Design of Networked Control Systems for Chemical Processes

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NETWORKED PROCESS CONTROL

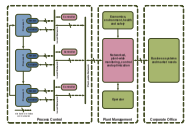
Looking ahead, it does not seem too farfetched to envision that process components will be thought of as embedded "plug and play" devices ... Such units will have widely different scales, but standard interconnects towards other physical devices and the Web.
by Tabor, AIChE J., March 2002

The increasing need to balance economic prosperity with sustainable EH&S performance and corporate social responsibility together with recent advances in the manufacturing of wireless sensor/actuator networks provide a strong motivation for introducing a new paradigm for networked, plant-wide monitoring and control.
by Christofides and, AIChE J, November, 2007.

Integration of wireless networks with plant networks will make business and process applications easier to use and more robust, giving workers more power and increasing their oversight of operations and the environment.
by Pere Ferrarons and Bob Karschnia, Chem. Eng. Prog., May, 2008

As wireless technologies have advanced, old limits have been overcome and new challenges have sprung up. Further growth is likely to be driven by specific application and cost-reduction needs.
by Matthew McKenna-Barry, Chem. Eng. Prog., February, 2010

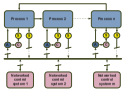
"SMART PLANT" OPERATIONS PARADIGM



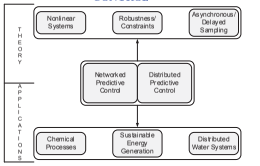
- Process control level: Augmentation of dedicated, local control systems with networked control systems using actuator and/or sensor (wired/wireless) networks (Christofides et al., AIChE J., 2007)
- Plant management level: Plant monitoring and fault-tolerant control using multiple asynchronous measurements from sensor networks / Plant optimization accounting for EH&S considerations in addition to economics

NETWORKED PROCESS CONTROL ARCHITECTURE

- Networked process control: issues need to be addressed (Hespanha et al., IEEE Control Syst. Mag., 2006; Antsaklis and Baillieul, Chem. Eng. Prog., 2008; Christofides et al., AIChE J., 2007)
  - New dynamics in the closed-loop system
    - ▷ Time-varying delays and data losses
  - Additional sensing and actuation capabilities
    - ▷ Multiple, heterogeneous, (e.g., asynchronous, delayed) measurements
  - Augmentation of existing, local control loops with control systems that utilize actuator/sensor networks
  - Cooperation between different controllers
    - ▷ Distributed model predictive control (DMPC)
- New techniques need to be developed for the design of networked control systems



NETWORKED AND DISTRIBUTED PREDICTIVE CONTROL



PRELIMINARIES

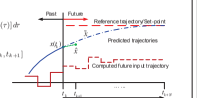
- System description
  $$\dot{x}(t) = f(x(t), u(t), w(t))$$
  - x is system state, u is control input, w is disturbance, f is a vector function
- Explicit nonlinear feedback control law: $u = h(x)$
  - Controller design techniques: Lyapunov-based control and geometric control (E. Sontag, Syst. Contr. Lett., 1989; Y. Ito and E. Sontag, Syst. Contr. Lett., 1994; P. Kokotovic and M. Arcak, Automatica, 2001; P. D. Christofides and N. H. El-Farra, Springer-Verlag, 2005)
  - Guarantees that the origin (steady state) is locally asymptotically stable
  - There exists a Lyapunov function $V(x)$ which satisfies
    $$\dot{V}(x) = \frac{\partial V}{\partial x} f(x, h(x), 0) < 0, \ \forall x \in \Omega$$ V: energy of a physical system
    - ▷ Stability region: $\Omega \subset D$ is a compact set containing the origin
- Optimality is not taken into account

LYAPUNOV-BASED MPC

Preliminaries

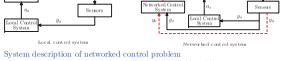
- Lyapunov-based MPC (LMPC)

$$\min_{u \in S(\Delta)} \int_{t_k}^{t_{k+N}} [\tilde{x}(\tau)^T Q_c \tilde{x}(\tau) + u(\tau)^T R_c u(\tau)] d\tau$$
s.t. $\dot{\tilde{x}}(t) = f(\tilde{x}(t), u(t), 0)$
$\dot{\hat{x}}(t) = f(\hat{x}(t), h(\hat{x}(t_k)), 0), \ t \in [t_k, t_{k+1})$
$\tilde{x}(t_k) = \hat{x}(t_k) = x(t_k)$
$u(t) \in U$
$\hat{x}(t) \in X$
$V(\hat{x}(t)) \leq V(\hat{x}(t_k)), \ \forall t \in [t_k, t_{k+1})$



