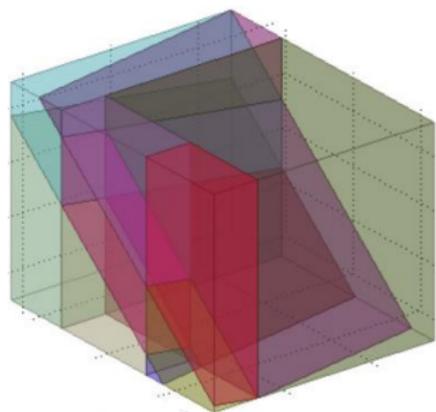


MODEL PREDICTIVE CONTROL

Alberto Bemporad

imt.lu/ab



Course page: http://cse.lab.imtlucca.it/~bemporad/mpc_course.html

COURSE STRUCTURE

- Basic concepts of model predictive control (MPC) and linear MPC
- Linear time-varying and nonlinear MPC
- Quadratic programming (QP) and explicit MPC
- Hybrid MPC, stochastic MPC, data-driven MPC
- Numerical examples (in MATLAB):
 - MPC Toolbox (linear/explicit/parameter-varying MPC)
 - Hybrid Toolbox (explicit MPC, hybrid systems)

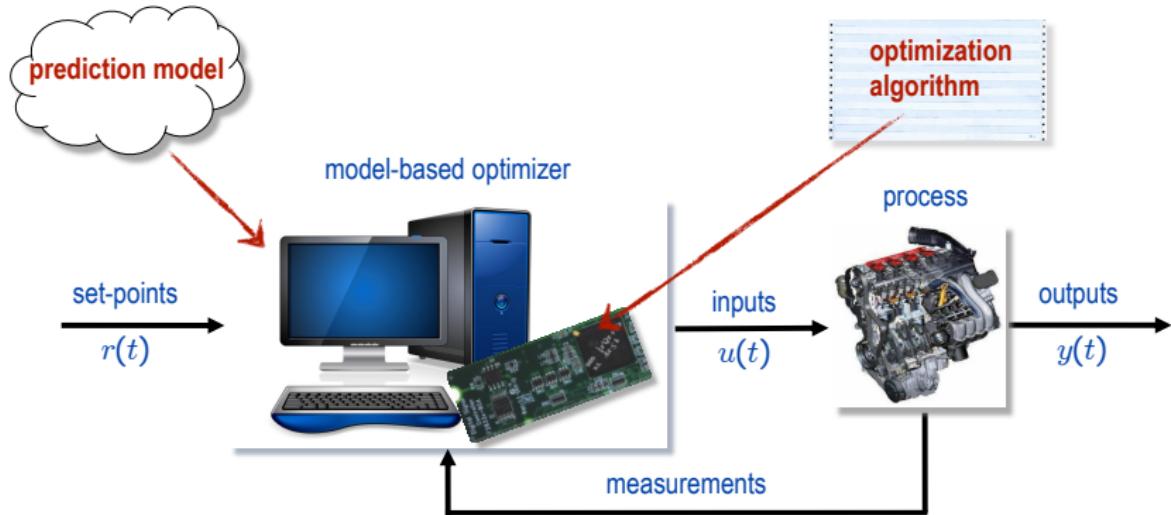
For additional background on linear systems and numerical optimization:

http://cse.lab.imtlucca.it/~bemporad/intro_control_course.html

http://cse.lab.imtlucca.it/~bemporad/optimization_course.html

MODEL PREDICTIVE CONTROL: BASIC CONCEPTS

MODEL PREDICTIVE CONTROL (MPC)



simplified
Use a dynamical model of the process to **predict** its future
evolution and choose the “best” **control action**
likely
a good

MODEL PREDICTIVE CONTROL (MPC)

- Goal: find the best control sequence over a future horizon of N steps

$$\min \sum_{k=0}^{N-1} \|W^y(y_k - r(t))\|_2^2 + \|W^u(u_k - u_r(t))\|_2^2$$

$$\text{s.t. } x_{k+1} = f(x_k, u_k) \quad \text{prediction model}$$

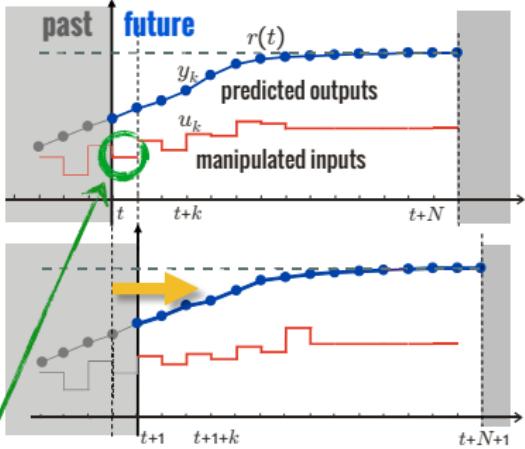
$$y_k = g(x_k)$$

$$u_{\min} \leq u_k \leq u_{\max} \quad \text{constraints}$$

$$y_{\min} \leq y_k \leq y_{\max}$$

$$x_0 = x(t) \quad \text{state feedback}$$

numerical optimization problem



- At each time t :

- get new measurements to update the estimate of the current state $x(t)$
- solve the optimization problem with respect to $\{u_0, \dots, u_{N-1}\}$
- apply only the first optimal move $u(t) = u_0^*$, discard the remaining samples

DAILY-LIFE EXAMPLES OF MPC

- MPC is like playing chess !



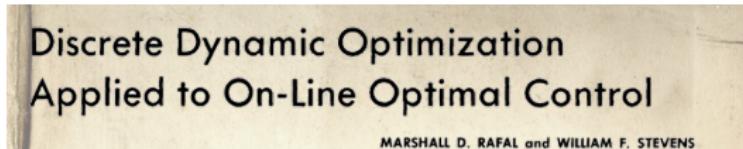
- On-line (event-based) re-planning used in GPS navigation



- You use MPC too when you drive !

MPC IN INDUSTRY

- The MPC concept dates back to the 60's



(Rafal, Stevens, AiChE Journal, 1968)



Том XIV «АВТОМАТИКА И ТЕЛЕМЕХАНИКА» № 7
1963

УДК 62-50

ПРИМЕНЕНИЕ МЕТОДОВ ЛИНЕЙНОГО ПРОГРАММИРОВАНИЯ
ДЛЯ СИНТЕЗА ИМПУЛЬСНЫХ АВТОМАТИЧЕСКИХ
СИСТЕМ

А. И. ПРОПОЙ

USE OF LINEAR PROGRAMMING METHODS
FOR SYNTHESIZING SAMPLED-DATA AUTOMATIC SYSTEMS

A. I. Propoi
Institute of Mathematics and Cybernetics of the Academy of Sciences of the Moldavian SSR
(Moscow) Translated from Avtomatika i Telemekhanika, Vol. 24, No. 7,
Translated from Avtomatika i Telemekhanika, Vol. 24, No. 7,
pp. 912-920, July, 1963
Original article submitted September 24, 1962

(Propoi, 1963)

- MPC used in the process industries since the 80's

(Qin, Badgewell, 2003) (Bauer, Craig, 2008)



©SimulateLive.com

Today APC (advanced process control) = MPC

- Industrial survey of MPC applications conducted in mid 1999

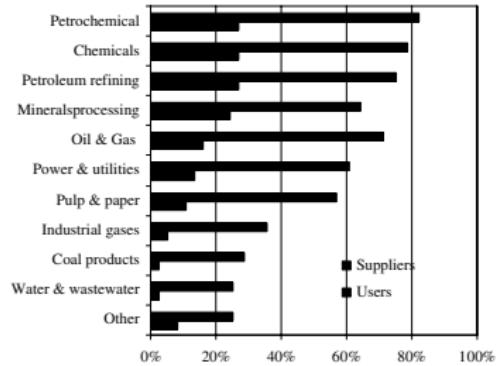
Area	Aspen Technology	Honeywell Hi-Spec	Adersa ^b	Invensys	SGS ^c	Total
Refining	1200	480	280	25		1985
Petrochemicals	450	80	—	20		550
Chemicals	100	20	3	21		144
Pulp and paper	18	50	—	—		68
Air & Gas	—	10	—	—		10
Utility	—	10	—	4		14
Mining/Metallurgy	8	6	7	16		37
Food Processing	—	—	41	10		51
Polymer	17	—	—	—		17
Furnaces	—	—	42	3		45
Aerospace/Defense	—	—	13	—		13
Automotive	—	—	7	—		7
Unclassified	40	40	1045	26	450	1601
Total	1833	696	1438	125	450	4542
First App.	DMC:1985 IDCOM-M:1987 OPC:1987	PCT:1984 RMPCT:1991	IDCOM:1973 HIECON:1986	1984	1985	
Largest App.	603 × 283	225 × 85	—	31 × 12	—	

Estimates based on vendor survey

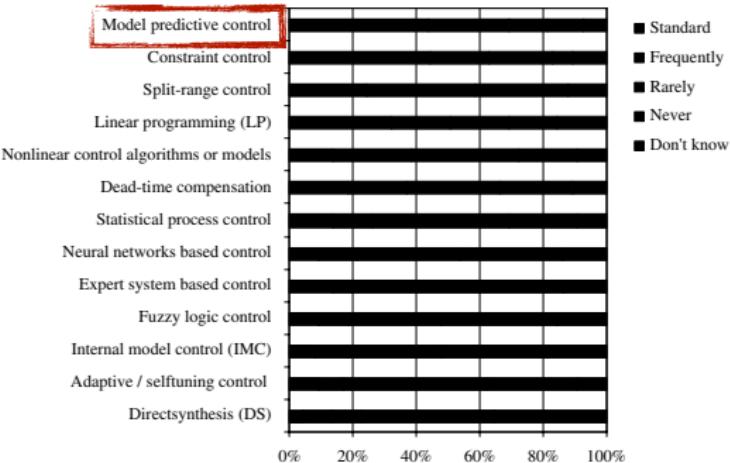
MPC IN INDUSTRY

(Bauer, Craig, 2008)

- Economic assessment of Advanced Process Control (APC)



participants of APC survey by industry (worldwide)



Industrial use of APC methods: survey results

- Impact of advanced control technologies in industry

TABLE 1 A list of the survey results in order of industry impact as perceived by the committee members.

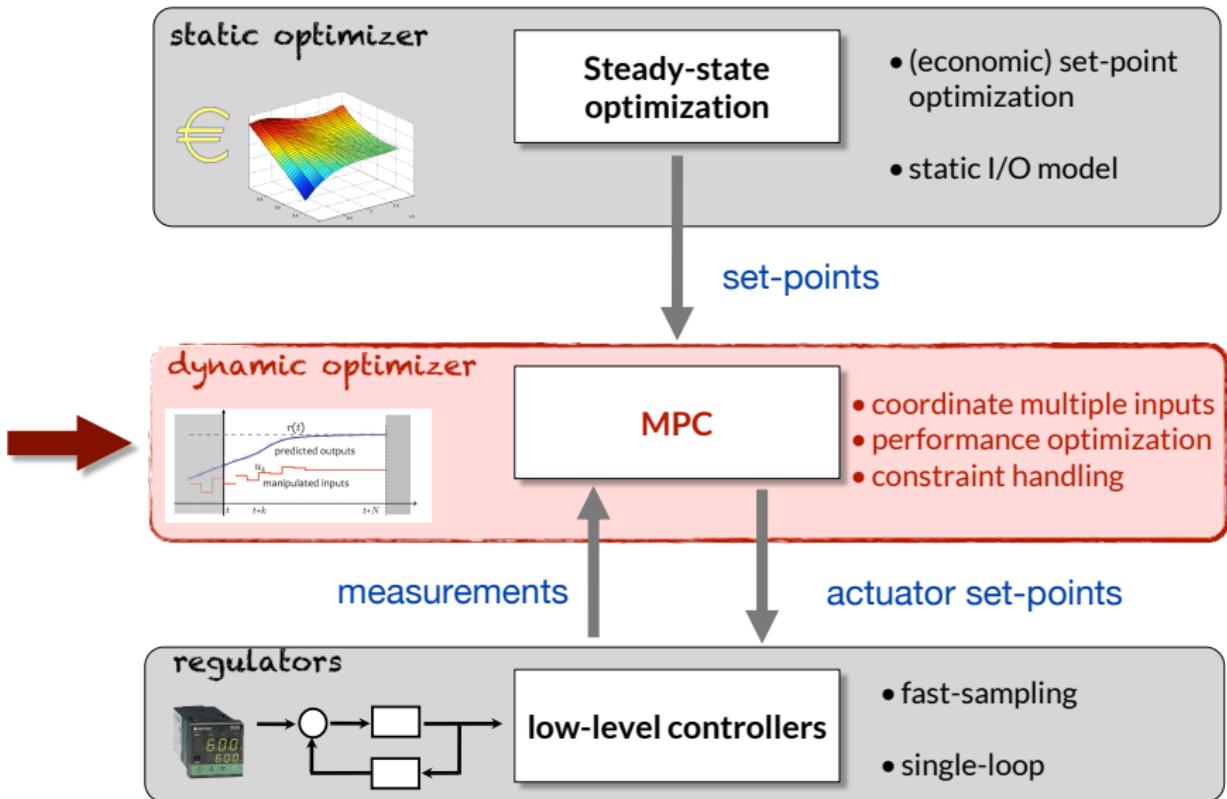
Rank and Technology	High-Impact Ratings	Low- or No-Impact Ratings
PID control	100%	0%
Model predictive control	78%	9%
System identification	61%	9%
Process data analytics	61%	17%
Soft sensing	52%	22%
Fault detection and identification	50%	18%
Decentralized and/or coordinated control	48%	30%
Intelligent control	35%	30%
Discrete-event systems	23%	32%
Nonlinear control	22%	35%
Adaptive control	17%	43%
Robust control	13%	43%
Hybrid dynamical systems	13%	43%

MPC IN INDUSTRY

(Samad, IFAC Newsletter, April 2019)

Control Technology	Current Impact		Future Impact	
	%	High Low/No	High	Low/No
PID control	91%	0%	78%	6%
System Identification	65%	5%	72%	5%
Estimation & filtering	64%	11%	63%	3%
Model-predictive control	62%	11%	85%	2%
Process data analytics	51%	15%	70%	8%
Fault detection & identification	48%	17%	8%	8%
Decentralized and/or coordinated control	29%	33%	54%	11%
Robust control	26%	35%	42%	23%
Intelligent control	24%	38%	5 9%	11%
Nonlinear control	21%	44%	42%	15%
Discrete-event systems	24%	45%	39%	27%
Adaptive control	18%	38%	44%	17%
Repetitive control	12%	74%	17%	51%
Other advanced control technology	11%	64%	25%	39%
Hybrid dynamical systems	11%	68%	33%	33%
Game theory	5%	76%	17%	52%

TYPICAL USE OF MPC



MPC OF AUTOMOTIVE SYSTEMS

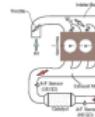
(Bemporad, Bernardini, Borrelli, Cimini, Di Cairano, Esen, Giorgetti, Graf-Plessen, Hrovat, Kolmanovsky, Levijoki, Livshiz, Long, Pattipati, Ripaccioli, Trimboli, Tseng, Verdejo, Yanakiev, ..., 2001-present)

Powertrain

engine control, magnetic actuators, robotized gearbox, power MGT in HEVs, cabin heat control, electrical motors

Vehicle dynamics

traction control, active steering, semiactive suspensions, autonomous driving

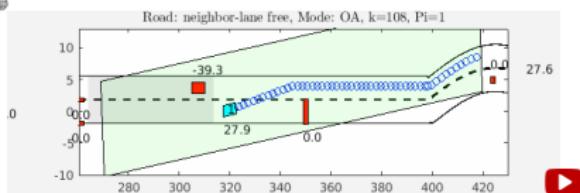


Jaguar

DENSO Automotive

Fiat

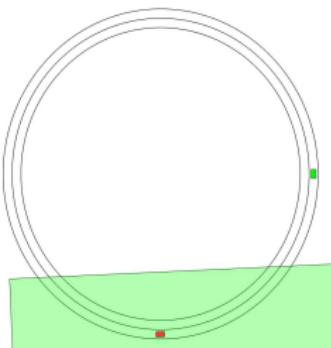
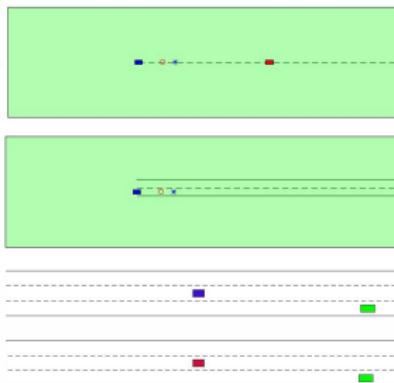
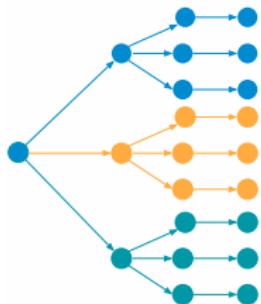
General Motors



Most automotive OEMs are looking into MPC solutions today

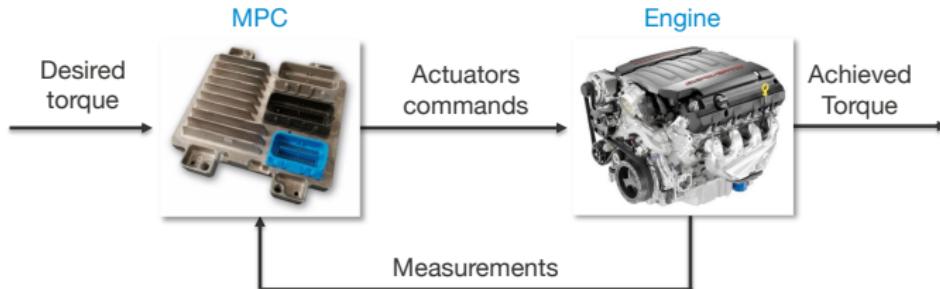
MPC FOR AUTONOMOUS DRIVING

- Coordinate **torque request** and **steering** to achieve **safe and comfortable** autonomous driving with no collisions
- MPC combines **path planning**, **path tracking**, and **obstacle avoidance**
- **Stochastic prediction models** are used to account for uncertainty and driver's behavior



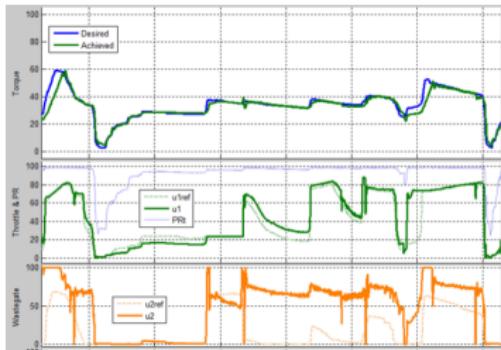
MPC OF GASOLINE TURBOCHARGED ENGINES

- Control **throttle, wastegate, intake & exhaust cams** to make engine torque track set-points, with max efficiency and satisfying **constraints**



numerical optimization problem
solved in real-time on ECU

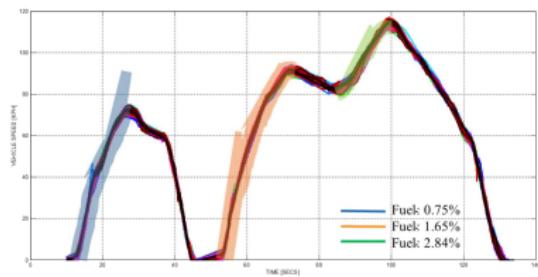
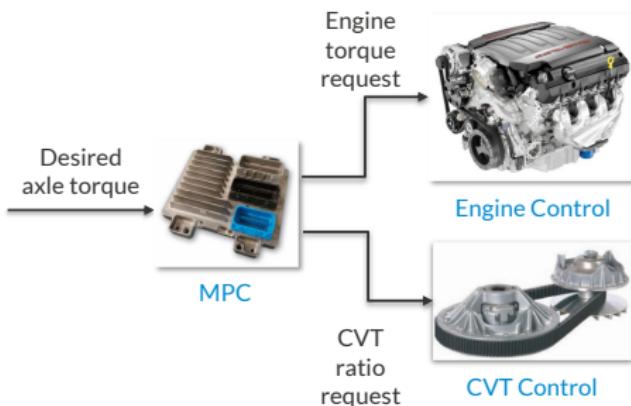
(Bemporad, Bernardini, Long, Verdejo, 2018)



engine operating at low pressure (66 kPa)

SUPERVISORY MPC OF POWERTRAIN WITH CVT

- Coordinate **engine torque request** and continuously variable transmission (CVT) **ratio** to improve fuel economy and drivability
- Real-time MPC is able to take into account **coupled dynamics** and **constraints**, optimizing performance also during transients



US06 Double Hill driving cycle

(Bemporad, Bernardini, Livshiz, Pattipati, 2018)

MPC IN AUTOMOTIVE PRODUCTION

The MPC developed by **General Motors** and **ODYS** for torque tracking in turbocharged gasoline engines **is in high-volume production since 2018**

- Multivariable system, **4 inputs, 4 outputs.**

QP solved **in real time on ECU**

(Bemporad, Bernardini, Long, Verdejo, 2018)

- Supervisory **MPC for powertrain control**

also in production since 2018

(Bemporad, Bernardini, Livshiz, Pattipati, 2018)



First known mass production of MPC in the automotive industry

<http://www.odys.it/odys-and-gm-bring-online-mpc-to-production>

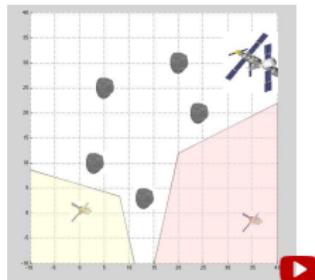
ODYS
Advanced Controls & Optimization

AEROSPACE APPLICATIONS OF MPC

- MPC capabilities explored in new space applications



cooperating UAVs



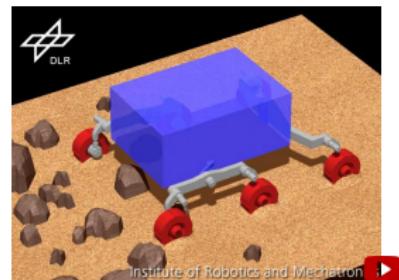
(Bemporad, Rocchi, 2011)

powered descent



(Pascucci, Bennani, Bemporad, 2016)

planetary rover



Institute of Robotics and Mechatronics

(Krenn et. al., 2012)

MPC IN AERONAUTIC INDUSTRY

PRESS RELEASE

Pratt & Whitney's F135 Advanced Multi-Variable Control Team Receives UTC's Prestigious George Mead Award for Outstanding Engineering Accomplishment

EAST HARTFORD, CONN., THURSDAY, **MAY 27, 2010**

Pratt & Whitney engineers Louis Celiberti, Timothy Crowley, James Fuller and Cary Powell won the George Mead Award – United Technologies Corp.'s highest award for outstanding engineering achievement – for their pioneering work in developing the world's first advanced multi-variable control (AMVC) design for the only engine that powers the F-35 Lightning II flight test program. Pratt & Whitney is a United Technologies Corp. (NYSE:UTX) company.

