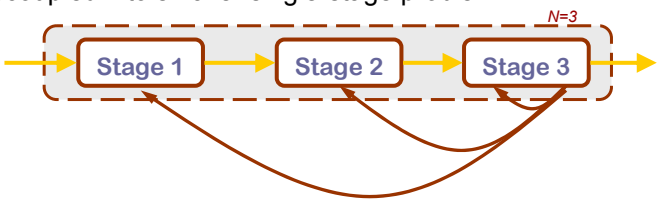
Multi-parametric/Explicit Model Predictive Control Theory – Recent Developments

- Robust Explicit MPC (Faísca et al, 2007, Pistikopoulos et al, 2009)
  - MPC problem posed in a dynamic programming framework - decoupled into smaller single-stage problem



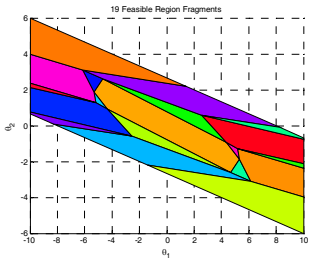
  - At each stage reduced (Robust) mp-QP is solved
    - Consider control, state and constraints only at current stage
    - Immunize constraints against uncertainty (Robustification)

Multi-parametric/Explicit Model Predictive Control Theory – Recent Developments

- Robust Explicit MPC Example

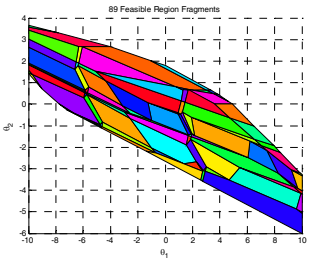
$$x_{t+j+1|t} = Ax_{t+j|t} + Bu_{t+j|t}$$
$$u_{\min} \le u_{t+j|t} \le u_{\max}$$
$$x_{\min} \le x_{t+j|t} \le x_{\max}$$

$$A = [a_{ij}] \in \Re^{n \times n},\ B = [b_{ij}] \in \Re^{n \times m}$$
$$a_{ij} \in \{a_{ij} : |a_{ij} - \bar{a}_{ij}| \le \varepsilon \bar{a}_{ij}\}$$
$$b_{ij} \in \{b_{ij} : |b_{ij} - \bar{b}_{ij}| \le \varepsilon \bar{b}_{ij}\}$$



no uncertainty

N=3



uncertainty 20%

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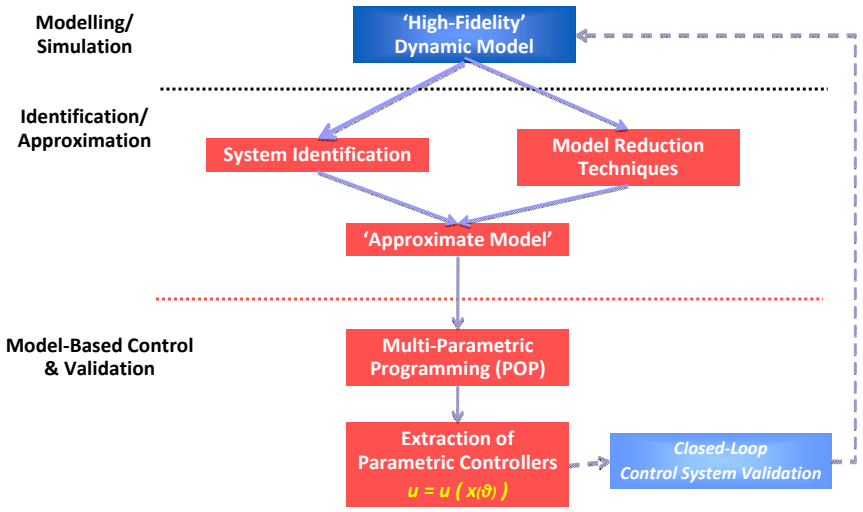
Multi-parametric/Explicit Model Predictive Control Theory – Future Directions