- Guaranteed stability of the closed-loop system (P. Mhaskar et al., IEEE Trans. Autom. Control, 2005; Christofides, Liu and Muñoz de la Peña, Springer, 2011)
  - Convergence is guaranteed by the stability constraint
  - Recursive feasibility is guaranteed by $h(x)$ for all $x \in \Omega$
- The LMPC inherits the stability properties and the stability region (i.e., Ω) of the controller $h(x)$ - applied in sample and hold (practical stability)

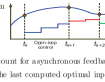
NETWORKED CONTROL PROBLEM



- System description of networked control problem
$$\dot{x}(t) = f(x(t), u_a(t), u_s(t), w(t))$$
$$y_s(t) = h_s(x(t))$$
$$y_a(t) = h_a(x(t))$$
  - Two sets of control inputs, u_a and u_s and measurements y_s and y_a
  - y_s is available continuously and y_a is obtained at times t_k (asynchronously)
  - State measurements x can be obtained from y_s and y_a
- Local control system stability (not necessary)
$$\dot{V}(x) = \frac{\partial V}{\partial x} f(x, k_s(h_s(x)), 0, 0) < 0, \ \forall x \in \Omega$$
  - The local controller $u_s = k(y_s)$, $u_a = 0$ can stabilize the closed-loop system
  - The local controller u_s only has access to the continuous measurement y_s

LMPC WITH ASYNCHRONOUS FEEDBACK

- Issues need to be considered in the presence of asynchronous measurements
  - Stability properties of LMPC for continuous feedback are lost
  - The standard receding horizon strategy cannot be applied
- Maximum time between two consecutive instants in which the loop is closed is bounded by a constant, T_m — allows for deterministic stability analysis
  - t_k, t_{k+1}: consecutive time instants in which the loop is closed
  - $t_{k+1} - t_k \leq T_m$



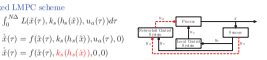
- Proposed approach
  - Modify the MPC formulation to account for asynchronous feedback explicitly
  - When loop is open, keep applying the last computed optimal input trajectory

(Muñoz de la Peña and Christofides, IEEE TAC, 2008; Liu et al., Int. J. Adapt. Control Signal Process., 2009)

NETWORKED CONTROL SYSTEM

(Liu et al., ACC, 2008; Int. J. Control, 2010)

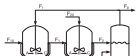
- Networked LMPC scheme
$$\min_{u_a \in S(\Delta)} \int_0^{N\Delta} L(\tilde{x}(\tau), k_s(h_s(\tilde{x})), u_a(\tau)) d\tau$$
$$\dot{\tilde{x}}(\tau) = f(\tilde{x}(\tau), k_s(h_s(\tilde{x})), u_a(\tau), 0)$$
$$\dot{\hat{x}}(\tau) = f(\hat{x}(\tau), k_s(h_s(\hat{x})), 0, 0)$$
$$\hat{x}(0) = \tilde{x}(0) = x(t_k)$$
$$\dot{V}(\hat{x}(\tau)) \leq V(\hat{x}(\tau)), \ \forall \tau \in [0, T_m]$$



- The inputs of the networked control system are defined as follows
$$u_a(t) = k_a(h_a(x)), \ \forall t$$
$$u_s(t) = u_s^*(t - t_k | t_k), \ \forall t \in [t_k, t_{k+1})$$
$$t_{k+1} - t_k \leq T_m \leq N\Delta$$
- Does not modify the existing local control system
- Maintains the local control system stability and improves performance
- Networked control system can be used to calculate the optimal set-points of the local control system based on additional information

APPLICATION TO A REACTOR-SEPARATOR SYSTEM

- Reactor-separator system with recycle
  - 9th order nonlinear system
  - Regulation in a stable equilibrium state
    - ▷ Improve the closed-loop performance