The AMVC, which uses a proprietary model predictive control methodology, is the most technically advanced propulsion system control ever produced by the aerospace industry, demonstrating the highest pilot rating for flight performance and providing independent control of vertical thrust and pitch from five sources. This innovative and industry-leading advanced design is protected with five broad patents for Pratt & Whitney and UTC, and is the new standard for propulsion system control for Pratt & Whitney military and commercial engines.



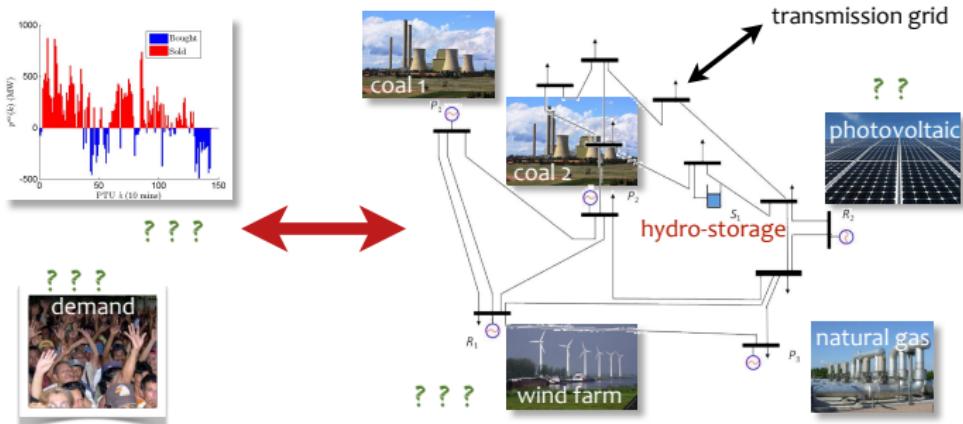
Pratt & Whitney

A United Technologies Company

<http://www.pw.utc.com/Press/Story/20100527-0100/2010>

MPC FOR SMART ELECTRICITY GRIDS

(Patrinos, Trimboli, Bemporad, 2011)



Dispatch power in smart distribution grids, **trade energy** on energy markets

Challenges: account for **dynamics**, network **topology**, physical **constraints**, and **stochasticity** (of renewable energy, demand, electricity prices)

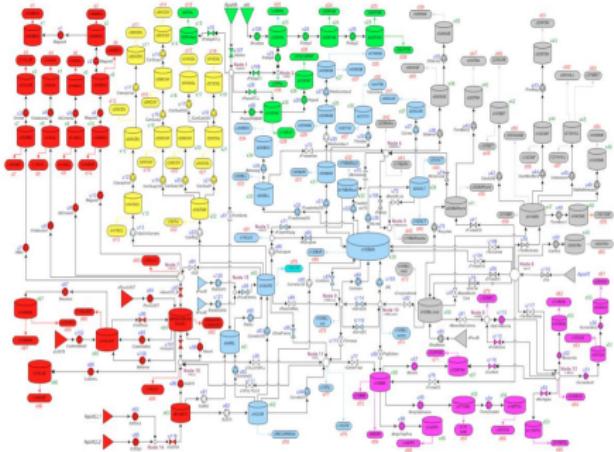
FP7-ICT project "E-PRICE - Price-based Control of Electrical Power Systems"
(2010-2013)

eprice

19/130

MPC OF DRINKING WATER NETWORKS

(Sampathirao, Sopasakis, Bemporad, Patrinos, 2017)



Drinking water
network of
Barcelona:



63 tanks
114 controlled flows
17 mixing nodes

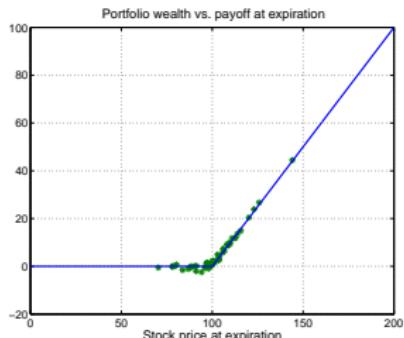
- $\approx 5\%$ savings on energy costs w.r.t. current practice
- Demand and minimum pressure requirements met, smooth control actions
- Computation time: ≈ 20 s on NVIDIA Tesla 2075 CUDA (sample time = 1 hr)

FP7-ICT project "EFFINET - Efficient Integrated Real-time Monitoring and Control of Drinking Water Networks"
(2012-2015)

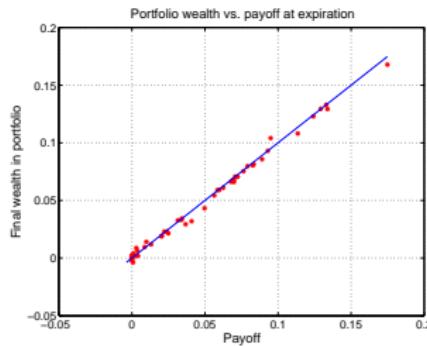
MPC FOR DYNAMIC HEDGING OF FINANCIAL OPTIONS

(Bemporad, Bellucci, Gabbiellini, Quantitative Finance, 2014)

- Goal: find a **dynamic hedging policy** of a portfolio replicating a **synthetic option**, so to **minimize risk** that payoff \neq portfolio wealth at expiration date
- A simple **linear stochastic model** describes the dynamics of **portfolio wealth**
- Stochastic MPC results:



European call



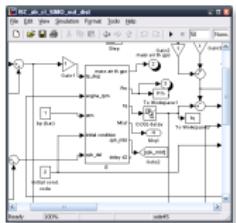
Napoleon cliquet

MPC RESEARCH IS DRIVEN BY APPLICATIONS

- Process control → **linear** MPC (some **nonlinear** too) 1970-2000
- Automotive control → **explicit, hybrid** MPC 2001-2010
- Aerospace systems and UAVs → **linear time-varying** MPC >2005
- Information and Communication Technologies (ICT)
(wireless nets, cloud) → **distributed/decentralized** MPC >2005
- Energy, finance, automotive, water → **stochastic** MPC >2010
- Industrial production → **embedded optimization** solvers for MPC >2010
- Machine learning → **data-driven** MPC today

MPC DESIGN FLOW

High-fidelity simulation model



(simplified) control-oriented prediction model

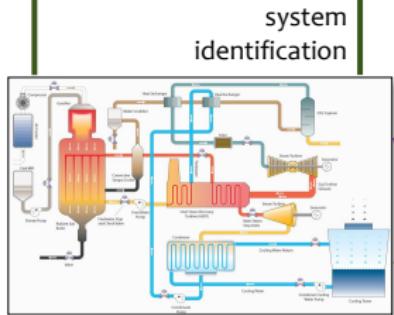
$$u \rightarrow G(z) \rightarrow y$$

performance index & constraints

MPC design

closed-loop simulation

physical modeling + parameter estimation



system identification

revise MPC setup

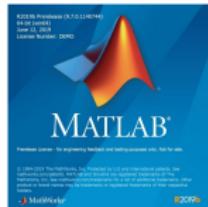
real-time code

```
/* z=A*x0; */  
for (i=0;i<m;i++) {  
    z[i]=A[i]*x[0];  
    for (j=1;j<n;j++) {  
        z[i]+=A[i+m*j]*x[j];  
    }  
}
```

experiments

MPC TOOLBOXES

- **MPC Toolbox** (The Mathworks, Inc.): (Bemporad, Ricker, Morari, 1998-today)
 - Part of Mathworks' official toolbox distribution
 - All written in **MATLAB** code
 - Great for education and research



- **Hybrid Toolbox:** (Bemporad, 2003-today)
 - Free download: <http://cse.lab.imtlucca.it/~bemporad/hybrid/toolbox>
 - Great for research and education
- **ODYS NL-MPC Toolbox:** (ODYS Srl, 2013-present)
 - Very flexible MPC design and **seamless integration** in production
 - Real-time **MPC code** and **QP solver** written in **plain C**
 - Support for nonlinear models
 - Designed and adopted for industrial production

8600+ downloads

1.5 downloads/day



BENEFITS OF MPC

- Long history (decades) of success of MPC in industry
- MPC is a **universal control methodology**:
 - to coordinate **multiple inputs/outputs**, arbitrary **models** (linear, nonlinear, ...)
 - to **optimize performance** under **constraints**
 - intuitive to **design**, easy to **calibrate** and **reconfigure** = **short development time**
- MPC is a mature technology also in fast-sampling applications (e.g. **automotive**)
 - modern ECUs can solve MPC problems in **real-time**
 - advanced MPC **software tools** are available for design/calibration/deployment

Ready to learn how MPC works ?

BASICS OF CONSTRAINED OPTIMIZATION

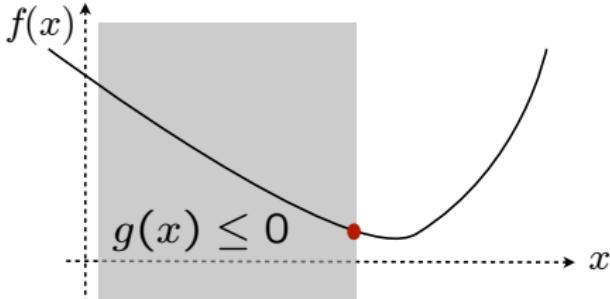
See more in “Numerical Optimization” course

http://cse.lab.imtlucca.it/~bemporad/optimization_course.html

MATHEMATICAL PROGRAMMING

$$\begin{aligned} \min_x \quad & f(x) \\ \text{s.t.} \quad & g(x) \leq 0 \end{aligned}$$

$x \in \mathbb{R}^n, f : \mathbb{R}^n \rightarrow \mathbb{R}, g : \mathbb{R}^n \rightarrow \mathbb{R}^m$



$$x = \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix}, \quad f(x) = f(x_1, x_2, \dots, x_n), \quad g(x) = \begin{bmatrix} g_1(x_1, x_2, \dots, x_n) \\ \vdots \\ g_m(x_1, x_2, \dots, x_n) \end{bmatrix}$$

In general, the problem is difficult to solve → **use software tools**

OPTIMIZATION SOFTWARE

- Comparison on benchmark problems:

<http://plato.la.asu.edu/bench.html>

- Taxonomy of many solvers for different classes of optimization problems:

<http://www.neos-guide.org>

- NEOS server for remotely solving optimization problems:



<http://www.neos-server.org>

- Good open-source optimization software:



<http://www.coin-or.org/>



- GitHub, MATLAB Central



- , Google



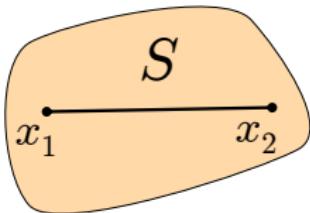
CONVEX SETS

DEFINITION

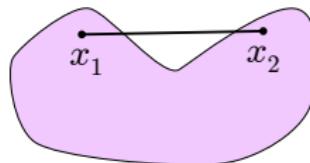
A set $S \subseteq \mathbb{R}^n$ is **convex** if for all $x_1, x_2 \in S$

$$\lambda x_1 + (1 - \lambda)x_2 \in S, \forall \lambda \in [0, 1]$$

convex set



nonconvex set



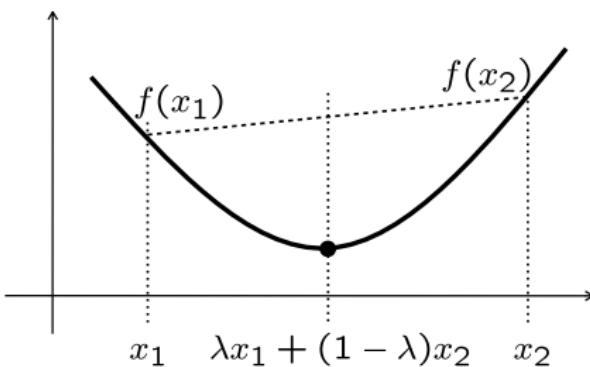
CONVEX FUNCTIONS

DEFINITION

$f : S \rightarrow \mathbb{R}$ is a **convex function** if S is convex and

$$f(\lambda x_1 + (1 - \lambda)x_2) \leq \lambda f(x_1) + (1 - \lambda)f(x_2)$$
$$\forall x_1, x_2 \in S, \lambda \in [0, 1]$$

Jensen's inequality

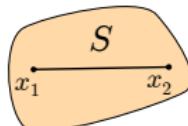
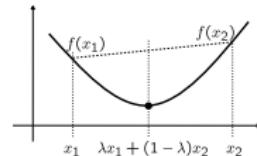


CONVEX OPTIMIZATION PROBLEM

The optimization problem

$$\begin{array}{ll} \min & f(x) \\ \text{s.t.} & x \in S \end{array}$$

is a **convex optimization problem** if S is a convex set
and $f : S \rightarrow \mathbb{R}$ is a convex function



- Often S is defined by **linear equality constraints** $Ax = b$ and **convex inequality constraints** $g(x) \leq 0$, $g : \mathbb{R}^n \rightarrow \mathbb{R}^m$ convex
- Every local solution is also a global one (we will see this later)
- Efficient solution algorithms exist
- Often occurring in many problems in engineering, economics, and science

Excellent textbook: "Convex Optimization" (Boyd, Vandenberghe, 2002)

POLYHEDRA

DEFINITION

Convex **polyhedron** = intersection of a finite set of half-spaces of \mathbb{R}^n

Convex **polytope** = bounded convex polyhedron

- **Hyperplane (H-)representation:**

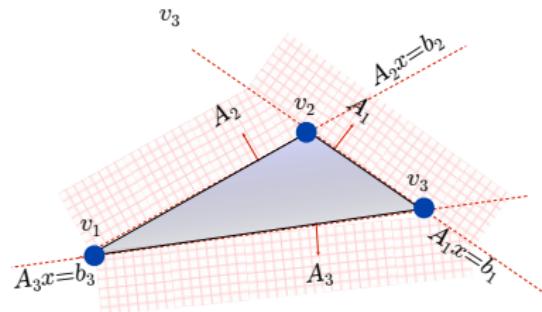
$$P = \{x \in \mathbb{R}^n : Ax \leq b\}$$

- **Vertex (V-)representation:**

$$P = \{x \in \mathbb{R}^n : x = \sum_{i=1}^q \alpha_i v_i + \sum_{j=1}^p \beta_j r_j\}$$

$$\alpha_i, \beta_j \geq 0, \sum_{i=1}^q \alpha_i = 1, v_i, r_j \in \mathbb{R}^n$$

when $q = 0$ the polyhedron is a **cone**



Convex hull = transformation from V- to H-representation

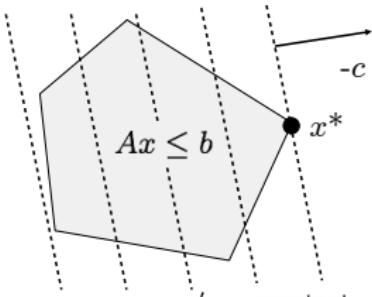
Vertex enumeration = transformation from H- to V-representation

v_i = **vertex**, r_j = **extreme ray**

LINEAR PROGRAMMING

- Linear programming (LP) problem:

$$\begin{aligned} \min \quad & c'x \\ \text{s.t.} \quad & Ax \leq b, x \in \mathbb{R}^n \end{aligned}$$



George Dantzig
(1914–2005)

- LP in standard form:

$$\begin{aligned} \min \quad & c'x \\ \text{s.t.} \quad & Ax = b \\ & x \geq 0, x \in \mathbb{R}^n \end{aligned}$$

- Conversion to standard form by introducing slack variables

$$\begin{cases} \sum_{j=1}^n a_{ij}x_j \leq b_i \\ x_j \geq 0 \end{cases} \Rightarrow \begin{cases} \sum_{j=1}^n a_{ij}x_j + s_i = b_i \\ s_i, x_j \geq 0 \end{cases}$$

- Nonnegative variables by splitting positive and negative part of x

$$\begin{cases} \sum_{j=1}^n a_{ij}x_j = b_i \\ x_j \text{ free} \end{cases} \Rightarrow \begin{cases} \sum_{j=1}^n a_{ij}(x_j^+ - x_j^-) = b_i \\ x_j^+, x_j^- \geq 0 \end{cases}$$

LINEAR PROGRAMMING (LP)

- Converting maximization to minimization

$$\max_x c'x = -(\min_x -c'x) \quad (\text{more generally: } \max_x f(x) = -\min_x \{-f(x)\})$$

- Equalities to double inequalities (not recommended)

$$\sum_{j=1}^n a_{ij}x_j = b_i \Rightarrow \begin{cases} \sum_{j=1}^n a_{ij}x_j \leq b_i \\ \sum_{j=1}^n a_{ij}x_j \geq b_i \end{cases}$$

- Change direction of an inequality

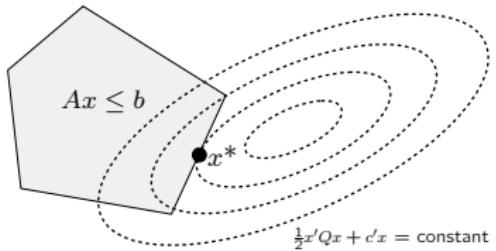
$$\sum_{j=1}^n a_{ij}x_j \geq b_i \Rightarrow \sum_{j=1}^n -a_{ij}x_j \leq -b_i$$

An LP can be always formulated using “min” and “ \leq ”

QUADRATIC PROGRAMMING (QP)

- Quadratic programming (QP) problem:

$$\begin{aligned} \min \quad & \frac{1}{2} x' Q x + c' x \\ \text{s.t.} \quad & A x \leq b, x \in \mathbb{R}^n \end{aligned}$$



- Convex optimization problem if $Q \succeq 0$ (Q = positive semidefinite matrix)¹
- Hard problem if $Q \not\succeq 0$ (Q = indefinite matrix)
- Without loss of generality we can assume $Q = Q'$ as

$$x' Q x = x' \left(\frac{Q+Q'}{2} + \frac{Q-Q'}{2} \right) x = x' \frac{Q+Q'}{2} x + \frac{1}{2} x' Q x - \left(\frac{1}{2} x' Q' x \right)' = x' \frac{Q+Q'}{2} x$$

¹A matrix $P \in \mathbb{R}^{n \times n}$ is **positive semidefinite** ($P \succeq 0$) if $x' P x \geq 0$ for all x .

It is **positive definite** ($P \succ 0$) if in addition $x' P x > 0$ for all $x \neq 0$.

It is **negative (semi)definite** ($P \prec 0, P \preceq 0$) if $-P$ is positive (semi)definite.

It is **indefinite** otherwise.