- Robust & Hybrid Explicit Control
  - Hybrid Systems - with Nonlinear, Continuous-time Dynamics (mp-DO, mp-MIDO)
  - Robust Stability of mp-(N)MPC
- Model Reduction/Approximations
  - Nonlinear model order reduction methods with mp-NMPC
  - Identification methods (& uncertainty modelling)
- Estimation
- Explicit Nonlinear MPC (mp-NMPC)
  - Linked to Multi-parametric Nonlinear Programming (mp-NLP)
  - Constrained Dynamic Programming - nonlinear systems
  - Continuous-time Dynamic models (mp-DO, mp-MIDO)

A framework for multi-parametric programming & MPC *(Pistikopoulos 2008, 2009)*



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Multi-Parametric Programming & Model Predictive Control – *are they meant for each other?*

YES!

But a lot of work remains to be done!

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MPC-on-a-chip Applications – Recent Developments

- Process Control
  - Air Separation (Air Products)
  - Hybrid PSA/Membrane Hydrogen Separation (EU/HY2SEPS, KAUST)
- Automotive
  - Active Valve Train Control (Lotus Engineering)
- Energy Systems
  - Hydrogen Storage (EU/DIAMANTE)
  - Fuel Cell

MPC-on-a-chip Applications – Recent Developments

- Biomedical Systems (MOBILE - ERC Advanced Grant Award)
  - Drug/Insulin, Anaesthesia and Chemotherapeutic Agents Delivery Systems
- Imperial Racing Green
  - Fuel cell powered Student Formula Car
- Aeronautics (EPSRC)
  - (Multiple) Unmanned Air Vehicles – with Cranfield University

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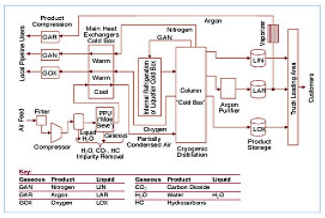
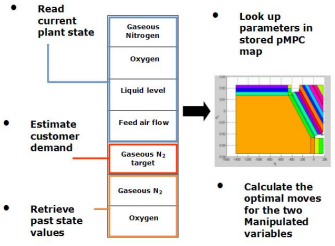
Small Air Separation Units

(Air Products, Mandler et al,2006)



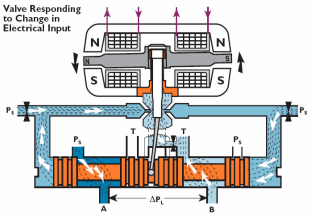


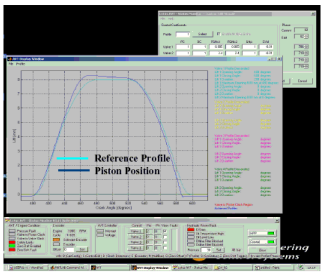
Implementation of lookup operation of pMPC for a small Nitrogen generator.

- Enable advanced MPC for small separation units
  - Optimize performance
  - Minimize operating costs
  - Satisfy product and equipment constraints
- Parametric MPC ideally suited
  - Supervises existing regulatory control
  - Off-line solution with minimum on-line load
  - Runs on existing PLC
  - Rapid installation compared to traditional MPC
- Advantages of Parametric MPC
  - 5% increased throughput
  - 5% less energy usage
  - 90% less waste
  - Installation on PLC in 1-day

Active Valve Train Control

(Lotus Engineering, Kosmidis et al, 2006)





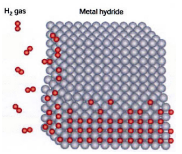
(b) 8mm trapezoidal profile

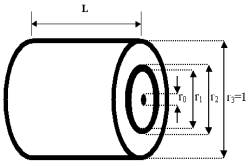
- Active Valve Trains (AVT):
  - Optimum combustion efficiency, Reduced Emissions, Elimination of butterfly valve, Cylinder deactivation, Controlled auto-ignition (CAI), Quieter operation
- Basic idea:
  - Control System sends signal to valve
  - This actuates piston attached to engine valve
  - Enables optimal control of valve timing over entire engine rpm range