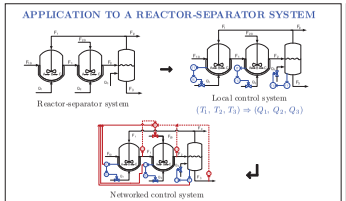
- Control configuration of local control system
  - Manipulated inputs: heat inputs into the three vessels Q_1, Q_2 and Q_3
  - Measurements: temperatures of the three units T_1, T_2 and T_3
- Control configuration of networked control system
  - Manipulated input: flow rate to vessel 2, F_{B2}
  - Additional asynchronous measurements: species concentrations in the three units x_{A1}, x_{B1} ($i = 1, 2, 3$)

APPLICATION TO A REACTOR-SEPARATOR SYSTEM

- Process model

$$\frac{dx_{A1}}{dt} = \frac{F_{10}}{V_1}(x_{A10} - x_{A1}) + \frac{F_2}{V_1}(x_{A,r} - x_{A1}) - k_1 e^{\frac{-E_1}{RT_1}} x_{A1}$$
$$\frac{dx_{B1}}{dt} = \frac{F_{10}}{V_1}(x_{B10} - x_{B1}) + \frac{F_2}{V_1}(x_{B,r} - x_{B1}) + k_1 e^{\frac{-E_1}{RT_1}} x_{A1} - k_2 e^{\frac{-E_2}{RT_1}} x_{B1}$$
$$\frac{dT_1}{dt} = \frac{F_{10}}{V_1}(T_{10} - T_1) + \frac{F_2}{V_1}(T_2 - T_1) + \frac{-\Delta H_1}{C_p} k_1 e^{\frac{-E_1}{RT_1}} x_{A1} + \frac{-\Delta H_2}{C_p} k_2 e^{\frac{-E_2}{RT_1}} x_{B1} + \frac{Q_1}{\rho C_p V_1}$$
$$\frac{dx_{A2}}{dt} = \frac{F_1}{V_2}(x_{A1} - x_{A2}) + \frac{F_{20}}{V_2}(x_{A20} - x_{A2}) - k_1 e^{\frac{-E_1}{RT_2}} x_{A2}$$
$$\frac{dx_{B2}}{dt} = \frac{F_1}{V_2}(x_{B1} - x_{B2}) + \frac{F_{20}}{V_2}(x_{B20} - x_{B2}) + k_1 e^{\frac{-E_1}{RT_2}} x_{A2} - k_2 e^{\frac{-E_2}{RT_2}} x_{B2}$$
$$\frac{dT_2}{dt} = \frac{F_1}{V_2}(T_1 - T_2) + \frac{F_{20}}{V_2}(T_{20} - T_2) + \frac{-\Delta H_1}{C_p} k_1 e^{\frac{-E_1}{RT_2}} x_{A2} + \frac{-\Delta H_2}{C_p} k_2 e^{\frac{-E_2}{RT_2}} x_{B2} + \frac{Q_2}{\rho C_p V_2}$$
$$\frac{dx_{A3}}{dt} = \frac{F_2}{V_3}(x_{A2} - x_{A3}) - \frac{F_r + F_p}{V_3}(x_{A3} - x_{A3})$$
$$\frac{dx_{B3}}{dt} = \frac{F_2}{V_3}(x_{B2} - x_{B3}) - \frac{F_r + F_p}{V_3}(x_{B3} - x_{B3})$$
$$\frac{dT_3}{dt} = \frac{F_2}{V_3}(T_2 - T_3) + \frac{Q_3}{\rho C_p V_3}$$

APPLICATION TO A REACTOR-SEPARATOR SYSTEM



APPLICATION TO A REACTOR-SEPARATOR SYSTEM

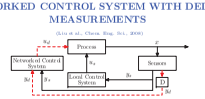
- Comparison from the point of view of performance
  - Performance index $L(x, u_s, u_a) = \sum x^T Q_c x$
  - $Q_c = diag([10^4 \ \ 10^4 \ \ 1 \ \ 10^4 \ \ 10^4 \ \ 1 \ \ 10^4 \ \ 10^4 \ \ 1])$