MIXED-INTEGER PROGRAMMING (MIP)

$$\begin{array}{ll}\text{min} & c'x \\ \text{s.t.} & Ax \leq b, x = \begin{bmatrix} x_c \\ x_b \end{bmatrix} \\ & x_c \in \mathbb{R}^{n_c}, x_b \in \{0, 1\}^{n_b}\end{array}$$

mixed-integer linear program (MILP)

$$\begin{array}{ll}\text{min} & \frac{1}{2} x' Q x + c' x \\ \text{s.t.} & Ax \leq b, x = \begin{bmatrix} x_c \\ x_b \end{bmatrix} \\ & x_c \in \mathbb{R}^{n_c}, x_b \in \{0, 1\}^{n_b}\end{array}$$

mixed-integer quadratic program (MIQP)

- Some variables are real, some are binary (0/1)
- A \mathcal{NP} -hard problem, in general
- Many good solvers are available (CPLEX, Gurobi, GLPK, Xpress-MP, CBC, ...)
For comparisons see <http://plato.la.asu.edu/bench.html>

MODELING LANGUAGES FOR OPTIMIZATION PROBLEMS

- **AMPL** (A Modeling Language for Mathematical Programming) most used modeling language, supports several solvers
- **OPL** (Optimization Programming Language), associated with commercial package IBM-CPLEX
- **MOSEL** associated with commercial package FICO Xpress
- **GAMS** (General Algebraic Modeling System) is one of the first modeling languages
- **LINGO** modeling language of Lindo Systems Inc.
- **GNU MathProg** a subset of AMPL associated with the free package GLPK (GNU Linear Programming Kit)

MODELING LANGUAGES FOR OPTIMIZATION PROBLEMS

- **YALMIP** MATLAB-based modeling language
- **CVX (CVXPY)** Modeling language for convex problems in MATLAB ( python)
- **CASADI + IPOPT** Nonlinear modeling + automatic differentiation, nonlinear programming solver (MATLAB,  python, C++)
- **Optimization Toolbox**' modeling language (part of MATLAB since R2017b)
- **PYOMO**  python-based modeling language
- **PuLP** A linear programming modeler for  python
- **JuMP** A modeling language for linear, quadratic, and nonlinear constrained optimization problems embedded in 

LINEAR MPC

LINEAR MPC - UNCONSTRAINED CASE

- Linear prediction model

$$\begin{cases} x_{k+1} = Ax_k + Bu_k \\ y_k = Cx_k \end{cases}$$

$$\begin{aligned} x &\in \mathbb{R}^n \\ u &\in \mathbb{R}^m \\ y &\in \mathbb{R}^p \end{aligned}$$

Notation:

$$\begin{aligned} x_0 &= x(t) \\ x_k &= x(t+k|t) \\ u_k &= u(t+k|t) \end{aligned}$$

- Relation between input and states: $x_k = A^k x_0 + \sum_{j=0}^{k-1} A^j B u_{k-1-j}$
- Performance index

$$J(z, x_0) = x_N' P x_N + \sum_{k=0}^{N-1} x_k' Q x_k + u_k' R u_k$$

$$\begin{aligned} R &= R' \succ 0 \\ Q &= Q' \succeq 0 \\ P &= P' \succeq 0 \end{aligned} \quad z = \begin{bmatrix} u_0 \\ u_1 \\ \vdots \\ u_{N-1} \end{bmatrix}$$

- **Goal:** find the sequence z^* that minimizes $J(z, x_0)$, i.e., that steers the state x to the origin optimally

COMPUTATION OF COST FUNCTION

$$\begin{aligned}
 J(z, x_0) &= x_0' Q x_0 + \underbrace{\left[\begin{array}{c} x_1 \\ x_2 \\ \vdots \\ x_{N-1} \\ x_N \end{array} \right]'}_{\bar{Q}} \left[\begin{array}{ccccc} Q & 0 & 0 & \dots & 0 \\ 0 & Q & 0 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & \dots & 0 & Q & 0 \\ 0 & 0 & \dots & 0 & P \end{array} \right] \left[\begin{array}{c} x_1 \\ x_2 \\ \vdots \\ x_{N-1} \\ x_N \end{array} \right] \\
 &\quad + \underbrace{\left[\begin{array}{c} u_0 \\ u_1 \\ \vdots \\ u_{N-1} \end{array} \right]'}_{\bar{R}} \left[\begin{array}{cccc} R & 0 & \dots & 0 \\ 0 & R & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & \dots & 0 & R \end{array} \right] \left[\begin{array}{c} u_0 \\ u_1 \\ \vdots \\ u_{N-1} \end{array} \right] \\
 \left[\begin{array}{c} x_1 \\ x_2 \\ \vdots \\ x_N \end{array} \right] &= \underbrace{\left[\begin{array}{cccc} B & 0 & \dots & 0 \\ AB & B & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ A^{N-1}B & A^{N-2}B & \dots & B \end{array} \right]}_{\bar{S}} \underbrace{\left[\begin{array}{c} u_0 \\ u_1 \\ \vdots \\ u_{N-1} \end{array} \right]}_z + \underbrace{\left[\begin{array}{c} A \\ A^2 \\ \vdots \\ A^N \end{array} \right]}_{\bar{T}} x_0
 \end{aligned}$$

$$\begin{aligned}
 J(z, x_0) &= (\bar{S}z + \bar{T}x_0)' \bar{Q} (\bar{S}z + \bar{T}x_0) + z' \bar{R} z + x_0' Q x_0 \\
 &= \frac{1}{2} z' \underbrace{2(\bar{R} + \bar{S}' \bar{Q} \bar{S})}_H z + x_0' \underbrace{2\bar{T}' \bar{Q} \bar{S}}_{F'} z + \frac{1}{2} x_0' \underbrace{2(Q + \bar{T}' \bar{Q} \bar{T})}_Y x_0
 \end{aligned}$$

LINEAR MPC - UNCONSTRAINED CASE

$$J(z, x_0) = \frac{1}{2} z' H z + x_0' F' z + \frac{1}{2} x_0' Y x_0$$

$$z = \begin{bmatrix} u_0 \\ u_1 \\ \vdots \\ u_{N-1} \end{bmatrix}$$

condensed
form of MPC

- The optimum is obtained by zeroing the gradient

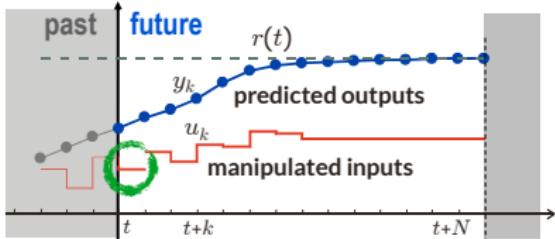
$$\nabla_z J(z, x_0) = Hz + Fx_0 = 0$$

and hence $z^* = \begin{bmatrix} u_0^* \\ u_1^* \\ \vdots \\ u_{N-1}^* \end{bmatrix} = -H^{-1}F x_0$ ("batch" solution)

- Alternative #1: find z^* via **dynamic programming** (Riccati iterations)
- Alternative #2: keep also x_1, \dots, x_N as optimization variables and the equality constraints $x_{k+1} = Ax_k + Bu_k$ (**non-condensed form**, which is very **sparse**)

UNCONSTRAINED LINEAR MPC ALGORITHM

@ each sampling step t :



- Minimize quadratic function (no constraints)

$$\min_z f(z) = \frac{1}{2} z' H z + \mathbf{x}'(t) F' z \quad z = \begin{bmatrix} u_0 \\ u_1 \\ \vdots \\ u_{N-1} \end{bmatrix}$$

- solution: $\nabla f(z) = Hz + F\mathbf{x}(t) = 0 \Rightarrow z^* = -H^{-1}F\mathbf{x}(t)$

$$\rightarrow u(t) = - \begin{bmatrix} I & 0 & \dots & 0 \end{bmatrix} H^{-1} F \mathbf{x}(t) = K \mathbf{x}(t)$$

unconstrained linear MPC = linear state-feedback!

CONSTRAINED LINEAR MPC

- Linear prediction model:
$$\begin{cases} x_{k+1} &= Ax_k + Bu_k \\ y_k &= Cx_k \end{cases} \quad \begin{array}{l} x \in \mathbb{R}^n \\ u \in \mathbb{R}^m \\ y \in \mathbb{R}^p \end{array}$$

- Constraints to enforce:

$$\begin{cases} u_{\min} \leq u(t) \leq u_{\max} \\ y_{\min} \leq y(t) \leq y_{\max} \end{cases} \quad \begin{array}{l} u_{\min}, u_{\max} \in \mathbb{R}^m \\ y_{\min}, y_{\max} \in \mathbb{R}^p \end{array}$$

- Constrained optimal control problem (quadratic performance index):

$$\begin{aligned} \min_z \quad & x'_N Px_N + \sum_{k=0}^{N-1} x'_k Q x_k + u'_k R u_k \\ \text{s.t.} \quad & u_{\min} \leq u_k \leq u_{\max}, \quad k = 0, \dots, N-1 \\ & y_{\min} \leq y_k \leq y_{\max}, \quad k = 1, \dots, N \end{aligned} \quad \begin{array}{lcl} R &=& R' \succ 0 \\ Q &=& Q' \succeq 0 \\ P &=& P' \succeq 0 \end{array} \quad z = \begin{bmatrix} u_0 \\ u_1 \\ \vdots \\ u_{N-1} \end{bmatrix}$$

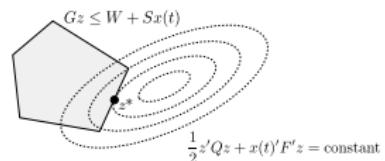
CONSTRAINED LINEAR MPC

- Linear prediction model: $x_k = A^k x_0 + \sum_{i=0}^{k-1} A^i B u_{k-1-i}$
- Optimization problem (condensed form):

$$V(x_0) = \frac{1}{2} x_0' Y x_0 + \min_z \quad \frac{1}{2} z' H z + x_0' F' z \quad (\text{quadratic objective})$$
$$\text{s.t.} \quad Gz \leq W + Sx_0 \quad (\text{linear constraints})$$

convex Quadratic Program (QP)

- $z = \begin{bmatrix} u_0 \\ u_1 \\ \vdots \\ u_{N-1} \end{bmatrix} \in \mathbb{R}^{Nm}$ is the optimization vector
- $H = H' \succ 0$, and H, F, Y, G, W, S depend on weights Q, R, P upper and lower bounds $u_{\min}, u_{\max}, y_{\min}, y_{\max}$ and model matrices A, B, C .



COMPUTATION OF CONSTRAINT MATRICES

- Input constraints $u_{\min} \leq u_k \leq u_{\max}, k = 0, \dots, N - 1$

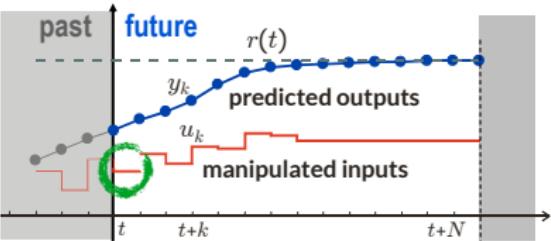
$$\left\{ \begin{array}{l} u_k \leq u_{\max} \\ -u_k \leq -u_{\min} \end{array} \right. \quad \xrightarrow{\hspace{1cm}} \quad \begin{bmatrix} 1 & 0 & \dots & 0 \\ 0 & 1 & \dots & 0 \\ \vdots & & \ddots & \vdots \\ 0 & \dots & 0 & 1 \\ -1 & 0 & \dots & 0 \\ 0 & -1 & \dots & 0 \\ \vdots & & \ddots & \vdots \\ 0 & \dots & 0 & -1 \end{bmatrix} z \leq \begin{bmatrix} u_{\max} \\ u_{\max} \\ \vdots \\ u_{\max} \\ -u_{\min} \\ -u_{\min} \\ \vdots \\ -u_{\min} \end{bmatrix} \quad z = \begin{bmatrix} u_0 \\ u_1 \\ \vdots \\ u_{N-1} \end{bmatrix}$$

- Output constraints $y_k = CA^k x_0 + \sum_{i=0}^{k-1} CA^i Bu_{k-1-i} \leq y_{\max}, k = 1, \dots, N$

$$\begin{bmatrix} CB & 0 & \dots & 0 \\ CAB & CB & \dots & 0 \\ \vdots & & & \vdots \\ CA^{N-1}B & \dots & CAB & CB \end{bmatrix} z \leq \begin{bmatrix} y_{\max} \\ y_{\max} \\ \vdots \\ y_{\max} \end{bmatrix} - \begin{bmatrix} CA \\ CA^2 \\ \vdots \\ CA^N \end{bmatrix} x_0$$

LINEAR MPC ALGORITHM

@ each sampling step t :



- Measure (or estimate) the current state $x(t)$

- Get the solution $z^* = \begin{bmatrix} u_0^* \\ u_1^* \\ \vdots \\ u_{N-1}^* \end{bmatrix}$ of the QP

$$\left\{ \begin{array}{ll} \min_z & \frac{1}{2} z' H z + \underbrace{x'(t) F' z}_{\text{feedback}} \\ \text{s.t.} & G z \leq W + S \underbrace{x(t)}_{\text{feedback}} \end{array} \right.$$

- Apply only $u(t) = u_0^*$, discarding the remaining optimal inputs u_1^*, \dots, u_{N-1}^*

DOUBLE INTEGRATOR EXAMPLE

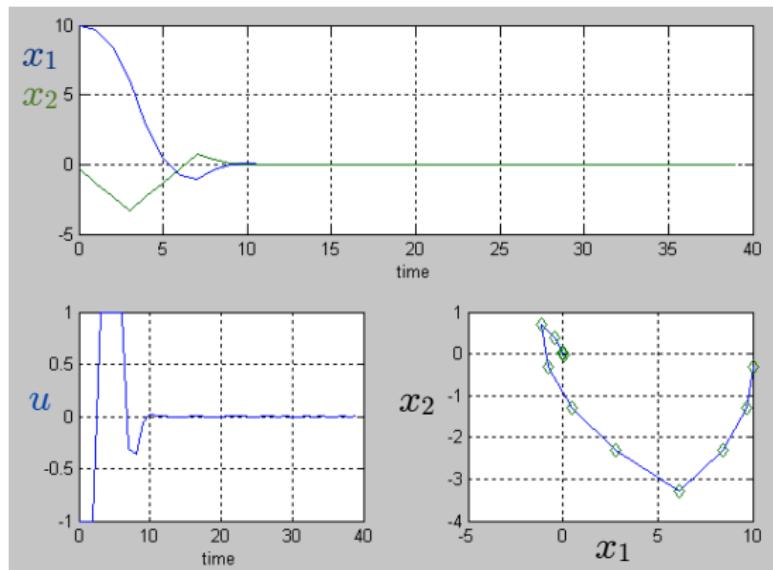
- System: $x_2(t) = x_2(0) + \sum_{k=0}^{t-1} u(t), y(t) = x_1(0) + \sum_{k=0}^{t-1} x_2(t)$
- Sample time: $T_s = 1 \text{ s}$
- State-space realization:
$$\begin{cases} x(t+1) &= [\begin{smallmatrix} 1 & 1 \\ 0 & 1 \end{smallmatrix}] x(t) + [\begin{smallmatrix} 0 \\ 1 \end{smallmatrix}] u(t) \\ y(t) &= [\begin{smallmatrix} 1 & 0 \end{smallmatrix}] x(t) \end{cases}$$
- Constraints: $-1 \leq u(t) \leq 1$
- Performance index: $\min \left(\sum_{k=0}^1 y_k^2 + \frac{1}{10} u_k^2 \right) + x'_2 [\begin{smallmatrix} 1 & 0 \\ 0 & 1 \end{smallmatrix}] x_2$
- QP matrices:

cost: $\frac{1}{2} z' H z + x'(t) F' z + \frac{1}{2} x'(t) Y x(t)$

constraints: $Gz \leq W + Sx(t)$

$$H = \begin{bmatrix} 4.2 & 2 \\ 2 & 2.2 \end{bmatrix}, F = \begin{bmatrix} 2 & 6 \\ 0 & 2 \end{bmatrix}$$
$$Y = \begin{bmatrix} 4 & 6 \\ 6 & 12 \end{bmatrix}, G = \begin{bmatrix} 1 & 0 \\ -1 & 0 \\ 0 & 1 \\ 0 & -1 \end{bmatrix}$$
$$W = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}, S = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

DOUBLE INTEGRATOR EXAMPLE



go to demo linear/doubleint.m (Hybrid Toolbox)
(see also mpcdoubleint.m in MPC Toolbox)

DOUBLE INTEGRATOR EXAMPLE

- Add constraint on second state at prediction time $t + 1$:

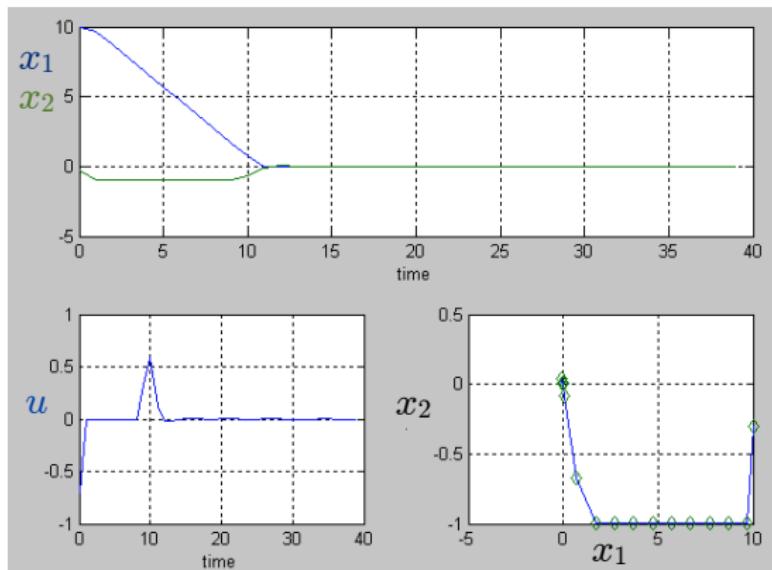
$$x_{2,k} \geq -1, k = 1$$

- New QP matrices:

$$H = \begin{bmatrix} 4.2 & 2 \\ 2 & 2.2 \end{bmatrix}, F = \begin{bmatrix} 2 & 6 \\ 0 & 2 \end{bmatrix}, Y = \begin{bmatrix} 4 & 6 \\ 6 & 12 \end{bmatrix}$$

$$G = \begin{bmatrix} -1 & 0 \\ 1 & 0 \\ -1 & 0 \\ 0 & 1 \\ 0 & -1 \end{bmatrix}, W = \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix}, S = \begin{bmatrix} 0 & 1 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

DOUBLE INTEGRATOR EXAMPLE



LINEAR MPC - TRACKING

- Objective: make the output $y(t)$ track a reference signal $r(t)$
- Let us parameterize the problem using the **input increments**

$$\Delta u(t) = u(t) - u(t-1)$$

- As $u(t) = u(t-1) + \Delta u(t)$ we need to extend the system with a new state $x_u(t) = u(t-1)$

$$\begin{cases} x(t+1) &= Ax(t) + Bu(t-1) + B\Delta u(t) \\ x_u(t+1) &= x_u(t) + \Delta u(t) \end{cases}$$

$$\begin{cases} \begin{bmatrix} x(t+1) \\ x_u(t+1) \end{bmatrix} &= \begin{bmatrix} A & B \\ 0 & I \end{bmatrix} \begin{bmatrix} x(t) \\ x_u(t) \end{bmatrix} + \begin{bmatrix} B \\ I \end{bmatrix} \Delta u(t) \\ y(t) &= \begin{bmatrix} C & 0 \end{bmatrix} \begin{bmatrix} x(t) \\ x_u(t) \end{bmatrix} \end{cases}$$

- Again a linear system with states $x(t), x_u(t)$ and input $\Delta u(t)$

LINEAR MPC - TRACKING

- Optimal control problem (quadratic performance index):

$$\begin{aligned} \min_z \quad & \sum_{k=0}^{N-1} \|W^y(y_{k+1} - r(t))\|_2^2 + \|W^{\Delta u} \Delta u_k\|_2^2 \\ \text{s.t.} \quad & [\Delta u_k \triangleq u_k - u_{k-1}], u_{-1} = u(t-1) \\ & u_{\min} \leq u_k \leq u_{\max}, k = 0, \dots, N-1 \\ & y_{\min} \leq y_k \leq y_{\max}, k = 1, \dots, N \\ & \Delta u_{\min} \leq \Delta u_k \leq \Delta u_{\max}, k = 0, \dots, N-1 \end{aligned}$$

$$z = \begin{bmatrix} \Delta u_0 \\ \Delta u_1 \\ \vdots \\ \Delta u_{N-1} \end{bmatrix} \text{ or } z = \begin{bmatrix} u_0 \\ u_1 \\ \vdots \\ u_{N-1} \end{bmatrix}$$

weight W^\cdot = diagonal matrix (more generally, Cholesky factor of
 $Q^\cdot = (W^\cdot)' W^\cdot$)

$$\min_z \quad J(z, x(t)) = \frac{1}{2} z' H z + [x'(t) \ r'(t) \ u'(t-1)] F' z$$

$$\text{s.t.} \quad Gz \leq W + S \begin{bmatrix} x(t) \\ r(t) \\ u(t-1) \end{bmatrix}$$

convex
Quadratic
Program

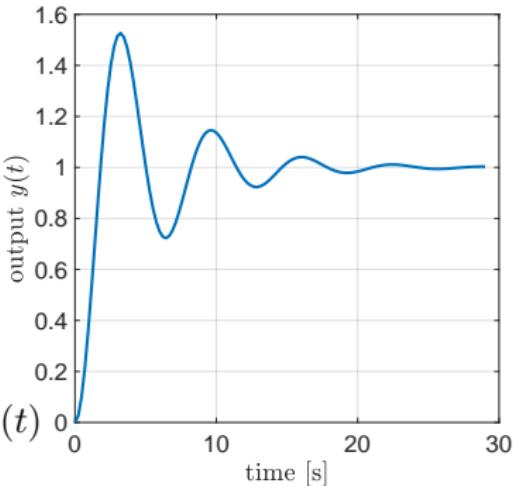
- Add the extra penalty $\|W^u(u_k - u_{\text{ref}}(t))\|_2^2$ to track **input references**
- Constraints may depend on $r(t)$, such as $e_{\min} \leq y_k - r(t) \leq e_{\max}$