Challenges for the AVT control

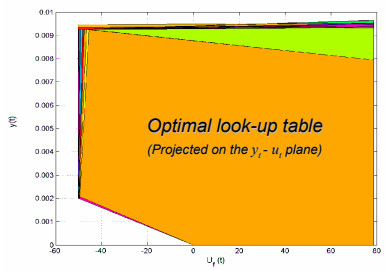
- **Nonlinear system dynamics:** Saturation, flow non-linearity, variation in fluid properties, non-linear opening of the orifices
- **Robustness** to various valve lift profiles
- **Fast dynamics** and sampling times (0.1ms)

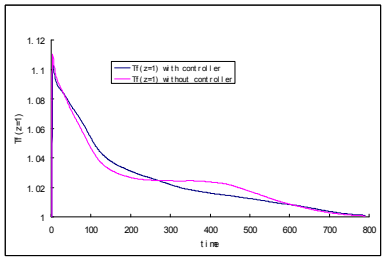
Multi-parametric Control of H_2 Storage in Metal-Hydride Beds *(EU-DIAMANTE, Georgiadis et al, 2008)*





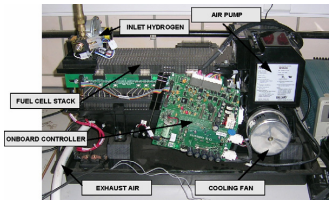
- Tracking the optimal temperature profile
- Ensure economic storage – expressed by the total required storage time
- Satisfy temperature and pressure constraints





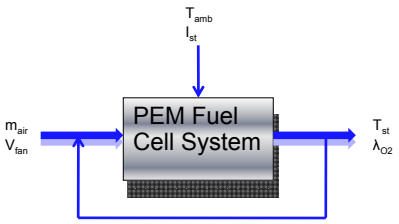
Fuel Cell Systems

- On-going implementation on 1.2kW Ballard PEM Fuel Cell
- Objective is to control oxygen excess ratio and stack temperature
- Controller is implemented on a DSP(digital Signal Processing) board
- Collaborative work with Fuel Cell Control Lab (**University of Seville**)

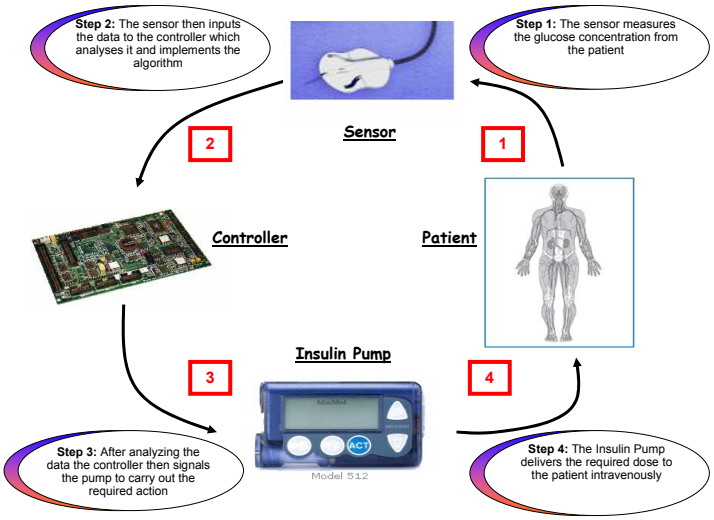


(Alejandro J. Del Real et al. 2007)

u: m_{air}, T_{st}
d: T_{amb}, I_{st}
y: T_{st}, V_{st}
θ: x_t , T_{amb}, I_{st} , T_{st} , V_{st} , $T_{st,sp}$, $V_{st,sp}$



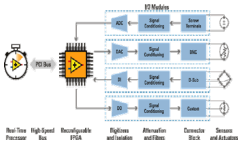
Biomedical Systems *(MOBILE ERC Advanced Grant)*



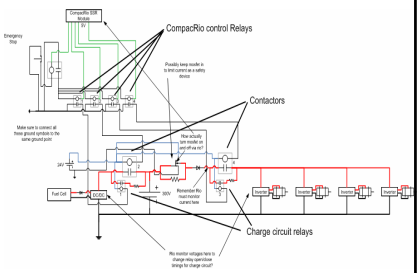
Imperial Racing Green Car

- Student Formula Project
- Control of Start-up/Shut-down of the FC
- Traction Motion Control

FPGA (MPC-on-a-Chip)



Control & Acquisition System



Multi-Parametric Programming & Model Predictive Control – *are they meant for each other?*

YES!