$x(t_k)$	NCS	LCS
1	1.179×10^5	2.760×10^5
2	1.164×10^5	2.776×10^5
3	1.273×10^5	2.991×10^5
4	1.351×10^5	3.177×10^5
5	1.304×10^5	3.240×10^5
6	1.560×10^5	3.742×10^5
7	1.645×10^5	3.934×10^5
8	1.701×10^5	4.107×10^5
9	1.902×10^5	4.408×10^5
10	1.846×10^5	4.492×10^5

- The closed-loop performance is improved by about 50% under the networked control system

NETWORKED CONTROL SYSTEM WITH DELAYED MEASUREMENTS

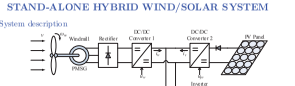
(Liu et al., Chem. Eng. Sci., 2008)



- Modeling of measurements with delays
  - Measurements received at asynchronous time instants with delays
  - Delays are time-varying
- LMPC with delayed measurements (Liu et al., Int. J. Adapt. Control Signal Process., 2009)
  - When a delayed measurement is received, the nominal model and applied inputs are used to estimate the current state
  - When the loop is open, apply the last optimal input trajectory
- Networked control system
  - Maintains the local control system stability and improves performance

STAND-ALONE HYBRID WIND/SOLAR SYSTEM

- System description

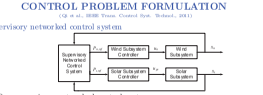


  - One supervisory networked control system
  - Computes the power references (set-points) for the two subsystems
  - Two local control systems
  - Operate the subsystems to track the power references
- Control objectives
  - Primary control objective is to operate the wind and solar subsystems to generate enough energy to satisfy the load demand
  - Secondary control objective is to optimize the operation
    - ▷ Maximum increasing rates on the generated powers to reduce surge currents and keep the system operated smoothly
    - ▷ No frequent discharge and charge of the battery to extend its life cycle
- Wind generation subsystem
  - ▷ Windmill ▷ Permanent-magnet synchronous generator (PMSG)
  - ▷ Rectifier ▷ DC/DC converter
- Solar generation subsystem
  - ▷ Photo-voltaic (PV) panel ▷ DC/DC converter
- Battery bank
- Load - Future load is assumed to be known
- DC bus

CONTROL PROBLEM FORMULATION

(Ji et al., IEEE Trans. Control Syst. Technol., 2011)

- Supervisory networked control system



SUPERVISORY NETWORKED CONTROL SYSTEM

(Ji et al., IEEE Trans. Control Syst. Technol., 2011)

- Proposed MDP design

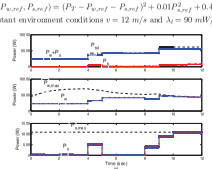
$$\min_{\substack{P_{w,ref} \in S(\Delta) \\ P_{s,ref} \in S(\Delta)}} \int_0^{N\Delta} L(\tilde{x}(\tau), P_{w,ref}(\tau), P_{s,ref}(\tau)) d\tau$$
$$P_{w,ref}(\tau) \leq \min\{P_{w,max}(\tau)\}, \ \tau \in [j\Delta, (j+1)\Delta)$$
$$P_{s,ref}(\tau) \leq \min\{P_{s,max}(\tau)\}, \ \tau \in [j\Delta, (j+1)\Delta)$$
$$P_{w,ref}(j+1)\Delta) - P_{w,ref}(j\Delta) \leq dP_{w,max}$$
$$P_{s,ref}((j+1)\Delta) - P_{s,ref}(j\Delta) \leq dP_{s,max}$$
$$\dot{\tilde{x}}(\tau) = f(\tilde{x}(\tau)) + g(\tilde{x}(\tau))u(\tau)$$
$$h(\tilde{x}) = 0$$
$$\tilde{x}(0) = x(t_k)$$

Feasibility
Constraints on power change rates
Process model

  - $L(x, P_{w,ref}, P_{s,ref})$ is a cost function
  - Power references are achievable for the two local control systems
  - $dP_{w,max}$ and $dP_{s,max}$ are upper bounds on the increasing rates of $P_{w,ref}$ and $P_{s,ref}$
  - System model is used to predict the maximum achievable power of subsystems