LINEAR MPC TRACKING EXAMPLE

- System: $y(t) = \frac{1}{s^2+0.4s+1} u(t)$
(or equivalently $\frac{d^2y}{dt^2} + 0.4\frac{dy}{dt} + y = u$)

- Sampling with period $T_s = 0.5$ s:

$$\begin{cases} x(t+1) &= \begin{bmatrix} 1.597 & -0.8187 \\ 1 & 0 \end{bmatrix} x(t) + \begin{bmatrix} 0.5 \\ 0 \end{bmatrix} u(t) \\ y(t) &= \begin{bmatrix} 0.2294 & 0.2145 \end{bmatrix} x(t) \end{cases}$$

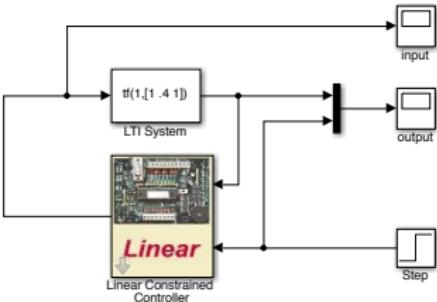


go to demo linear/example3.m (Hybrid Toolbox)

LINEAR MPC TRACKING EXAMPLE

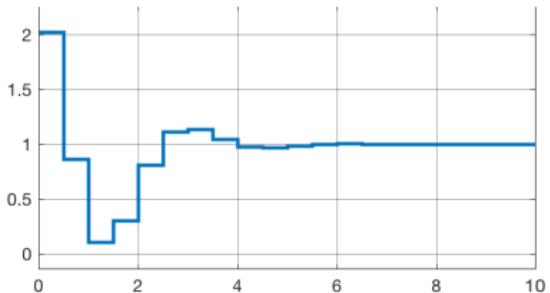
- Performance index:

$$\min \sum_{k=0}^9 (y_{k+1} - r(t))^2 + 0.04\Delta u_k^2$$

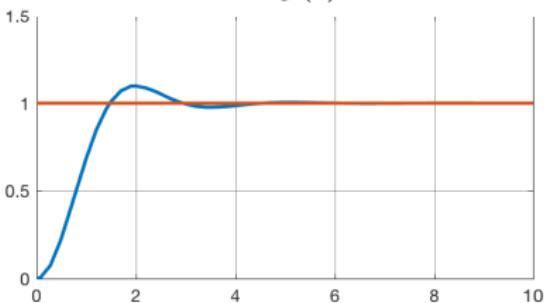


- Closed-loop MPC results:

$u(t)$

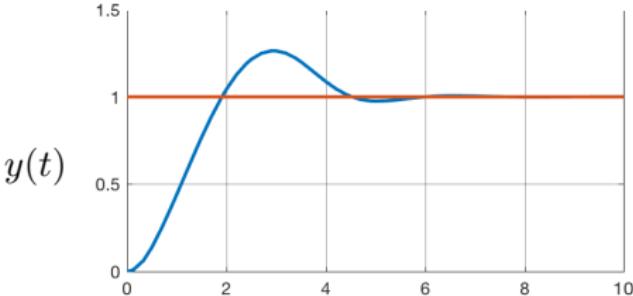
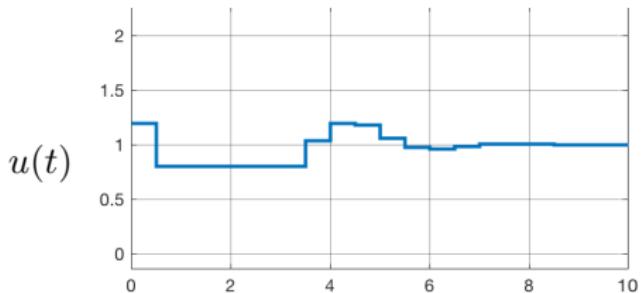


$y(t)$

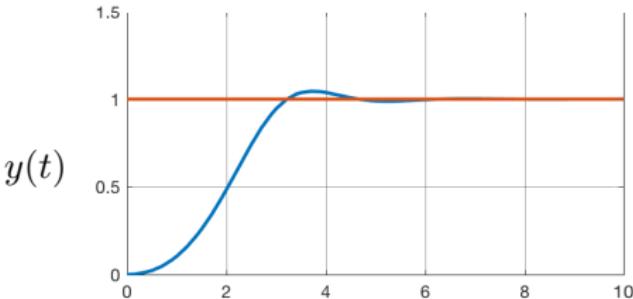
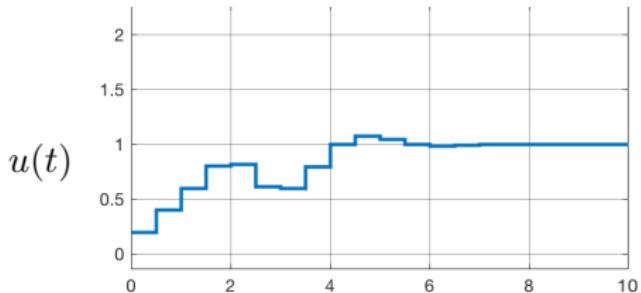


LINEAR MPC TRACKING EXAMPLE

- Impose constraint $0.8 \leq u(t) \leq 1.2$ (amplitude)



- Impose instead constraint $-0.2 \leq \Delta u(t) \leq 0.2$ (slew-rate)

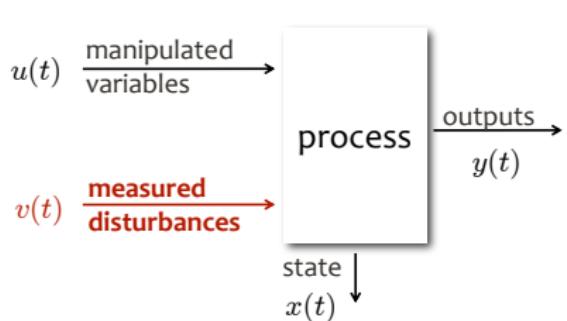


MEASURED DISTURBANCES

- **Measured disturbance** $v(t)$ = input that is measured but not manipulated

$$\begin{cases} x_{k+1} &= Ax_k + Bu_k + B_v v(t) \\ y_k &= Cx_k + D_v v(t) \end{cases}$$

$$x_k = A^k x_0 + \sum_{j=0}^{k-1} A^j B u_{k-1-j} + A^j B_v v(t)$$



- Same performance index, same constraints. We still have a QP:

$$\begin{aligned} \min_z \quad & \frac{1}{2} z' H z + [x'(t) \ r'(t) \ u'(t-1) \ v'(t)] F' z \\ \text{s.t.} \quad & Gz \leq W + S \begin{bmatrix} x(t) \\ r(t) \\ u(t-1) \\ v(t) \end{bmatrix} \end{aligned}$$

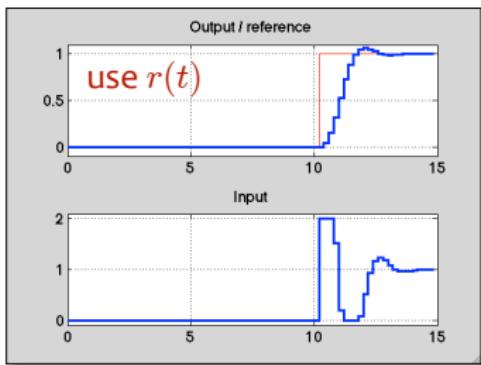
- Note that MPC naturally provides **feedforward action** on $v(t)$ and $r(t)$

ANTICIPATIVE ACTION (A.K.A. "PREVIEW")

$$\min_{\Delta U} \sum_{k=0}^{N-1} \|W^y(y_{k+1} - r_{k+1})\|_2^2 + \|W^{\Delta u} \Delta u(k)\|_2^2$$

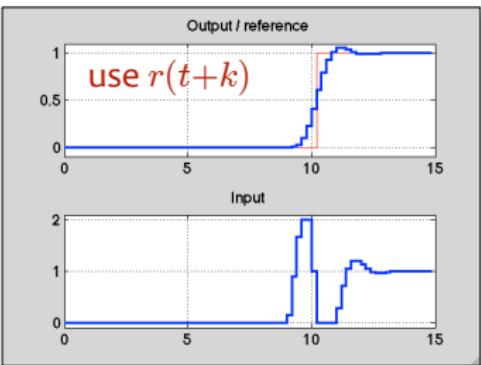
- Reference **not known** in advance (**causal**):

$$r_k \equiv r(t), \forall k = 0, \dots, N-1$$



- Future refs (partially) **known** in advance (**anticipative action**):

$$r_k = r(t+k), \forall k = 0, \dots, N-1$$



go to `demo_mpcpreview.m` (MPC Toolbox)

- Same idea also applies for **preview of measured disturbances**

SOFT CONSTRAINTS

- **Relax** output constraints to prevent QP infeasibility

$$\min_z \quad \sum_{k=0}^{N-1} \|W^y(y_{k+1} - r(t))\|_2^2 + \|W^{\Delta u} \Delta u_k\|_2^2 + \rho_\epsilon \epsilon^2$$

subj. to $x_{k+1} = Ax_k + Bu_k, k = 0, \dots, N-1$
 $u_{\min} \leq u_k \leq u_{\max}, k = 0, \dots, N-1$
 $\Delta u_{\min} \leq \Delta u_k \leq \Delta u_{\max}, k = 0, \dots, N-1$
 $y_{\min} - \epsilon V_{\min} \leq y_k \leq y_{\max} + \epsilon V_{\max}, k = 1, \dots, N$

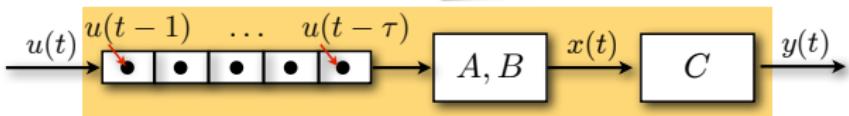
$$z = \begin{bmatrix} \Delta u(0) \\ \vdots \\ \Delta u(N-1) \\ \epsilon \end{bmatrix}$$

- ϵ = “panic” variable, with weight $\rho_\epsilon \gg W^y, W^{\Delta u}$
- V_{\min}, V_{\max} = vectors with entries ≥ 0 . The larger the i -th entry of vector V , the relatively softer the corresponding i -th constraint
- Infeasibility can be due to:
 - modeling errors
 - disturbances
 - wrong MPC setup (e.g., prediction horizon is too short)

DELAYS - METHOD #1

- Linear model with **delays**

$$\begin{aligned}x(t+1) &= Ax(t) + Bu(t - \tau) \\y(t) &= Cx(t)\end{aligned}$$



- Map delays to poles in $z = 0$:

$$x_k(t) \triangleq u(t-k) \Rightarrow x_k(t+1) = x_{k-1}(t), k = 1, \dots, \tau$$

$$\begin{bmatrix} x \\ x_\tau \\ x_{\tau-1} \\ \vdots \\ x_1 \end{bmatrix} (t+1) = \begin{bmatrix} A & B & 0 & 0 & \cdots & 0 \\ 0 & 0 & I_m & 0 & \cdots & 0 \\ 0 & 0 & 0 & I_m & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & 0 \end{bmatrix} \begin{bmatrix} x \\ x_\tau \\ x_{\tau-1} \\ \vdots \\ x_1 \end{bmatrix} (t) + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \vdots \\ I_m \end{bmatrix} u(t)$$

- Apply MPC to the extended system
- Note:** the prediction horizon $N \geq \tau$, otherwise u_0, \dots, u_{N-1} have no effect on the output!

DELAYS - METHOD #2

- Linear model with **delays**:
$$\begin{cases} x(t+1) &= Ax(t) + Bu(t - \tau) \\ y(t) &= Cx(t) \end{cases}$$
- **Delay-free** model: $\bar{x}(t) \triangleq x(t + \tau)$ 
$$\begin{cases} \bar{x}(t+1) &= A\bar{x}(t) + Bu(t) \\ \bar{y}(t) &= C\bar{x}(t) \end{cases}$$
- Design MPC for delay-free model, $u(t) = f_{\text{MPC}}(\bar{x}(t))$
- Compute the predicted state

$$\bar{x}(t) = \hat{x}(t + \tau) = A^\tau x(t) + \sum_{j=0}^{\tau-1} A^j B \underbrace{u(t-1-j)}_{\text{past inputs!}}$$

- Compute the MPC control move $u(t) = f_{\text{MPC}}(\hat{x}(t + \tau))$
- For better closed-loop performance and improved robustness, $\hat{x}(t + \tau)$ can be computed by a more complex model than (A, B, C)

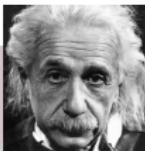
GOOD MODELS FOR (MPC) CONTROL

- Computation complexity depends on chosen prediction model
- Good models for MPC must be
 - **Descriptive** enough to capture the most significant dynamics of the system



- **Simple** enough for solving the optimization problem

“Things should be made as simple as possible, but not any simpler.”



Albert Einstein
(1879–1955)

MPC THEORY

- After the industrial success of MPC, a lot of research done:
 - linear MPC \Rightarrow linear prediction model
 - nonlinear MPC \Rightarrow nonlinear prediction model
 - robust MPC \Rightarrow uncertain (linear) prediction model
 - stochastic MPC \Rightarrow stochastic prediction model
 - distributed/decentralized MPC \Rightarrow multiple MPCs cooperating together
 - economic MPC \Rightarrow MPC based on arbitrary (economic) performance indices
 - hybrid MPC \Rightarrow prediction model integrating logic and dynamics
 - explicit MPC \Rightarrow off-line (exact/approximate) computation of MPC
 - solvers for MPC \Rightarrow on-line numerical algorithms for solving MPC problems
- Main theoretical issues: feasibility, stability, solution algorithms (Mayne, 2014)

Research on solution algorithms with guaranteed theoretical properties has the most impact in industrial practice.

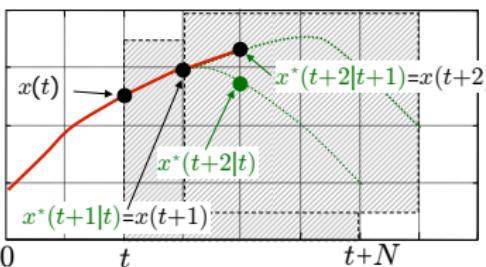
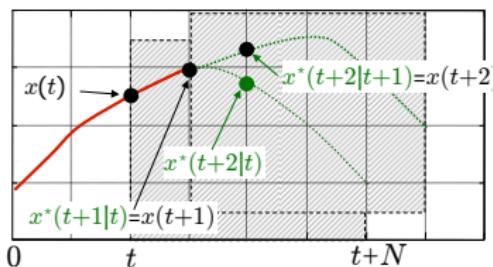
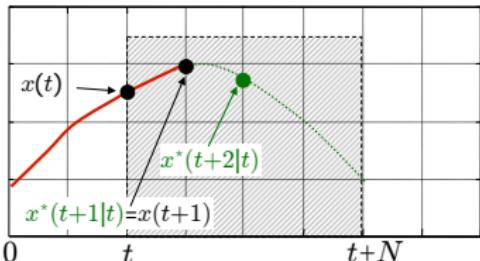
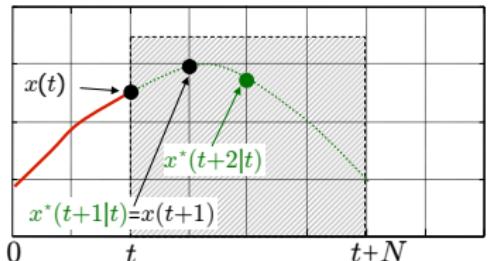
$$\begin{aligned} \min_z \quad & \sum_{k=0}^{N-1} \|W^y(y_{k+1} - r(t))\|^2 + \|W^{\Delta u} \Delta u_k\|^2 \\ \text{subj. to} \quad & u_{\min} \leq u_k \leq u_{\max}, \quad k = 0, \dots, N-1 \\ & y_{\min} \leq y_k \leq y_{\max}, \quad k = 1, \dots, N \\ & \Delta u_{\min} \leq \Delta u_k \leq \Delta u_{\max}, \quad k = 0, \dots, N-1 \end{aligned}$$

QP problem

- **Feasibility:** Will the QP problem be feasible at all sampling instants t ?
- **Input constraints** only: always feasible if $u/\Delta u$ constraints are consistent
- **Hard output constraints:**
 - When $N < \infty$ there is no guarantee that the QP problem will remain feasible at all t , even in the nominal case
 - $N = \infty$ ok in the nominal case, but we have an infinite number of constraints!
 - **Maximum output admissible set theory:** $N < \infty$ is enough (Gutman, Ckwikel, 1987)
(Gilbert, Tan, 1991) (Chmielewski, Manousiouthakis, 1996) (Kerrigan, Maciejowski, 2000)

PREDICTED AND ACTUAL TRAJECTORIES

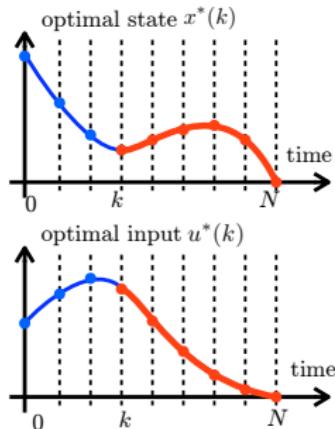
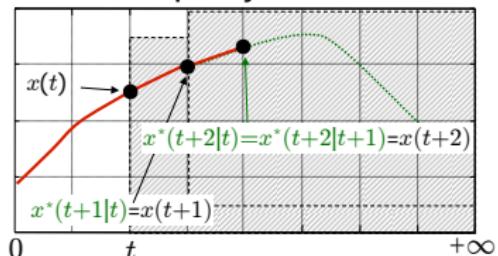
- Consider **predicted** and **actual** trajectories



- Even assuming perfect model and no disturbances, **predicted** open-loop trajectories and **actual** closed-loop trajectories can be different

PREDICTED AND ACTUAL TRAJECTORIES

- Special case: when the horizon is **infinite**, open-loop trajectories and closed-loop trajectories coincide.



- This follows by **Bellman's principle of optimality**:

"Given the optimal sequence $u^*(0), \dots, u^*(N - 1)$ and the corresponding optimal trajectory $x^*(0), \dots, x^*(N)$, the subsequence $u^*(k), \dots, u^*(N - 1)$ is optimal for the problem on the horizon $[k, N]$, starting from the optimal state $x^*(k)$."

``An optimal policy has the property that, regardless of the decisions taken to enter a particular state, the remaining decisions made for leaving that stage must constitute an optimal policy.'' (Bellman, 1957)



Richard Bellman
(1920–1984)

CONVERGENCE AND STABILITY

$$\min_z \quad x'_N P x_N + \sum_{k=0}^{N-1} x'_k Q x_k + u'_k R u_k$$

QP problem

$$\begin{aligned} \text{s.t.} \quad & u_{\min} \leq u_k \leq u_{\max}, \quad k = 0, \dots, N-1 \\ & y_{\min} \leq C x_k \leq y_{\max}, \quad k = 1, \dots, N \end{aligned}$$

$$Q = Q' \succeq 0, R = R' \succ 0, P = P' \succeq 0$$

- Stability is a complex function of the model (A, B, C) and the MPC parameters $N, Q, R, P, u_{\min}, u_{\max}, y_{\min}, y_{\max}$
- **Stability constraints** and weights on the terminal state can be imposed over the prediction horizon to ensure stability of MPC

BASIC CONVERGENCE PROPERTIES

(Keerthi, Gilbert, 1988) (Bemporad, Chisci, Mosca, 1994)

- **Theorem:** Let the MPC law be based on

$$\begin{aligned} V^*(x(t)) = \min & \sum_{k=0}^{N-1} x_k' Q x_k + u_k' R u_k \\ \text{s.t.} & x_{k+1} = Ax_k + Bu_k \\ & u_{\min} \leq u_k \leq u_{\max} \\ & y_{\min} \leq Cx_k \leq y_{\max} \\ & x_N = 0 \quad \leftarrow \text{"terminal constraint"} \end{aligned}$$

with $R, Q \succ 0, u_{\min} < 0 < u_{\max}, y_{\min} < 0 < y_{\max}$.