Success stories – generality?

MPC-on-a-chip – Future Directions

- Application types for Multi-parametric Programming & MPC
  - **Type 1** - Large scale and expensive industrial processes with slow/medium dynamics
  - **Type 2** - Medium scale and cost industrial processes with medium/fast dynamics
  - **Type 3** - Small scale and inexpensive processes/equipment with medium/fast dynamics

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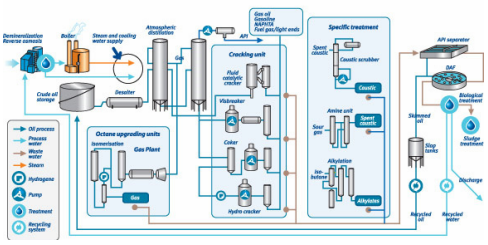
MPC-on-a-chip – Future Directions

- **Type 1** – Large scale and expensive industrial processes with slow/medium dynamics



MPC-on-a-chip – Future Directions

- **Type 1** - Large scale and expensive industrial processes with slow/medium dynamics
  - Control hardware/software availability
  - MPC implementation mainly via online optimization
  - Explicit MPC can play a role for low level process control
  - Hybrid (on-line + off-line) approach possible

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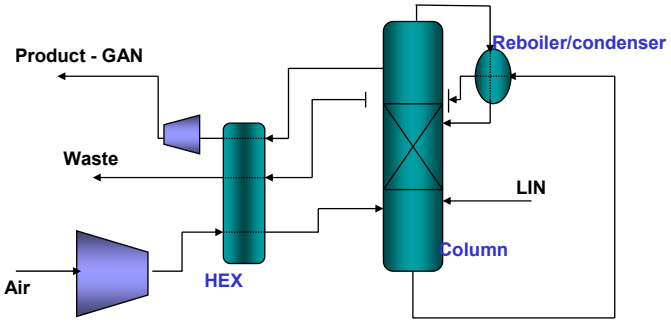
MPC-on-a-chip – Future Directions

- **Type 2** – medium scale and cost industrial processes with medium/fast dynamics



MPC-on-a-chip – Future Directions

- **Type 2** – medium scale and cost industrial processes with medium/fast dynamics
  - Limited Control hardware/software availability
  - Online optimization/MPC usually prohibitive
  - Multi-parametric MPC **ideal** – proved in previous applications (Air Separation, Automotive)

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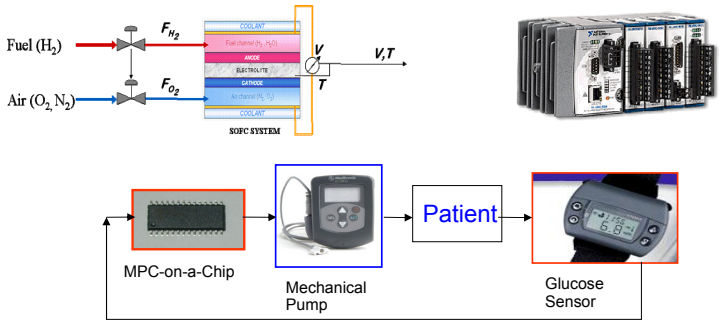
MPC-on-a-chip – Future Directions

- **Type 3** – small scale and inexpensive processes/equipment with medium/fast dynamics



MPC-on-a-chip – Future Directions

- **Type 3** – small scale and inexpensive processes/equipment with medium/fast dynamics
  - Available control hardware/software limited - not suitable for online MPC
  - Multi-parametric MPC technology **essential**
  - MPC-on-a-Chip part of embedded (all-in-one) system
  - Suitable for new technologies (FPGA, wireless)

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Multi-Parametric Programming & Model Predictive Control – *are they meant for each other?*

YES

in most cases (but not for all)

"We owe to our parents our being

and to our teachers our well being"

Alexander the Great

Centre for Process Systems Engineering
Imperial College London

… to our teachers

- Professor Anastasios Karabelas

- Professor Stavros Nychas

THANK YOU!