SIMULATION RESULTS

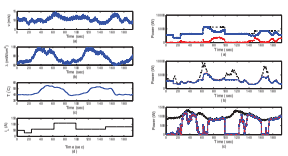
- Short time period simulation
  - $L(x, P_{w,ref}, P_{s,ref}) = (P_T - P_{w,ref} - P_{s,ref})^2 + 0.01P_{w,ref}^2 + 0.4\Delta P_{w,ref}^2$
  - Constant environment conditions $v = 12$ m/s and $\lambda_l = 90$ mW/cm^2



- The supervisory control system coordinates the wind and solar subsystems as well as the battery bank to best satisfy the power demand

SIMULATION RESULTS

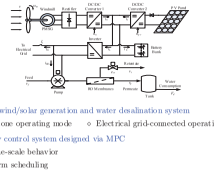
- High-frequency disturbance of weather condition



- The supervisory control system is robust to high-frequency weather disturbances

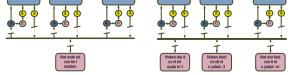
INTEGRATED WIND/SOLAR AND RO SYSTEM

(Ji et al., IEEE Trans. Control Syst. Technol., accepted)



- Integrated wind/solar generation and water desalination system
  - Stand-alone operating mode
  - Electrical grid-connected operating mode
- Supervisory control system designed via MPC
  - Two-time-scale behavior
  - Long-term scheduling
  - Efficiently coordinates wind/solar/battery/RO subsystems and optimally provides power to the electrical grid

DISTRIBUTED PROCESS CONTROL ARCHITECTURE



- Centralized process control architecture
  - Computational complexity
  - Organization and maintenance
  - Fault tolerance
- More towards distributed process control architecture
  - Control inputs are evaluated in more than one distributed controllers
- Issues need to be addressed
  - Coordination of controllers to guarantee closed-loop stability and performance
  - Communication strategy between distributed controllers

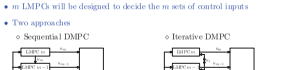
DISTRIBUTED PROCESS CONTROL PROBLEM

- System description
$$\dot{x}(t) = f(x(t)) + \sum_{i=1}^{m} g_i(x(t))u_i(t) + k(x(t))w(t)$$
  - u_i $(i = 1, \ldots, m)$: m sets of control inputs with $|u_i| \leq u_i^{max}$ $(i = 1, \ldots, m)$
  - $f(x)$, $g_i(x)$ $(i = 1, \ldots, m)$ and $k(x)$: vector functions
- Nonlinear feedback control law, $u = h(x) = [h_1(x) \ \ldots \ h_m(x)]^T$
$$\dot{V}(x) = \frac{\partial V(x)}{\partial x}(f(x) + \sum_{i=1}^{m} g_i(x)h_i(x)) < 0$$
  - Renders the origin of the nominal system asymptotically stable under the control: $u_i = h_i(x)$ $(i = 1, \ldots, m)$
  - Satisfies the input constraints on u_i $(i = 1, \ldots, m)$
  - Stability region: $\Omega \subset D$ is a compact set containing the origin
- Distributed model predictive control (DMPC) - each MPC optimizes the same (global) cost function (cooperative, distributed MPC)

DMPC ARCHITECTURES

(Liu et al., AIChE J., 2009; AIChE J., 2010)

- m LMPCs will be designed to decide the m sets of control inputs
- Two approaches



- Sequential DMPC: One-directional communication, each controller is evaluated once at a sampling time
- Iterative DMPC: Bi-directional communication, controllers iterate to achieve convergence at a sampling time

SEQUENTIAL DMPC

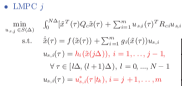
(Liu et al., AIChE J., 2009; AIChE J., 2010)

- Proposed implementation strategy for sequential DMPC
  1. At each sampling time t_k, all the LMPC controllers receive the state measurement $x(t_k)$ from the sensors
  2. For $j = m$ to 1