If the **optimization problem is feasible at time $t = 0$** then

$$\lim_{t \rightarrow \infty} x(t) = 0, \quad \lim_{t \rightarrow \infty} u(t) = 0$$

and the constraints are satisfied at all time $t \geq 0$, for all $R, Q \succ 0$.

- Many more convergence and stability results exist (Mayne, 2014)

CONVERGENCE PROOF

Proof: Main idea: use the **value function** $V^*(x(t))$ as a **Lyapunov-like function**

- Let z_t = optimal control sequence at time t , $z_t = [u_0^t \dots u_{N-1}^t]'$
- By construction $\bar{z}_{t+1} = [u_1^t \dots u_{N-1}^t \ 0]'$ is a feasible sequence at time $t + 1$
- The cost of \bar{z}_{t+1} is $V^*(x(t)) - x'(t)Qx(t) - u'(t)Ru(t) \geq V^*(x(t+1))$
- $V^*(x(t))$ is monotonically decreasing and ≥ 0 , so $\exists \lim_{t \rightarrow \infty} V^*(x(t)) \triangleq V_\infty$
- Hence
$$0 \leq x'(t)Qx(t) + u'(t)Ru(t) \leq V^*(x(t)) - V^*(x(t+1)) \rightarrow 0 \text{ for } t \rightarrow \infty$$
- Since $R, Q \succ 0$, $\lim_{t \rightarrow \infty} x(t) = 0$, $\lim_{t \rightarrow \infty} u(t) = 0$ ■

Reaching the global optimum exactly is not needed to prove convergence

A LITTLE MORE GENERAL CONVERGE RESULT

THEOREM

Consider again the linear system described by (A, B, C) and the MPC control law based on optimizing

$$\begin{aligned} V^*(x(t)) = \min & \quad \sum_{k=0}^{N-1} y_k' Q_y y_k + u_k' R u_k \\ \text{s.t.} & \quad x_{k+1} = Ax_k + Bu_k \\ & \quad u_{\min} \leq u_k \leq u_{\max} \\ & \quad y_{\min} \leq y_k \leq y_{\max} \end{aligned}$$

If the optimization problem is feasible at time $t = 0$ then for either $N = \infty$ or $x_N = 0$ and for all $R = R' \succ 0$, $Q_y = Q'_y \succ 0$

$$\lim_{t \rightarrow \infty} y(t) = 0, \quad \lim_{t \rightarrow \infty} u(t) = 0$$

and the constraints are satisfied at all time $t \geq 0$. Moreover, if (C, A) is a detectable pair then $\lim_{t \rightarrow \infty} x(t) = 0$.

CONVERGENCE PROOF

Proof:

- The shifted optimal sequence $\bar{z}_{t+1} = [u_1^t \dots u_{N-1}^t 0]'$ (or $\bar{z}_{t+1} = [u_1^t u_2^t \dots]'$ in case $N = \infty$) is feasible sequence at time $t + 1$ and has cost

$$V^*(x(t)) - y'(t)Q_y y(t) - u'(t)R u(t) \geq V^*(x(t+1))$$

- Therefore, by convergence of $V^*(x(t))$, we have that

$$0 \leq y'(t)Q_y y(t) + u'(t)R u(t) \leq V^*(x(t)) - V^*(x(t+1)) \rightarrow 0$$

for $t \rightarrow \infty$

- Since $R, Q_y \succ 0$, also $\lim_{t \rightarrow \infty} y(t) = 0$, $\lim_{t \rightarrow \infty} u(t) = 0$
- For all $k = 0, \dots, n-1$ we have that

$$0 = \lim_{t \rightarrow \infty} y'(t+k)Q_y y(t+k) = \lim_{t \rightarrow \infty} \|LC(A^k x(t) + \sum_{j=0}^{k-1} A^j B u(t+k-1-j))\|_2^2$$

where $Q_y = L'L$ (Cholesky factorization) and L is nonsingular

CONVERGENCE PROOF (CONT'D)

- As $u(t) \rightarrow 0$, also $LCA^kx(t) \rightarrow 0$, and since L is nonsingular $CA^kx(t) \rightarrow 0$ too, for all $k = 0, \dots, n - 1$
- Hence $\Theta x(t) \rightarrow 0$, where Θ is the observability matrix of (C, A)
- If (C, A) is observable then Θ is nonsingular and hence $\lim_{t \rightarrow \infty} x(t) = 0$
- If (C, A) is only detectable, we can make a canonical observability decomposition and show that the observable states converge to zero
- As also $u(t) \rightarrow 0$ and the unobservable subsystem is asymptotically stable, the unobservable states must converge to zero asymptotically too



EXTENSION TO REFERENCE TRACKING

- We want to track a constant reference r . Assume x_r and u_r exist such that

$$\begin{aligned}x_r &= Ax_r + Bu_r \\r &= Cx_r\end{aligned}\quad \text{(equilibrium state/input)}$$

- Formulate the MPC problem (assume $u_{\min} < u_r < u_{\max}$, $y_{\min} < r < y_{\max}$)

$$\begin{array}{ll}\min & \sum_{k=0}^{N-1} (y_k - r)' Q_y (y_k - r) + (u_k - u_r)' R (u_k - u_r) \\ \text{s.t.} & x_{k+1} = Ax_k + Bu_k \\ & u_{\min} \leq u_k \leq u_{\max}, \quad y_{\min} \leq Cx_k \leq y_{\max} \\ & \color{red}{x_N = x_r}\end{array}$$

- We can repeat the convergence proofs in the **shifted-coordinates**

$$x_{k+1} - x_r = A(x_k - x_r) + B(u_k - u_r), \quad y_k - r = C(x_k - x_r)$$

- Drawback:** the approach only works well in nominal conditions, as the input reference u_r depends on A, B, C (inverse static model)

STABILITY CONSTRAINTS

1. No stability constraint, infinite prediction horizon

$$N \rightarrow \infty$$

(Keerthi, Gilbert, 1988) (Rawlings, Muske, 1993) (Bemporad, Chisci, Mosca, 1994)

2. End-point constraint

$$x_N = 0$$

(Kwon, Pearson, 1977) (Keerthi, Gilbert, 1988) (Bemporad, Chisci, Mosca, 1994)

3. Relaxed terminal constraint

$$x_N \in \Omega$$

(Scokaert, Rawlings, 1996)

4. Contraction constraint

$$\|x_{k+1}\| \leq \alpha \|x(t)\|, \alpha < 1$$

(Polak, Yang, 1993) (Bemporad, 1998)

All the proofs in (1,2,3) use the value function $V^*(x(t)) = \min_z J(z, x(t))$ as a Lyapunov function.

CONTROL AND CONSTRAINT HORIZONS

$$\min_z \quad \sum_{k=0}^{N-1} \|W^y(y_k - r(t))\|_2^2 + \|W^{\Delta u} \Delta u_k\|_2^2 + \rho_\epsilon \epsilon^2$$

subj. to $u_{\min} \leq u_k \leq u_{\max}, k = 0, \dots, N - 1$

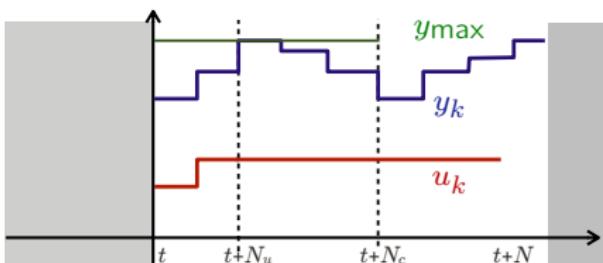
$\Delta u_{\min} \leq \Delta u_k \leq \Delta u_{\max}, k = 0, \dots, N - 1$

$\Delta u_k = 0, k = \text{N}_u, \dots, N - 1$

$y_{\min} - \epsilon V_{\min} \leq y_k \leq y_{\max} + \epsilon V_{\max}, k = 1, \dots, \text{N}_c$

- The **input horizon** N_u limits the number of free variables

- Reduced performance
 - Reduced computation time
- typically** $N_u = 1 \div 5$



- The **constraint horizon** N_c limits the number of constraints
 - Higher chance of violating output constraints
 - Reduced computation time

MPC AND LINEAR QUADRATIC REGULATION (LQR)

- Special case: $J(z, x_0) = x'_N P x_N + \sum_{k=0}^{N-1} x'_k Q x_k + u'_k R u_k$, $N_u = N$, with matrix P solving the Algebraic Riccati Equation

$$P = A'PA - A'PB(B'PB + R)^{-1}B'PA + Q$$



Jacopo Francesco Riccati
(1676–1754)

(unconstrained) **MPC = LQR** for any choice of the prediction horizon N

Proof: : Easily follows from Bellman's principle of optimality (dynamic programming): $x'_N P x_N$ = optimal "cost-to-go" from time N to ∞ .

MPC AND CONSTRAINED LQR

- Consider again the constrained MPC law based on minimizing

$$\begin{aligned} \min_z \quad & x_N'Px_N + \sum_{k=0}^{N-1} x_k'Qx_k + u_k'Ru_k \\ \text{s.t.} \quad & u_{\min} \leq u_k \leq u_{\max}, \quad k = 0, \dots, N-1 \\ & y_{\min} \leq y_k \leq y_{\max}, \quad k = 1, \dots, N \\ & \color{red}{u_k = Kx_k}, \quad k = N_u, \dots, N-1 \end{aligned}$$

- Choose matrix P and terminal gain K by solving the LQR problem

$$\begin{aligned} K &= -(R + B'PB)^{-1}B'PA \\ P &= (A + BK)'P(A + BK) + K'RK + Q \end{aligned}$$

- In a polyhedral region around the origin, **constrained MPC = constrained LQR** for any choice of the prediction and control horizons N, N_u

(Sznaier, Damborg, 1987) (Chmielewski, Manousiouthakis, 1996) (Scokaert, Rawlings, 1998)
(Bemporad, Morari, Dua Pistikopoulos, 2002)

- The larger the horizon N , the larger the region where MPC \equiv constrained LQR

MPC AND CONSTRAINED LQR

- Some MPC formulations also include the **terminal constraint** $x_N \in \mathcal{X}_\infty$

$$\mathcal{X}_\infty = \left\{ x : \begin{bmatrix} u_{\min} \\ y_{\min} \end{bmatrix} \leq \begin{bmatrix} K \\ C \end{bmatrix} (A + BK)^k x \leq \begin{bmatrix} u_{\max} \\ y_{\max} \end{bmatrix}, \forall k \geq 0 \right\}$$

that is the **maximum output admissible set** for the closed-loop system $(A + BK, B, C)$ and constraints $u_{\min} \leq Kx \leq u_{\max}, y_{\min} \leq Cx \leq y_{\max}$

- This makes MPC \equiv constrained LQR **where the MPC problem is feasible**
- Recursive feasibility is ensured by the terminal constraint for all $x(0)$ such that the MPC problem is feasible @ $t = 0$
- The domain of feasibility may be reduced because of the additional constraint

DOUBLE INTEGRATOR EXAMPLE

- Model and constraints:
$$\begin{cases} x(t+1) = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix} x(t) + \begin{bmatrix} 0 \\ 1 \end{bmatrix} u(t) \\ y(t) = \begin{bmatrix} 1 & 0 \end{bmatrix} x(t) \\ -1 \leq u(t) \leq 1 \end{cases}$$

- Objective:

$$\min \sum_{k=0}^{\infty} y_k^2 + \frac{1}{10} u_k^2 \quad \left| \begin{array}{l} u_k = Kx_k, \forall k \geq N_u, K = \text{LQR gain} \\ N_u = N = 2 \end{array} \right.$$

$\xrightarrow{\hspace{1cm}} \left(\sum_{k=0}^1 y_k^2 + \frac{1}{10} u_k^2 \right) + x_2' \underbrace{\begin{bmatrix} 2.1429 & 1.2246 \\ 1.2246 & 1.3996 \end{bmatrix}}_{\substack{\text{solution of algebraic} \\ \text{Riccati equation}}} x_2$

- QP matrices (cost function normalized by max singular value of H)

$$H = \begin{bmatrix} 0.8365 & 0.3603 \\ 0.3603 & 0.2059 \end{bmatrix}, F = \begin{bmatrix} 0.4624 & 1.2852 \\ 0.1682 & 0.5285 \end{bmatrix}$$
$$G = \begin{bmatrix} 1 & 0 \\ -1 & 0 \\ 0 & 1 \\ 0 & -1 \end{bmatrix}, W = \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \end{bmatrix}, S = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

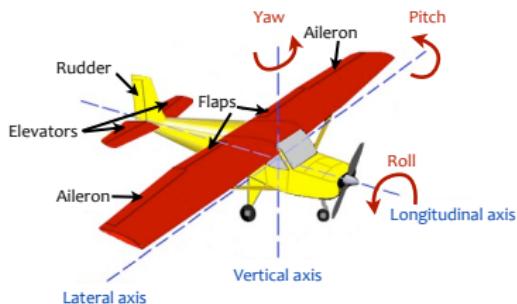
EXAMPLE: AFTI-F16 AIRCRAFT



Linearized model:

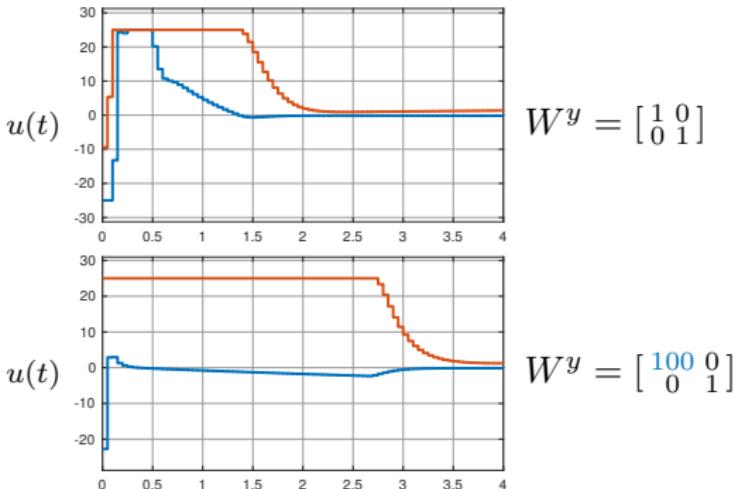
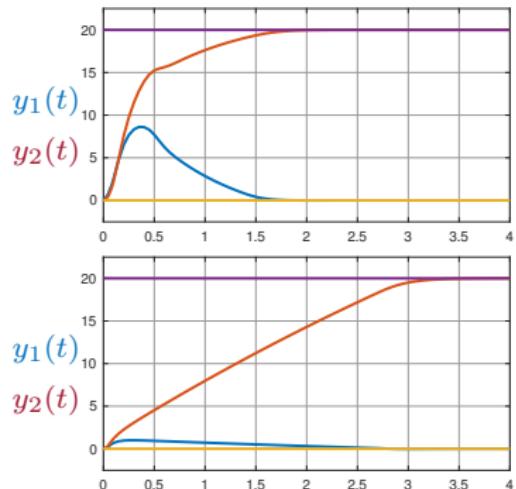
$$\begin{cases} \dot{x} = \begin{bmatrix} -0.0151 & -60.5651 & 0 & -32.174 \\ -0.0001 & -1.3411 & 0.9929 & 0 \\ 0.00018 & 43.2541 & -0.86939 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} x + \begin{bmatrix} -2.516 & -13.136 \\ -0.1689 & -0.2514 \\ -17.251 & -1.5766 \\ 0 & 0 \end{bmatrix} u \\ y = \begin{bmatrix} 0 & 1 & 0 & 0 \end{bmatrix} x \end{cases}$$

- Inputs: elevator and flaperon (=flap+aileron) angles
- Outputs: attack and pitch angles
- Sampling time: $T_s = 0.05$ sec (+ ZOH)
- Constraints: $\pm 25^\circ$ on both angles
- Open-loop unstable, poles are
 $-7.6636, -0.0075 \pm 0.0556j, 5.4530$
go to demo `linear/afti16.m` (Hybrid Toolbox)
see also `afti16.m` (MPC Toolbox)



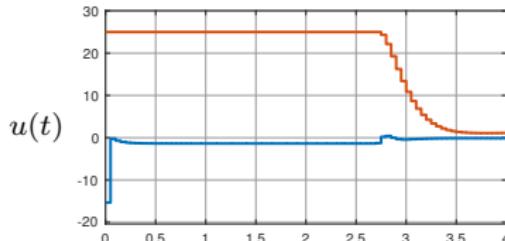
EXAMPLE: AFTI-F16 AIRCRAFT

- Prediction horizon $N = 10$, control horizon $N_u = 2$
- Input weights $W^{\Delta u} = \begin{bmatrix} 0.1 & 0 \\ 0 & 0.1 \end{bmatrix}$, $W^u = 0$
- Input constraints $u_{\min} = -u_{\max} = \begin{bmatrix} 25^\circ \\ 25^\circ \end{bmatrix}$



EXAMPLE: AFTI-F16 AIRCRAFT

- Add output constraints $y_{1,\min} = -y_{1,\max} = 0.5^\circ$

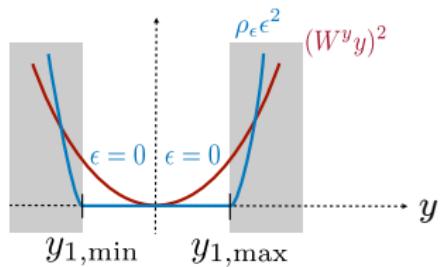


$$W^y = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

- Soft output constraint = convex penalty with dead zone

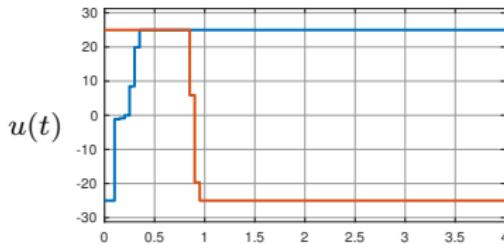
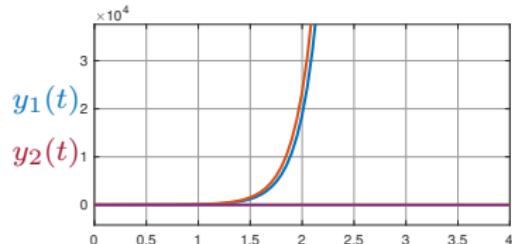
$$\min \rho \epsilon^2$$

$$\text{s.t. } y_{1,\min} - \epsilon V_{1,\min} \leq y_1 \leq y_{1,\max} - \epsilon V_{1,\max}$$



EXAMPLE: AFTI-F16 AIRCRAFT

- Linear control (=unconstrained MPC) + input clipping



$$W^y = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

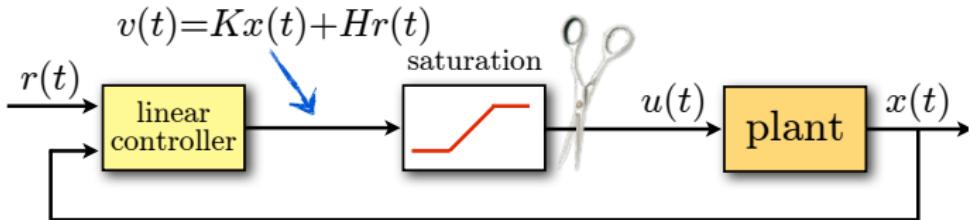


unstable!

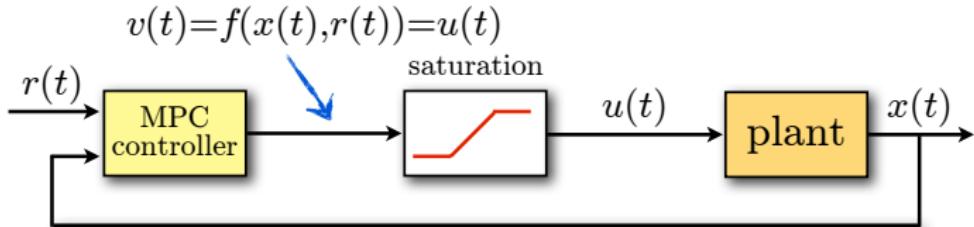
Saturation needs to be considered in the control design!

SATURATION

- Saturation is dangerous because it breaks the control loop



- MPC takes it into account automatically (and optimally)



TUNING GUIDELINES

$$\min_{\Delta U} \quad \sum_{k=0}^{N-1} \|W^y(y_{k+1} - r(t))\|_2^2 + \|W^{\Delta u} \Delta u_k\|_2^2 + \rho_\epsilon \epsilon^2$$

subj. to $\Delta u_{\min} \leq \Delta u_k \leq \Delta u_{\max}, k = 0, \dots, N_u - 1$

$\Delta u_k = 0, k = N_u, \dots, N - 1$

$u_{\min} \leq u_k \leq u_{\max}, k = 0, \dots, N_u - 1$

$y_{\min} - \epsilon V_{\min} \leq y_k \leq y_{\max} + \epsilon V_{\max}, k = 1, \dots, N_c$

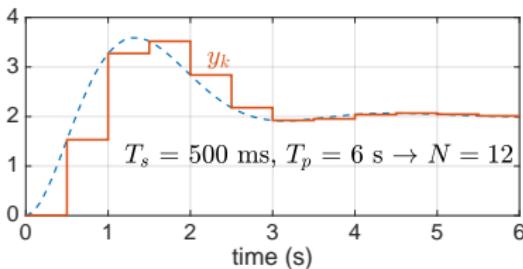
- **weights**: the larger the ratio $W^y/W^{\Delta u}$ the more aggressive the controller
- **input horizon**: the larger N_u , the more “optimal” but more complex the controller
- **prediction horizon**: the smaller N , the more aggressive the controller
- **constraints horizon**: the smaller N_c , the simpler the controller
- **limits**: controller less aggressive if $\Delta u_{\min}, \Delta u_{\max}$ are small
- **penalty** ρ_ϵ : pick up smallest ρ_ϵ that keeps soft constraints reasonably satisfied

Always try to set N_u as small as possible!

TUNING GUIDELINES - EFFECT OF SAMPLING TIME

- Let T_s = sampling time used in MPC predictions
- For predicting T_p time units in the future we must set

$$N = \left\lceil \frac{T_p}{T_s} \right\rceil$$



- Slew-rate constraints $\dot{u}_{\min} \leq \frac{du}{dt} \leq \dot{u}_{\max}$ on actuators are related to T_s by

$$\dot{u} \triangleq \frac{du}{dt} \approx \frac{u_k - u_{k-1}}{T_s}$$

$$\overbrace{T_s \dot{u}_{\min}}^{\Delta u_{\min}} \leq \Delta u_k \leq \overbrace{T_s \dot{u}_{\max}}^{\Delta u_{\max}}$$

TUNING GUIDELINES - EFFECT OF SAMPLING TIME

- The MPC cost to minimize can be thought in continuous-time as

$$\begin{aligned} J &= \int_0^{T_p} \left(\|W^y(y(\tau) - r)\|_2^2 + \|W^u(u(\tau) - u_r)\|_2^2 + \|W^{\dot{u}}\dot{u}(\tau)\|_2^2 \right) d\tau + \rho_\epsilon \epsilon^2 \\ &\approx T_s \left(\sum_{k=0}^{N-1} \|W^y(y_{k+1} - r)\|_2^2 + \|W^u(u_k - u_r)\|_2^2 + \underbrace{\|W^{\dot{u}} T_s^{-1} \Delta u_k\|_2^2}_{W^{\Delta u}} + \rho_\epsilon T_s^{-1} \epsilon^2 \right) \end{aligned}$$

- Hence, when changing the sampling time from T_1 to T_2 , can keep the same MPC cost function by leaving W^y , W^u unchanged and simply rescaling

$$W_2^{\Delta u} = \frac{W^{\dot{u}}}{T_2} = \frac{T_1}{T_2} \frac{W^{\dot{u}}}{T_1} = \frac{T_1}{T_2} W_1^{\Delta u} \quad \rho_{\epsilon 2} = \frac{\rho_\epsilon}{T_2} = \frac{T_1}{T_2} \frac{\rho_\epsilon}{T_1} = \frac{T_1}{T_2} \rho_{\epsilon 1}$$

- Note:** T_s used for controller execution can be \neq than T_s used in prediction
- Small controller $T_s \Rightarrow$ fast **reaction** to set-point changes / disturbances

SCALING

- Humans think infinite precision ...computers do not !
- Numerical difficulties may arise if variables assume very small/large values
- Example:

$$\begin{array}{ll} y_1 \in [-1e-4, 1e-4] & [\text{V}] \\ y_2 \in [-1e4, 1e4] & [\text{Pa}] \end{array} \quad \longrightarrow \quad \begin{array}{ll} y_1 \in [-0.1, 0.1] & [\text{mV}] \\ y_2 \in [-10, 10] & [\text{kPa}] \end{array}$$

- Ideally all variables should be in $[-1, 1]$. For example, one can replace y with y/y_{\max}
- Scaling also possible after formulating the QP problem (=**preconditioning**)

PRE-STABILIZATION OF OPEN-LOOP UNSTABLE MODELS

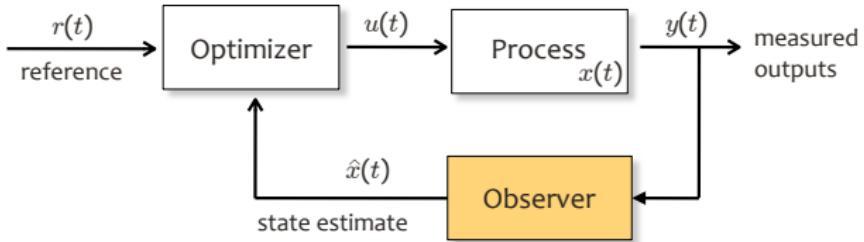
- Numerical issues may arise with **open-loop unstable** models
- When condensing the QP we substitute $x_k = A^k x_0 + \sum_{j=0}^{k-1} A^j B u_{k-1-j}$ that may lead to a badly conditioned Hessian matrix H

$$H = \begin{bmatrix} B & 0 & \dots & 0 \\ AB & B & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ A^{N-1}B & A^{N-2}B & \dots & B \end{bmatrix}' \begin{bmatrix} Q & 0 & 0 & \dots & 0 \\ 0 & Q & 0 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & \dots & 0 & Q & 0 \\ 0 & 0 & \dots & 0 & P \end{bmatrix} \begin{bmatrix} B & 0 & \dots & 0 \\ AB & B & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ A^{N-1}B & A^{N-2}B & \dots & B \end{bmatrix} + \begin{bmatrix} R & 0 & \dots & 0 \\ 0 & R & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & \dots & 0 & R \end{bmatrix}$$

- **Pre-stabilizing** the system with $u_k = Kx_k + v_k$ leads to $x_{k+1} = A_K x_k + B v_k$, $A_K \triangleq A + BK$, and therefore $x_k = A_K^k x_0 + \sum_{j=0}^{k-1} A_K^j B v_{k-1-j}$
- Input constraints become mixed constraints $u_{\min} \leq Kx_k + v_k \leq u_{\max}$
- K can be chosen for example by pole-placement or LQR

OBSERVER DESIGN FOR MPC

STATE OBSERVER FOR MPC

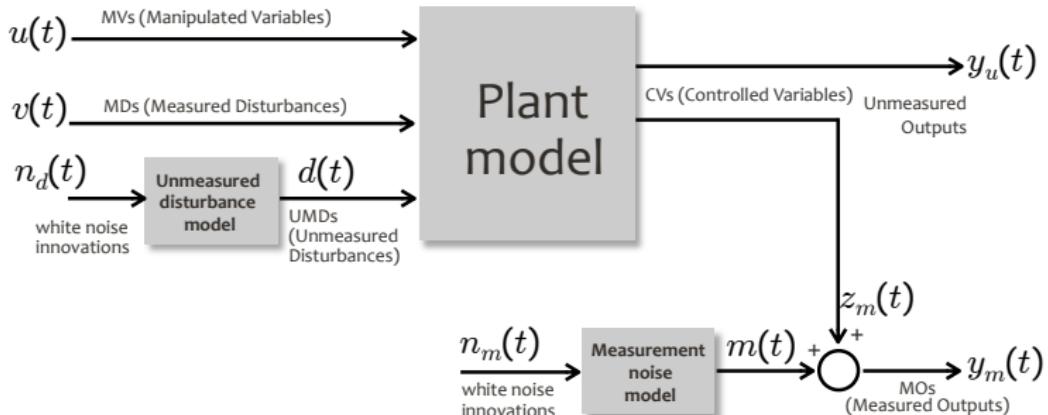


- Full state $x(t)$ of process may not be available, only outputs $y(t)$
- Even if $x(t)$ is available, noise should be filtered out
- Prediction and process models may be quite different
- The state $x(t)$ may not have any physical meaning
(e.g., in case of model reduction or subspace identification)

We need to use a state observer

- Example: Luenberger observer $\hat{x}(t + 1) = A\hat{x}(t) + Bu(t) + L(y(t) - C\hat{x}(t))$

EXTENDED MODEL FOR OBSERVER DESIGN



unmeasured disturbance model

$$\begin{cases} x_d(t+1) &= \bar{A}x_d(t) + \bar{B}n_d(t) \\ d(t) &= \bar{C}x_d(t) + \bar{D}n_d(t) \end{cases}$$

measurement noise model

$$\begin{cases} x_m(t+1) &= \tilde{A}x_m(t) + \tilde{B}n_m(t) \\ m(t) &= \tilde{C}x_m(t) + \tilde{D}n_m(t) \end{cases}$$

- Note: the measurement noise model is not needed during optimization

KALMAN FILTER DESIGN

- Plant model

$$\begin{cases} x(t+1) = Ax(t) + B_u u(t) + B_v v(t) + B_d d(t) \\ y(t) = Cx(t) + D_v v(t) + D_d d(t) \end{cases}$$



Rudolf Emil Kalman
(1930–2016)

- Full model for designing Kalman filter

$$\begin{aligned} \begin{bmatrix} x(t+1) \\ x_d(t+1) \\ x_m(t+1) \end{bmatrix} &= \begin{bmatrix} AB_d\bar{C} & 0 \\ 0 & \bar{A} & 0 \\ 0 & 0 & \tilde{A} \end{bmatrix} \begin{bmatrix} x(t) \\ x_d(t) \\ x_m(t) \end{bmatrix} + \begin{bmatrix} B_u \\ 0 \\ 0 \end{bmatrix} u(t) + \begin{bmatrix} B_v \\ 0 \\ 0 \end{bmatrix} v(t) + \\ &\quad \begin{bmatrix} B_d\bar{D} \\ \bar{B} \\ 0 \end{bmatrix} n_d(t) + \begin{bmatrix} 0 \\ 0 \\ \tilde{B} \end{bmatrix} n_m(t) + \begin{bmatrix} B_u \\ 0 \\ 0 \end{bmatrix} n_u(t) \\ y_m(t) &= [C_m \ D_{dm}\bar{C} \ \tilde{C}] \begin{bmatrix} x(t) \\ x_d(t) \\ x_m(t) \end{bmatrix} + D_{vm}v(k) + \bar{D}_m n_d(t) + \tilde{D}_m n_m(t) \end{aligned}$$

- $n_d(k)$ = source of **modeling errors**
- $n_m(k)$ = source of **measurement noise**
- $n_u(k)$ = white noise on input u (added to compute the Kalman gain)

OBSERVER IMPLEMENTATION

- Measurement update

$$\hat{y}_m(t|t-1) = C_m \hat{x}(t|t-1)$$

$$\hat{x}(t|t) = \hat{x}(t|t-1) + M(y_m(t) - \hat{y}_m(t|t-1))$$

- Time update

$$\hat{x}(t+1|t) = A\hat{x}(t|t-1) + Bu(t) + L(y_m(t) - \hat{y}_m(t|t-1))$$

- Note that if $L = AM$ then $\hat{x}(t+1|t) = A\hat{x}(t|t) + Bu(t)$
- The **separation principle** holds (under certain assumptions)
(Muske, Meadows, Rawlings, 1994)

I/O FEEDTHROUGH

- We always assumed **no feedthrough from u to measured y**

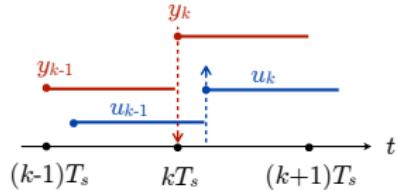
$$y_k = Cx_k + Du_k + D_v v_k + D_d d_k, \quad D_m = 0$$

- This avoids **static loops** between state observer, as $\hat{x}(t|t)$ depends on $u(t)$ via $\hat{y}_m(t|t-1)$, and MPC ($u(t)$ depends on $\hat{x}(t|t)$)
- Often $D = 0$ is not a limiting assumption as
 - often **actuator dynamics** must be considered (u is the set-point to a low-level controller of the actuators)
 - most physical models described by ordinary differential equations are **strictly causal**, and so is the discrete-time version of the model
- In case $D \neq 0$, we can assume a **delay** in executing the commanded u

$$y_k = C_m x_k + D u_{k-1}$$

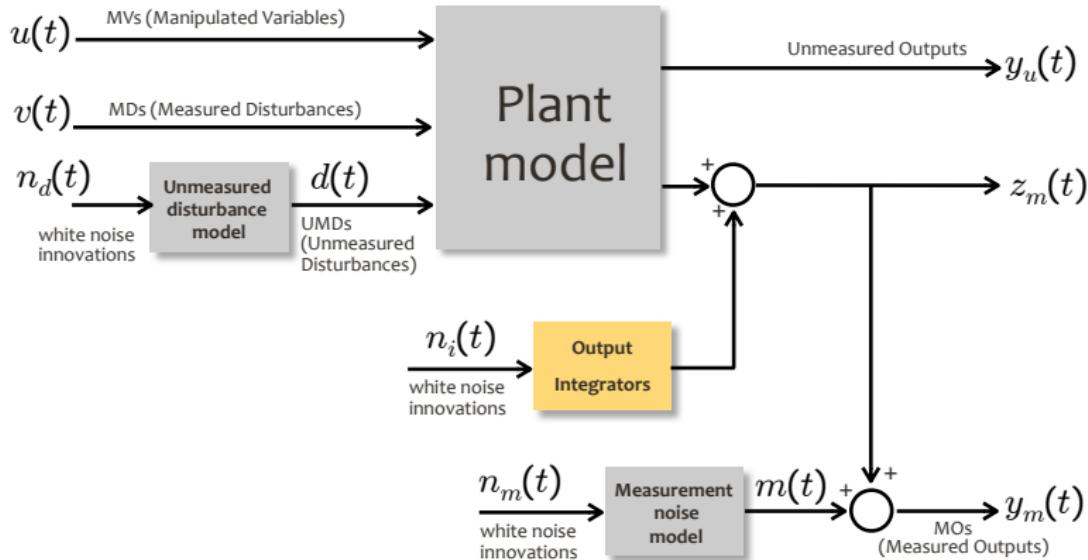
and treat $u(t-1)$ as an extra state

- Not an issue for **unmeasured** outputs



INTEGRAL ACTION IN MPC

OUTPUT INTEGRATORS



- Introduce **output integrators** as additional disturbance models
- Under certain conditions, observer + controller provide **zero offset** in steady-state

OUTPUT INTEGRATORS AND OFFSET-FREE TRACKING

- Add constant unknown disturbances on measured outputs:

$$\begin{cases} x_{k+1} = Ax_k + Bu_k \\ d_{k+1} = d_k \\ y_k = Cx_k + d_k \end{cases}$$

- Use the extended model to design a state observer (e.g., Kalman filter) that estimates both the state $\hat{x}(t)$ and disturbance $\hat{d}(t)$ from $y(t)$
- Why we get offset-free tracking in steady-state (intuitively):
 - the observer makes $C\hat{x}(t) + \hat{d}(t) \rightarrow y(t)$ (estimation error)
 - the MPC controller makes $C\hat{x}(t) + \hat{d}(t) \rightarrow r(t)$ (predicted tracking error)
 - the combination of the two makes $y(t) \rightarrow r(t)$ (actual tracking error)
- In steady state, the term $\hat{d}(t)$ compensates for model mismatch
- See more on survey paper (Pannocchia, Gabiccini, Artoni, 2015)

OUTPUT INTEGRATORS AND OFFSET-FREE TRACKING

(Pannocchia, Rawlings, 2003)

- More general result: consider the disturbance model

$$\begin{cases} x_{k+1} = Ax_k + Bu_k + B_d d_k \\ d_{k+1} = d_k \\ y_k = Cx_k + D_d d_k \end{cases}$$

special case: **output integrators**

$$B_d = 0, D_d = I$$

THEOREM

Let the number n_d of disturbances be equal to the number n_y of measured outputs.

Then all pairs (B_d, D_d) satisfying

$$\text{rank} \begin{bmatrix} I - A & -B_d \\ C & D_d \end{bmatrix} = n_x + n_y$$

guarantee zero offset in steady-state ($y = r$), provided that constraints are not active in steady-state and the closed-loop system is asymptotically stable.

DISTURBANCE MODEL EXAMPLE

- Open-loop system: $A = \begin{bmatrix} 1 & -1 & -2 & 1 \\ 0 & -2 & 3 & 2 \\ 0 & 2 & -1 & -1 \\ 0 & 2 & 0 & -2 \end{bmatrix}$, $B = \begin{bmatrix} 1 \\ 0 \\ 1 \\ 1 \end{bmatrix}$, $C_m = [1 \ 1 \ 0 \ 0]$
- We cannot add an **output integrator** since the pair $([\begin{smallmatrix} A & 0 \\ 0 & 1 \end{smallmatrix}], [\begin{smallmatrix} C & 1 \end{smallmatrix}])$ is not observable
- Add an **input integrator**: $B_d = B$, $D_d = 0$, $\text{rank } [\begin{smallmatrix} A & B_d \\ C_m & D_d \end{smallmatrix}] = 5 = n_x + n_y$



$$\left\{ \begin{array}{rcl} x(t+1) & = & Ax(t) + B(u(t) + d(t)) \\ d(t+1) & = & d(t) \\ y(t) & = & Cx(t) + 0 \cdot d(t) \end{array} \right.$$

ERROR FEEDBACK

(Kwakernaak, Sivan, 1972)

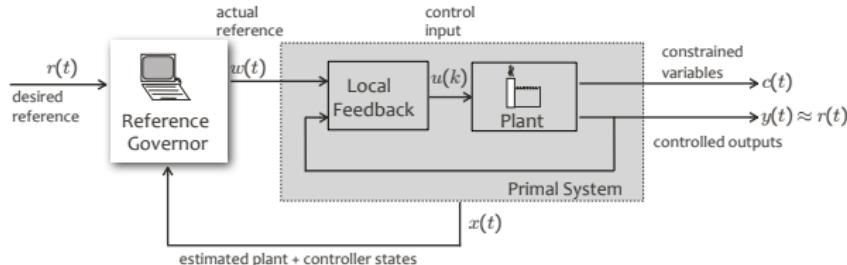
- Idea: add the integral of the tracking error as an additional state (original idea developed for integral action in state-feedback control)
- Extended prediction model:

$$\left\{ \begin{array}{lcl} x(t+1) & = & Ax(t) + B_u u(t) + 0 \cdot r(t) & \leftarrow r(t) \text{ is seen as a meas. disturbance} \\ q(t+1) & = & q(t) + \underbrace{Cx(t) - r(t)}_{\text{tracking error}} & \leftarrow \text{integral action} \\ y(t) & = & Cx(t) \end{array} \right.$$

- $\|W^i q\|_2^2$ is penalized in the cost function, otherwise it is useless. W^i is a new tuning knob
- Intuitively, if the MPC closed-loop is asymptotically stable then $q(t)$ converges to a constant, and hence $y(t) - r(t)$ converges to zero.

REFERENCE / COMMAND GOVERNOR

(Bemporad, Mosca, 1994) (Gilbert, Kolmanovsky, Tan, 1994) (Garone, Di Cairano, Kolmanovsky, 2016)



- MPC manipulates set-points to a linear feedback loop to enforce constraints
- Separation of problems:
 - Local feedback guarantees offset-free tracking $y(t) - w(t) \rightarrow 0$ in steady-state **in the absence of constraints**
 - Actual reference $w(t)$ generated by MPC to **take care of constraints**
- Advantages: small-signal properties preserved, fewer variables to optimize

$$w(t) = \arg \min_w \|w - r(t)\|_2^2$$

s.t. $c_{t+k} \in \mathcal{C}$

INTEGRAL ACTION AND Δu -FORMULATION

- In control systems, **integral action** occurs if the controller has a transfer-function from the output to the input of the form

$$u(t) = \frac{B(z)}{(z - 1)A(z)}y(t), \quad B(1) \neq 0$$

- One may think that the Δu -formulation of MPC provides integral action ...

... is it true ?