    2.1. LMPC j receives the entire future input trajectories of u_i, $i = m, \ldots, j+1$, from LMPC $j+1$ and evaluates the future input trajectory of u_j based on $x(t_k)$ and the received future input trajectories
    2.2. LMPC j sends the first step input value of u_j to its actuators and the entire future input trajectories of u_i, $i = m, \ldots, j$, to LMPC $j-1$

DESIGN OF LMPC CONTROLLERS

- LMPC j
$$\min_{u_{s,j} \in S(\Delta)} \int_0^{N\Delta} [\tilde{x}^T(\tau) Q_c \tilde{x}(\tau) + \sum_{i=1}^{m} u_{s,i}(\tau)^T R_{c,i} u_{s,i}(\tau)] d\tau$$
s.t. $\dot{\tilde{x}}(\tau) = f(\tilde{x}(\tau)) + \sum_{i=1}^{m} g_i(\tilde{x}(\tau))u_{s,i}$
$u_{s,i}(\tau) = h_i(\tilde{x}(j\Delta)), \ i = 1, \ldots, j-1,$
$\forall \tau \in [l\Delta, (l+1)\Delta), \ l = 0, \ldots, N-1$
$u_{s,i}(\tau) = u_{s,i}^*(\tau | t_k), \ i = j+1, \ldots, m$
$u_{s,i}(\tau) \in U_i$
$\tilde{x}(0) = x(t_k)$
$\frac{\partial V(x(t_k))}{\partial x} g_j(x(t_k)) u_{s,j}(0) \leq \frac{\partial V(x(t_k))}{\partial x} g_j(x(t_k)) h_j(x(t_k))$

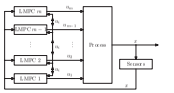


  - LMPC j assumes that LMPC $j-1$ to LMPC 1 apply $h(x)$
  - LMPC j receives input trajectories of all the LMPCs evaluated before it
  - Stability constraint guarantees practical stability
- Receding horizon scheme
$$u_i(t) = u_{s,i}^*(t - t_k | t_k), \ i = 1, \ldots, m, \ \forall t \in [t_k, t_{k+1})$$

ITERATIVE DMPC

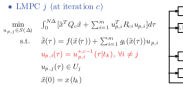
(Liu et al., AIChE J., 2009; AIChE J., 2010)

- Proposed implementation strategy for iterative DMPC
  1. At t_k, all the controllers receive $x(t_k)$ and then evaluate future input trajectories with initial input guesses generated by $h(\cdot)$
  2. At iteration c ($c \geq 1$):
    2.1. Each LMPC controller evaluates its own future input trajectory
    2.2. The controllers exchange their future input trajectories. Based on all the input trajectories, each controller calculates and stores the value of the cost function
  3. If a termination condition is satisfied, each controller sends the first step value of the future input trajectory corresponding to the smallest value of the cost function to its actuators; if the termination condition is not satisfied, go to step 2 ($c = c + 1$)



DESIGN OF LMPC CONTROLLERS

- LMPC j (at iteration c)
$$\min_{u_{s,j} \in S(\Delta)} \int_0^{N\Delta} [\tilde{x}^T Q_c \tilde{x} + \sum_{i=1}^{m} u_{s,i}^T R_{c,i} u_{s,i}] d\tau$$
s.t. $\dot{\tilde{x}}(\tau) = f(\tilde{x}(\tau)) + \sum_{i=1}^{m} g_i(\tilde{x}(\tau))u_{s,i}$
$u_{s,j}(\tau) = u_{s,j}^{c-1}(\tau | t_k), \ \forall i \neq j$
$u_{s,j}(\tau) \in U_j$
$\tilde{x}(0) = x(t_k)$
$\frac{\partial V(x(t_k))}{\partial x} g_j(x(t_k)) u_{s,j}(0) \leq \frac{\partial V(x(t_k))}{\partial x} g_j(x(t_k)) h_j(x(t_k))$



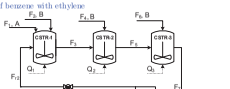
  - ▷ At iteration c, each LMPC assumes that all the other LMPCs use the inputs calculated at iteration $c-1$
  - Stability constraint guarantees practical stability
- Receding horizon scheme: $u_i(t) = u_{s,i}^*(t - t_k | t_k)$, $i = 1, \ldots, m$, $\forall t \in [t_k, t_{k+1})$
- Termination conditions
  - Difference between the values of cost function of two consecutive iterations
  - Maximum iteration number/maximum computational time