- **Example:** we want to regulate the output $y(t)$ to zero of the scalar system

$$\begin{aligned}x(t + 1) &= \alpha x(t) + \beta u(t) \\y(t) &= x(t)\end{aligned}$$

INTEGRAL ACTION AND Δu -FORMULATION

- Design an unconstrained MPC controller with horizon $N = 1$

$$\begin{aligned}\Delta u(t) &= \arg \min_{\Delta u_0} \Delta u_0^2 + \rho y_1^2 \\ \text{s.t. } \Delta u_0 &= u_0 - u(t-1) \\ y_1 &= x_1 = \alpha x(t) + \beta(\Delta u_0 + u(t-1))\end{aligned}$$

- By substitution, we get

$$\begin{aligned}\Delta u(t) &= \arg \min_{\Delta u_0} \Delta u_0^2 + \rho(\alpha x(t) + \beta u(t-1) + \beta \Delta u_0)^2 \\ &= \arg \min_{\Delta u_0} (1 + \rho \beta^2) \Delta u_0^2 + 2\beta\rho(\alpha x(t) + \beta u(t-1)) \Delta u_0 \\ &= -\frac{\beta\rho\alpha}{1+\rho\beta^2} x(t) - \frac{\rho\beta^2}{1+\rho\beta^2} u(t-1)\end{aligned}$$

- Since $x(t) = y(t)$ and $u(t) = u(t-1) + \Delta u(t)$ we get the linear controller

$$u(t) = -\frac{\frac{\rho\beta\alpha}{1+\rho\beta^2} z}{z - \frac{1}{1+\rho\beta^2}} y(t) \quad \leftarrow \text{No pole in } z = 1$$

- Reason: MPC gives a feedback gain on both $x(t)$ and $u(t-1)$, not just on $x(t)$

INTEGRAL ACTION AND Δu -FORMULATION

- Numerical test (with MPC Toolbox)

```
alpha=.5;
beta=3;
sys=ss(alpha,beta,1,0);sys.ts=1;
rho=1;p=1;m=1;
weights=struct('OV',rho,'MVRate',1);
mpc1=mpc(sys,1,p,m,weights);
setoutdist(mpc1,'remove',1); % no output disturbance model
mpc1tf=tf(mpc1);
sum(mpc1tf.den{1})

ans = 0.9000
```

- Now add an output integrator as disturbance model

```
setoutdist(mpc1,'integrators'); % add output disturbance model
mpc1tf=tf(mpc1);
sum(mpc1tf.den{1})

ans = -6.4185e-16
```

MPC AND INTERNAL MODEL PRINCIPLE

- Assume we have an **internal model** of the reference signal $r(t)$

$$\begin{aligned}x^r(t+1) &= A_r x^r(t) \\ r(t) &= C_r x^r(t)\end{aligned}$$

- Consider the augmented prediction model

$$\begin{bmatrix} x_{k+1} \\ x_{k+1}^r \end{bmatrix} = \begin{bmatrix} A & 0 \\ 0 & A_r \end{bmatrix} \begin{bmatrix} x_k \\ x_k^r \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} u_k$$

- Design a state observer (e.g., via pole-placement) to estimate $x(t), x^r(t)$ from
$$\begin{bmatrix} y(t) \\ r(t) \end{bmatrix} = \begin{bmatrix} C & 0 \\ 0 & C_r \end{bmatrix} \begin{bmatrix} x(t) \\ x^r(t) \end{bmatrix}$$
- Design an MPC controller with output $e_k = y_k - r_k = [C \ -C_r] \begin{bmatrix} x_k \\ x_k^r \end{bmatrix}$

MPC AND INTERNAL MODEL PRINCIPLE

- Penalize $\sum_{k=1}^N e_k$ (+small penalty on u or Δu)
- Set control horizon $N_u = N$
- Example: $r(t) = r_0 \sin(\omega t + \phi_0)$, $\omega = 1 \text{ rad/s}$

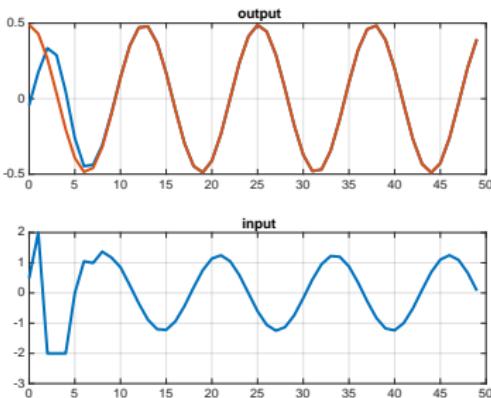
$$A = \begin{bmatrix} 1.6416 & -0.7668 & 0.2416 \\ 0 & 0 & 0 \\ 0 & 0.125 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 0.5 \\ 0 \\ 0 \end{bmatrix}$$

$$C = [0.1349 \ 0.0159 \ -0.1933]$$

$$A_r = \begin{bmatrix} 1.7552 & -1 \\ 1 & 0 \end{bmatrix}$$

$$C_r = [.2448 \ .2448]$$



observer poles placed in
 $\{0.3, 0.4, 0.5, 0.6, 0.7\}$

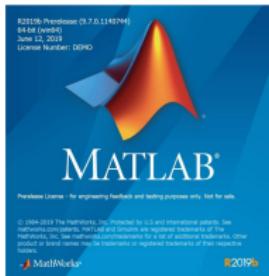
sample time $T_s = 0.5 \text{ s}$

input saturation $-2 \leq u(t) \leq 2$

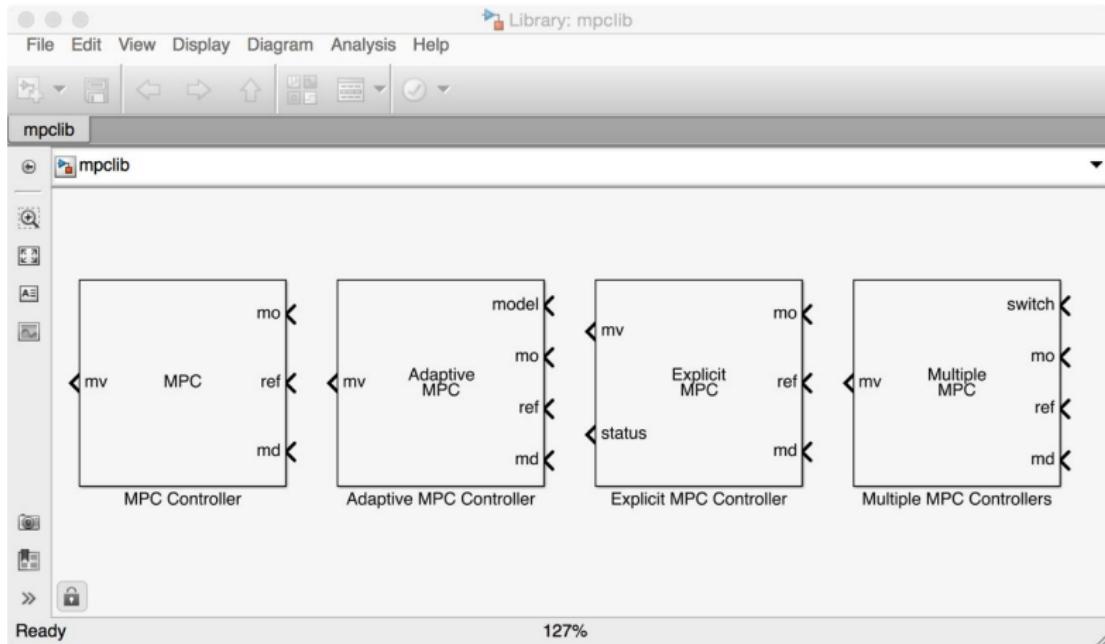
MODEL PREDICTIVE CONTROL TOOLBOX

(Bemporad, Ricker, Morari, 1998-present)

- Several **linear MPC** design features available:
 - **explicit** MPC
 - **time-varying**/adaptive models, weights, constraints
 - stability/frequency analysis of closed-loop (inactive constraints)
 - ...
- Prediction models can be generated by the Identification Toolbox or automatically linearized from Simulink
- Fast **command-line** MPC functions
(compiled EML-code)
- **Graphical User Interface**
- **Simulink library** (compiled EML-code)



MPC SIMULINK LIBRARY



```
>> mpclib
```

MPC SIMULINK BLOCK

Function Block Parameters: MPC Controller

MPC (mask) (link)

The MPC Controller block lets you design and simulate a model predictive controller defined in the Model Predictive Control Toolbox.

Parameters

MPC Controller mpcobj Design

Initial Controller State [] Review

Block Options

General Online Features Others

Additional Imports

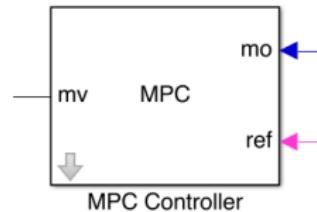
- Measured disturbance (md)
- External manipulated variable (ext.mv)

Additional Outputs

- Optimal cost (cost)
- Optimal control sequence (mv.seq)
- Optimization status (qp.status)
- Estimated plant, disturbance and noise model states (est.state)

State Estimation

- Use custom estimated states instead of measured outputs ($x[k|k]$)



MPC SIMULINK BLOCK

Function Block Parameters: MPC Controller

MPC (mask) (link)

The MPC Controller block lets you design and simulate a model predictive controller defined in the Model Predictive Control Toolbox.

Parameters

MPC Controller Design

Initial Controller State Review

Block Options

General Online Features Others

Constraints

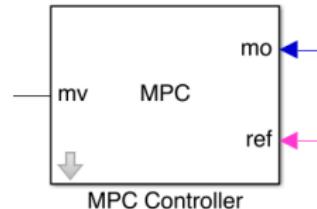
Plant input and output limits (umin, umax, ymin, ymax)

Weights

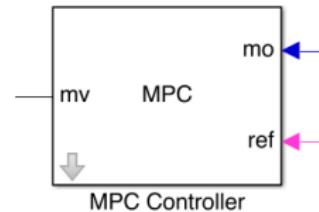
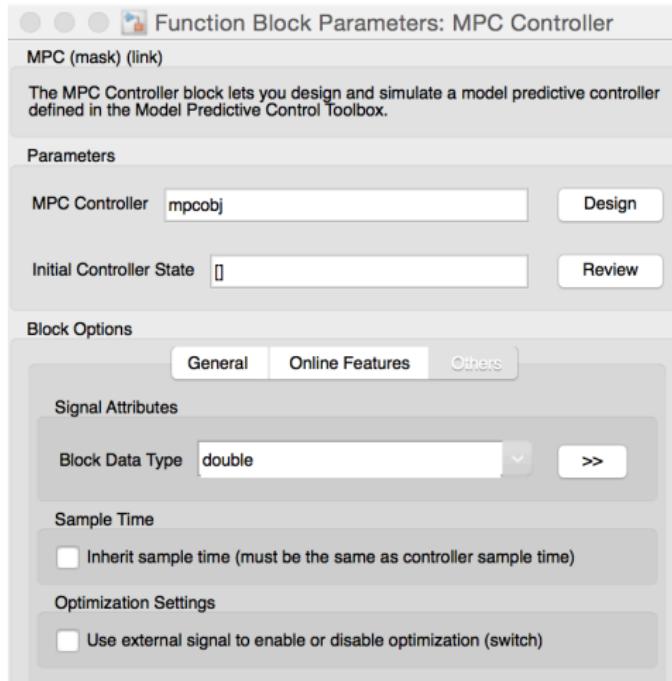
Weights on plant outputs (y.wt)
 Weights on manipulated variables (u.wt)
 Weights on manipulated variable changes (du.wt)
 Weight on overall constraint softening (ecr.wt)

MV Targets

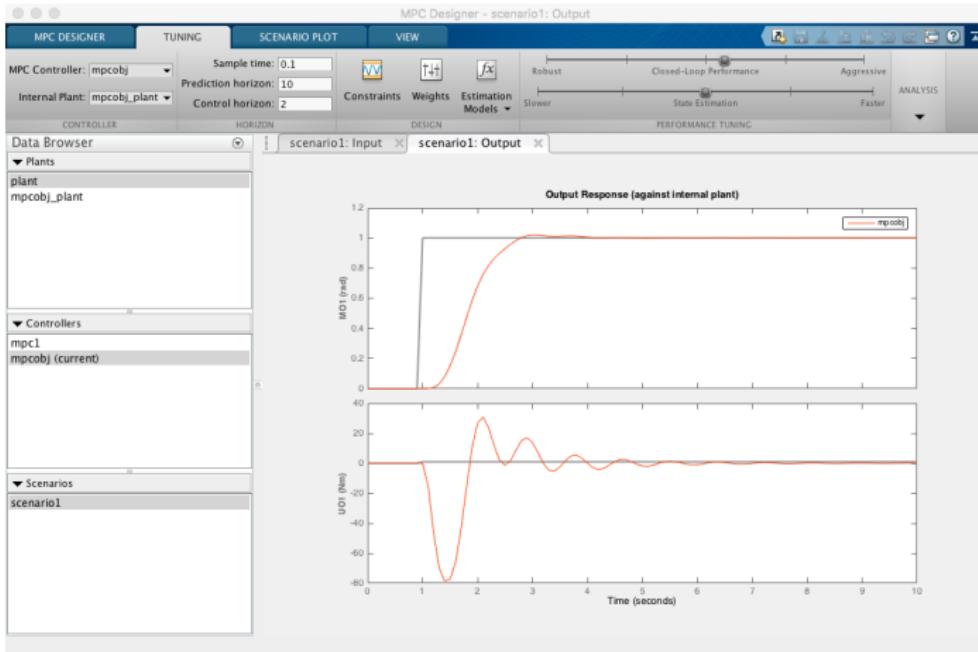
Targets for manipulated variables (mv.target)



MPC SIMULINK BLOCK



MPC GRAPHICAL USER INTERFACE

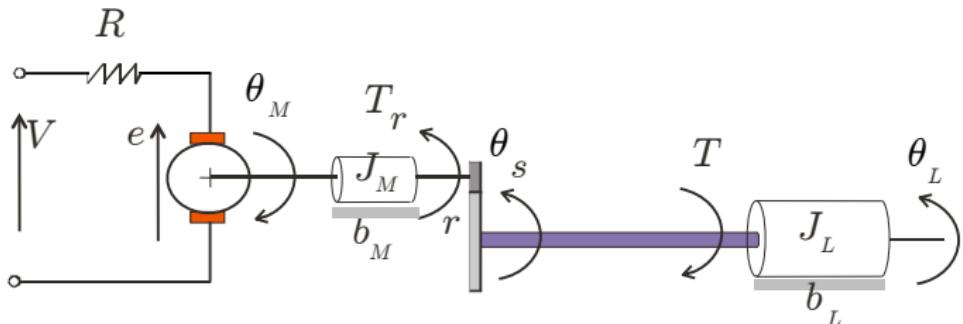


>> mpcDesigner

(old version: >> mpctool)

See video on Mathworks' web site ([link](#))

EXAMPLE: MPC OF A DC SERVOMOTOR



Symbol	Value (MKS)	Meaning
L_S	1.0	shaft length
d_S	0.02	shaft diameter
J_S	negligible	shaft inertia
J_M	0.5	motor inertia
β_M	0.1	motor viscous friction coefficient
R	20	resistance of armature
k_T	10	motor constant
ρ	20	gear ratio
k_θ	1280.2	torsional rigidity
J_L	$50J_M$	nominal load inertia
β_L	25	load viscous friction coefficient
T_s	0.1	sampling time

>> mpcmotor

see also
`linear/dcmotor.m`
(Hybrid Toolbox)

DC SERVOMOTOR MODEL

$$\begin{aligned}\dot{x} &= \begin{bmatrix} 0 & 1 & 0 & 0 \\ -\frac{k_\theta}{J_L} & -\frac{\beta_L}{J_L} & \frac{k_\theta}{\rho J_L} & 0 \\ 0 & 0 & 0 & 1 \\ \frac{k_\theta}{\rho J_M} & 0 & -\frac{k_\theta}{\rho^2 J_M} & -\frac{\beta_M + k_T^2/R}{J_M} \end{bmatrix} x + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{k_T}{R J_M} \end{bmatrix} V \\ \theta_L &= \begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix} x \\ T &= \begin{bmatrix} k_\theta & 0 & -\frac{k_\theta}{\rho} & 0 \end{bmatrix} x\end{aligned}$$
$$x = \begin{bmatrix} \theta_L \\ \dot{\theta}_L \\ \theta_M \\ \dot{\theta}_M \end{bmatrix}$$
$$y = \begin{bmatrix} \theta_L \\ T \end{bmatrix}$$

```
>> [plant, tau] = mpcmotormodel;
>> plant = setmpcsignals(plant,'MV',1,'MO',1,'UO',2);
```

DC SERVOMOTOR CONSTRAINTS

- The input DC voltage V is bounded within the range

$$|V| \leq 220 \text{ V}$$

- Finite shear strength $\tau_{adm} = 50 \text{ N/mm}^2$ requires that the torsional torque T satisfies the constraint

$$|T| \leq 78.5398 \text{ Nm}$$

- Sampling time of model/controller: $T_s = 0.1s$

```
>> MV = struct('Min',-220,'Max',220);
>> OV = struct('Min',{-Inf,-78.5398},'Max',{Inf,78.5398});
>> Ts = 0.1;
```

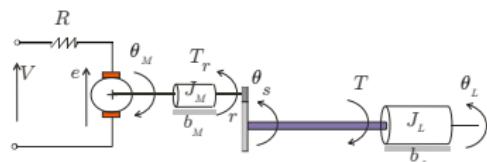
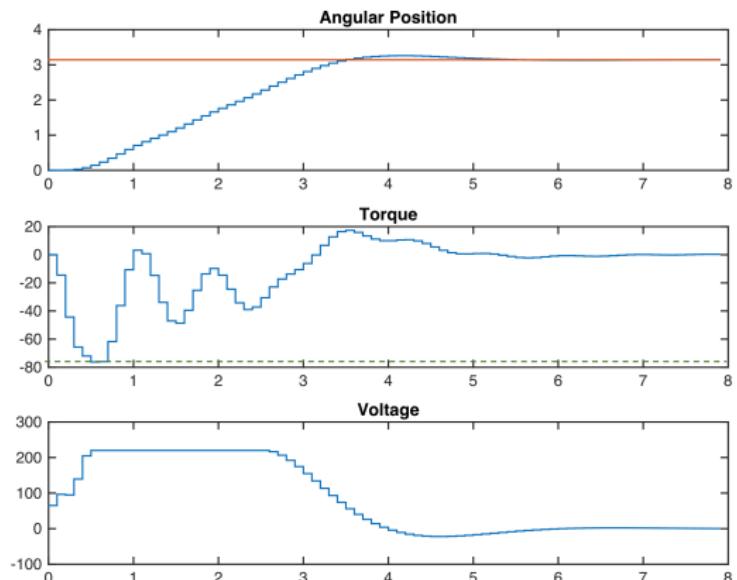
DC SERVOMOTOR - MPC SETUP

$$\min_{\Delta U} \quad \sum_{k=0}^{p-1} \|W^y(y_{k+1} - r(t))\|^2 + \|W^{\Delta u} \Delta u_k\|^2 + \rho_\epsilon \epsilon^2$$

subj. to $\Delta u_{\min} \leq \Delta u_k \leq \Delta u_{\max}, k = 0, \dots, m-1$
 $\Delta u_k = 0, k = m, \dots, p-1$
 $u_{\min} \leq u_k \leq u_{\max}, k = 0, \dots, m-1$
 $y_{\min} - \epsilon V_{\min} \leq y_k \leq y_{\max} + \epsilon V_{\max}, k = 1, \dots, p$

```
>> Weights = struct('MV',0,'MVRate',0.1,'OV',[0.1 0]);
>> p = 10;
>> m = 2;
>> mpcobj = mpc(plant,Ts,p,m,Weights,MV,OV);
```

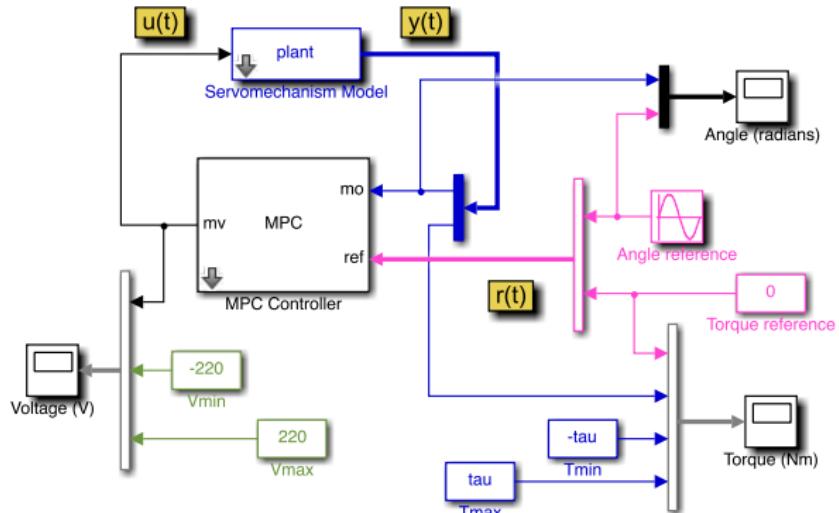
DC SERVOMOTOR - CLOSED-LOOP SIMULATION



Closed-loop simulation using the `sim` command

```
>> Tstop = 8; % seconds  
>> Tf = round(Tstop/Ts); % simulation iterations  
>> r = [pi*ones(Tf,1) zeros(Tf,1)];  
>> [y1,t1,u1] = sim(mpcoobj,Tf,r);
```

DC SERVOMOTOR - CLOSED-LOOP SIMULATION



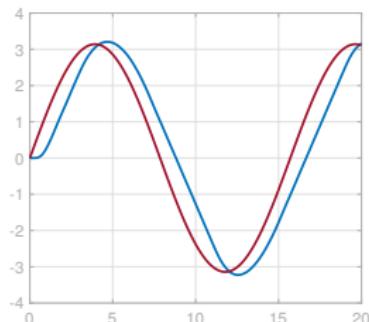
Closed-loop
simulation in
Simulink

Copyright 1990-2014 The MathWorks, Inc.

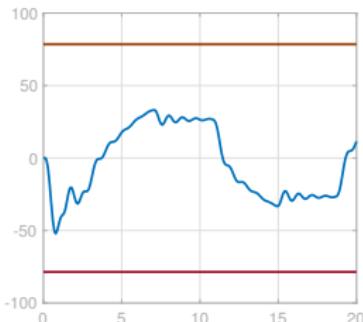
```
>> mdl = 'mpc_motor';
>> open_system(mdl)
>> sim(mdl)
```

DC SERVOMOTOR - CLOSED-LOOP SIMULATION

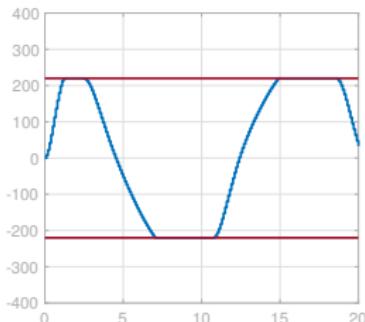
$\theta_L(t)$



$T(t)$



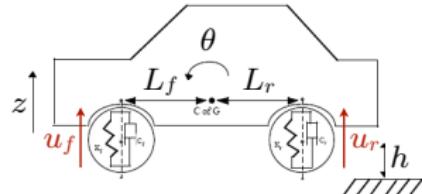
$V(t)$



- same MPC tuning parameters
- setpoint $r(t) = \pi \sin(0.4t)$ deg

EXAMPLE: MPC OF ACTIVE SUSPENSIONS

- Take simulation model `sldemo_suspn` in MATLAB



$$F_{front} = 2K_f(L_f\theta - (z + h)) + 2C_f(L_f\dot{\theta} - \dot{z}) + u_f$$

F_{front}, F_{rear} = upward force on body from front/rear suspension

K_f, K_r = front and rear suspension spring constant

C_f, C_r = front and rear suspension damping rate

L_f, L_r = horizontal distance from c.g. to front/rear suspension

$\theta, \dot{\theta}$ = pitch (rotational) angle and its rate of change

z, \dot{z} = bounce (vertical) distance and its rate of change

- For control purposes we add external forces u_f, u_r as manipulated variables
- The system has 4 states: $\theta, \dot{\theta}, z, \dot{z}$
- Measured disturbances: road height h , pitch moment from vehicle acceleration

EXAMPLE: MPC OF ACTIVE SUSPENSIONS

- Step #1: get a linear discrete-time model (4 inputs, 3 outputs, 4 states)

```
>> plant_mdl = 'suspension_model';
>> op = operspec(plant_mdl);
>> [op_point, op_report] = findop(plant_mdl,op);
>> sys = linearize(plant_mdl, op_point);
>> Ts = 0.025; % sample time (s)
>> plant = c2d(sys,Ts);

>> plant = setmpcsignals(plant,'MV',[1 2],'MD',...
[3 4],'MO',[1 2],'UO',3);
```

EXAMPLE: MPC OF ACTIVE SUSPENSIONS

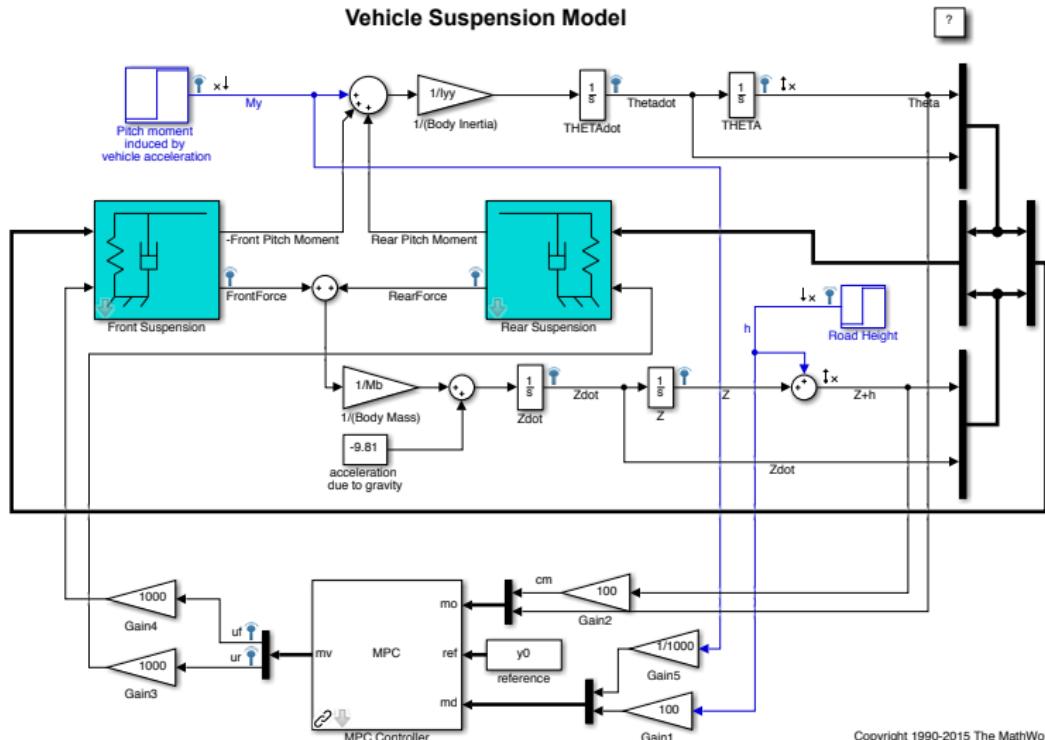
- Step #2: design the MPC controller

```
>> dfmax = .1/.1; % [kN/s]
>> MV = struct('RateMin',-Ts*dfmax, Ts*dfmax, ...
    'RateMax',Ts*dfmax,Ts*dfmax);
>> OV = [];
>> Weights = struct('MV',[0 0], 'MVRate',[.01 .01], ...
    'OV',[.01 0 10]);

>> p = 50; % Prediction horizon
>> m = 5; % Control horizon

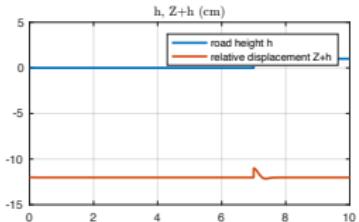
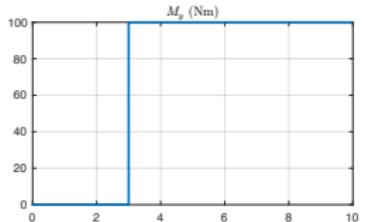
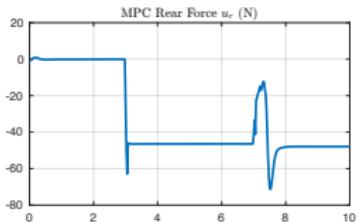
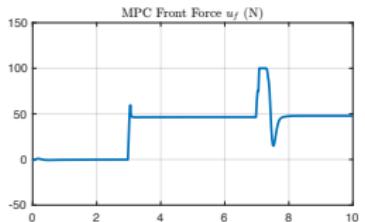
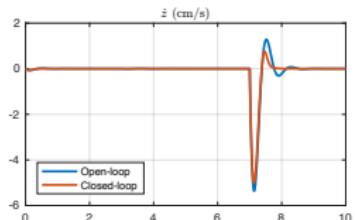
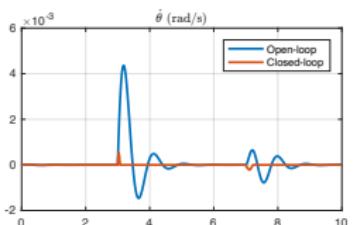
>> mpcobj = mpc(plant,Ts,p,m,Weights,MV,OV);
```

EXAMPLE: MPC OF ACTIVE SUSPENSIONS



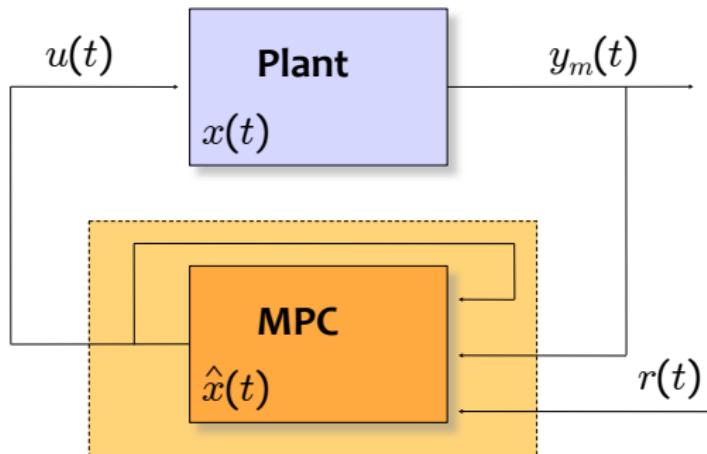
EXAMPLE: MPC OF ACTIVE SUSPENSIONS

- Closed-loop MPC results



FREQUENCY ANALYSIS OF MPC (FOR SMALL SIGNALS)

- Unconstrained MPC gain + linear observer = linear dynamical system
- Closed-loop MPC analysis can be performed using standard frequency-domain tools (e.g., Bode plots for sensitivity analysis)



```
>> sys=ss(mpcobj)  
>> sys=tf(mpcobj)
```



returns the LTI object of the MPC controller
(when constraints are inactive)

CONTROLLER MATCHING

- Given a desired linear controller $u = K_d x$, find a set of weights Q, R, P defining an MPC problem such that

$$-\begin{bmatrix} I & 0 & \dots & 0 \end{bmatrix} H^{-1} F = K_d$$

i.e., the MPC law coincides with K_d when the constraints are inactive

- Recall that the QP matrices are $H = 2(\bar{R} + \bar{S}' \bar{Q} \bar{S})$, $F = 2\bar{S}' \bar{Q} \bar{T}$, where

$$\bar{Q} = \begin{bmatrix} Q & 0 & 0 & \dots & 0 \\ 0 & Q & 0 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & \dots & 0 & Q & 0 \\ 0 & 0 & \dots & 0 & P \end{bmatrix}, \quad \bar{R} = \begin{bmatrix} R & 0 & 0 & \dots & 0 \\ 0 & R & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & \dots & 0 & R \end{bmatrix}, \quad \bar{S} = \begin{bmatrix} B & 0 & \dots & 0 \\ AB & B & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ A^{N-1}B & A^{N-2}B & \dots & B \end{bmatrix}, \quad \bar{T} = \begin{bmatrix} A \\ A^2 \\ \vdots \\ A^N \end{bmatrix}$$

- The above inverse optimality problem can be cast to a convex problem

(Di Cairano, Bemporad, 2010)

- More general result: see (Zanon, Bemporad, 2020)

CONTROLLER MATCHING - EXAMPLE

(Di Cairano, Bemporad, 2010)

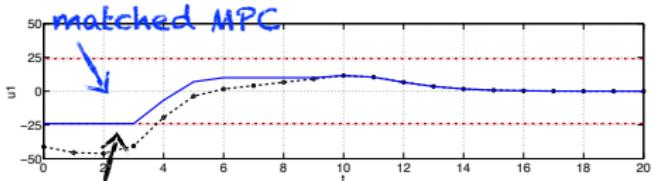
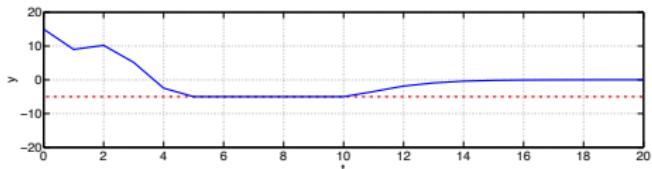
- Open-loop process: $y(t) = 1.8y(t-1) + 1.2y(t-2) + u(t-1)$
- Constraints: $-24 \leq u(t) \leq 24, y(t) \geq -5$
- Desired controller = PID with gains $K_I = 0.248, K_P = 0.752, K_D = 2.237$

$$\begin{aligned} u(t) &= -\left(K_I \mathcal{I}(t) + K_P y(t) + \frac{K_D}{T_s}(y(t) - y(t-1))\right) \\ \mathcal{I}(t) &= \mathcal{I}(t-1) + T_s y(t) \end{aligned} \quad x(t) = \begin{bmatrix} y(t-1) \\ y(t-2) \\ \mathcal{I}(t-1) \\ u(t-1) \end{bmatrix}$$

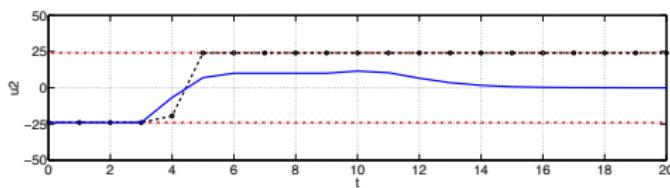
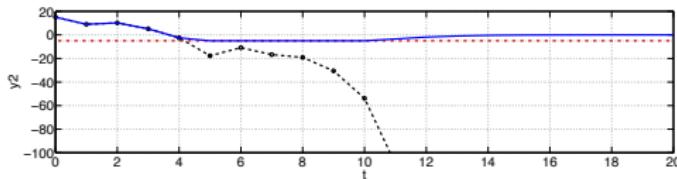
- Matching result (using inverse LQR):

$$Q^* = \begin{bmatrix} 6.401 & 0.064 & -0.001 & 0.020 \\ 0.064 & 6.605 & 0.006 & 0.080 \\ -0.001 & 0.006 & 6.647 & -0.020 \\ 0.019 & 0.080 & -0.020 & 6.378 \end{bmatrix}, R^* = 1, P^* = \begin{bmatrix} 422.7 & 241.7 & 50.39 & 201.4 \\ 241.7 & 151.0 & 32.13 & 120.4 \\ 50.39 & 32.13 & 19.85 & 26.75 \\ 201.4 & 120.4 & 26.75 & 106.6 \end{bmatrix}$$

CONTROLLER MATCHING - EXAMPLE



what PID would apply



- Note: This is not trivially a saturation of a PID controller. In this case saturating the PID output leads to closed-loop instability!

LINEAR MPC BASED ON LINEAR PROGRAMMING

LINEAR MPC BASED ON LP

(Propoi, 1963) (Bemporad, Borrelli, Morari, 2003)

- Linear prediction model: $\begin{cases} x_{k+1} = Ax_k + Bu_k & x \in \mathbb{R}^n \\ y_k = Cx_k & u \in \mathbb{R}^m \\ & y \in \mathbb{R}^p \end{cases}$
- Constraints to enforce:

$$\begin{cases} u_{\min} \leq u(t) \leq u_{\max} \\ y_{\min} \leq y(t) \leq y_{\max} \end{cases}$$

- Constrained optimal control problem (∞ -norms): $\|v\|_\infty \triangleq \max_{i=1,\dots,n} |v_i|$

$$\min_z \|Px_N\|_\infty + \sum_{k=0}^{N-1} \|Qx_k\|_\infty + \|Ru_k\|_\infty$$

$$\text{s.t. } u_{\min} \leq u_k \leq u_{\max}, k = 0, \dots, N-1 \\ y_{\min} \leq y_k \leq y_{\max}, k = 1, \dots, N$$

$$\begin{array}{ll} R, Q, P \\ \text{full rank} \end{array} z = \begin{bmatrix} u_0 \\ u_1 \\ \vdots \\ u_{N-1} \end{bmatrix}$$

LINEAR MPC BASED ON LP

- Basic trick: introduce slack variables ($Q^i = i\text{-th row of } Q$)

$$\begin{array}{lcl} \epsilon_k^x & \geq & \|Qx_k\|_\infty \\ \epsilon_k^u & \geq & \|R u_k\|_\infty \\ \epsilon_N^x & \geq & \|Px_k\|_\infty \end{array} \quad \rightarrow \quad \begin{array}{lcl} \epsilon_k^x & \geq & Q^i x_k & i = 1, \dots, n \\ \epsilon_k^u & \geq & -Q^i x_k & k = 0, \dots, N-1 \\ \epsilon_k^u & \geq & R^i u_k & i = 1, \dots, m \\ \epsilon_k^u & \geq & -R^i u_k & k = 0, \dots, N-1 \\ \epsilon_N^x & \geq & P^i x_N & i = 1, \dots, n \\ \epsilon_N^x & \geq & -P^i x_N \end{array}$$

- Example:

$$\begin{aligned} \min_x |x| \rightarrow \min_{x,\epsilon} & \quad \epsilon \\ \text{s.t.} \quad & \epsilon \geq x \\ & \epsilon \leq -x \end{aligned}$$

LINEAR MPC BASED ON LP

- Linear prediction model: $x_k = A^k x_0 + \sum_{i=0}^{k-1} A^i B u_{k-1-i}$
- Optimization problem:

$$V(x_0) = \min_z [1 \dots 1 \ 0 \dots 0] z \quad (\text{linear objective})$$

$$\text{s.t. } Gz \leq W + Sx_0 \quad (\text{linear constraints})$$

Linear Program (LP)

- optimization vector: $z \triangleq [\epsilon_0^u \dots \epsilon_{N-1}^u \ \epsilon_1^x \dots \epsilon_N^x \ u'_0, \dots, u'_{N-1}]' \in \mathbb{R}^{N(n_u+2)}$
- G, W, S are obtained from weights Q, R, P , and model matrices A, B, C
- Q, R, P can be selected to guarantee closed-loop stability

(Bemporad, Borrelli, Morari, 2003)

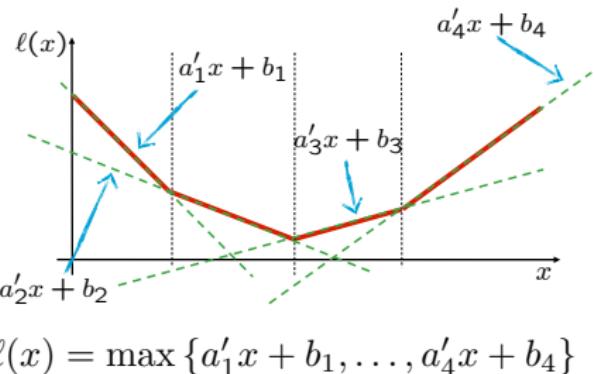
EXTENSION TO ARBITRARY CONVEX PWA FUNCTIONS

RESULT

Every convex piecewise affine function $\ell : \mathbb{R}^n \rightarrow \mathbb{R}$ can be represented as the max of affine functions, and vice versa

(Schechter, 1987)

Example: $\ell(x) = |x| = \max\{x, -x\}$



- Constrained optimal control problem

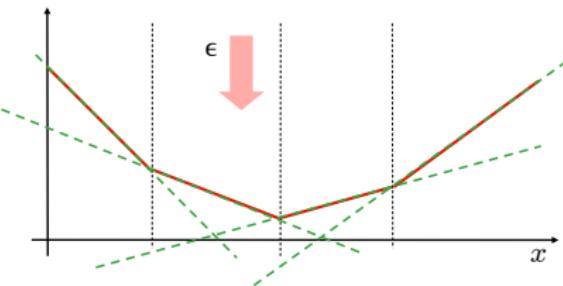
$$\min_U \quad \ell_N(x_N) + \sum_{k=0}^{N-1} \ell_k(x_k, u_k)$$

$$\text{s.t.} \quad g_k(x_k, u_k) \leq 0, \quad k = 0, \dots, N-1 \\ g_N(x_N) \leq 0$$

ℓ_k, ℓ_N, g_k, g_N are arbitrary convex piecewise affine (PWA) functions

CONVEX PWA OPTIMIZATION PROBLEMS AND LP

- Minimization of a **convex PWA function** $\ell(x)$:



$$\begin{aligned} & \min_{\epsilon, x} \quad \epsilon \\ \text{s.t.} \quad & \left\{ \begin{array}{l} \epsilon \geq a'_1 x + b_1 \\ \epsilon \geq a'_2 x + b_2 \\ \epsilon \geq a'_3 x + b_3 \\ \epsilon \geq a'_4 x + b_4 \end{array} \right. \end{aligned}$$

- By construction $\epsilon \geq \max\{a'_1 x + b_1, a'_2 x + b_2, a'_3 x + b_3, a'_4 x + b_4\}$
- By contradiction it is easy to show that at the optimum we have that

$$\epsilon = \max\{a'_1 x + b_1, a'_2 x + b_2, a'_3 x + b_3, a'_4 x + b_4\}$$

- Convex PWA constraints** $\ell(x) \leq 0$ can be handled similarly by imposing $a'_i x + b_i \leq 0, \forall i = 1, 2, 3, 4$

LP-BASED VS QP-BASED MPC

- QP- and LP-based share the same set of feasible inputs ($Gz \leq W + Sx$)
- When constraints dominate over performance there is little difference between them (e.g., during transients)
- Small-signal response, however, is usually less smooth with LP than with QP, because in LP an optimal point is always on a vertex



$$\left\{ z : \begin{array}{l} Gz \leq W + Sx \\ \bar{G}z + \bar{E}\epsilon \leq \bar{W} + \bar{S}x \end{array} \right\}$$

$$\{z : Gz \leq W + Sx\}$$

ϵ = additional slack variables introduced
to represent convex PWA costs