CONVERGENCE OF THE ITERATIVE DMPC

- The optimal cost of the iterative DMPC is upper bounded by the cost of the nonlinear controller $h(x)$
  - $h(x)$ is a feasible solution to the iterative DMPC ($x(0) \in \Omega$)
  - Implementation strategy of the iterative DMPC
- Guaranteed convergence for linear systems
  - The optimization problem of LMPC j is convex
  - Using a suitable input update rule, as $c \to \infty$, the optimal cost of the iterative DMPC converges to the one of the corresponding centralized control system
- For general nonlinear systems, the convergence of the optimal cost of the iterative DMPC to the centralized control system is not guaranteed in general

APPLICATION TO A CHEMICAL PROCESS

- Alkylation of benzene with ethylene



  - Three distributed LMPC controllers
    - ▷ LMPC 1: Q_1, Q_2, Q_3 LMPC 2: Q_4, Q_5 LMPC 3: F_4, F_6
  - Input constraints are considered
  - LMPC sampling time $\Delta = 30$ s
  - $h(x)$ is designed based on $V(x) = x^T P x$ via Lyapunov-based control

APPLICATION TO A CHEMICAL PROCESS

Mean Evaluation Times

- Mean evaluation times of LMPC optimization problems for 100 evaluations

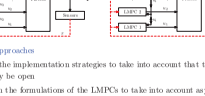
		$N = 1$ (s)	$N = 3$ (s)	$N = 6$ (s)
Centrazed LMPC		2.192	8.694	27.890
Sequential	LMPC 1	0.472	2.358	6.515
	LMPC 2	0.497	1.700	4.493
	LMPC 3	0.365	1.453	3.991
Iterative (1 iteration)	LMPC 1	0.484	2.371	6.280
	LMPC 2	0.426	1.716	4.413
	LMPC 3	0.185	0.854	2.355

- Sequential DMPC vs Centralized: evaluation time is reduced by 36% - 46%
- Iterative DMPC vs Centralized: for one iteration, evaluation time is reduced by more than 70%; 3 - 4 iterations are possible in 1 evaluation of the Centralized LMPC

APPLICATION TO A CHEMICAL PROCESS

Optimality properties

- Performance index
$$J = \sum_{i=1}^{M} x(t_i)^T Q_c x(t_i) + u_1(t_i)^T R_{c1} u_1(t_i) + u_2(t_i)^T R_{c2} u_2(t_i) + u_3(t_i)^T R_{c3} u_3(t_i)$$
  - Simulation time: $t_M = 1000$ s, $N = 1$



▷ Blue: Centralized ▷ Red: Iterative Black: Sequential

- The cost of the iterative DMPC converges to that of the centralized LMPC

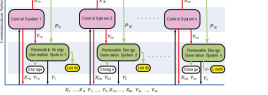
DMPC WITH ASYNCHRONOUS/DELAYED FEEDBACK

(Liu et al., Automatica, 2010; IEEE Trans. Autom. Control, in press)

- Sequential and iterative DMPC with asynchronous and delayed feedback

- Proposed approaches
  - Modify the implementation strategies to take into account that the control loop may be open
  - Redesign the formulations of the LMPCs to take into account asynchronous and delayed feedback explicitly
  - In the case of delayed measurements, iterative DMPC has to be used
    - ▷ Bi-directional communication

ELECTRICAL GRID INTEGRATED WITH DISTRIBUTED RENEWABLE ENERGY GENERATION



- Coordination of renewable energy generation systems with the electrical grid
- Cooperation between different control systems
- A two-time-scale framework will be adopted to study the network behavior

CONCLUSIONS

- Networked predictive control
  - Augmentation of local control systems with networked control systems
    - ▷ Take advantage of asynchronous and delayed measurements
    - ▷ Maintains the local control system stability and improves performance
- Distributed model predictive control
  - Sequential DMPC: controllers are evaluated in sequence
  - Iterative DMPC: controllers are evaluated in parallel
  - Significant reduction in evaluation time compared with centralized design
- Applications to chemical processes and wind-solar energy generation system

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