Interrelation between agent technology and distributed model predictive control

Control in Steel,

Distributed Autonomous Control Solutions

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Andreas Wolff

VDEh-Betriebsforschungsinstitut GmbH

Research Fund for Coal & Steel

What is an agent?

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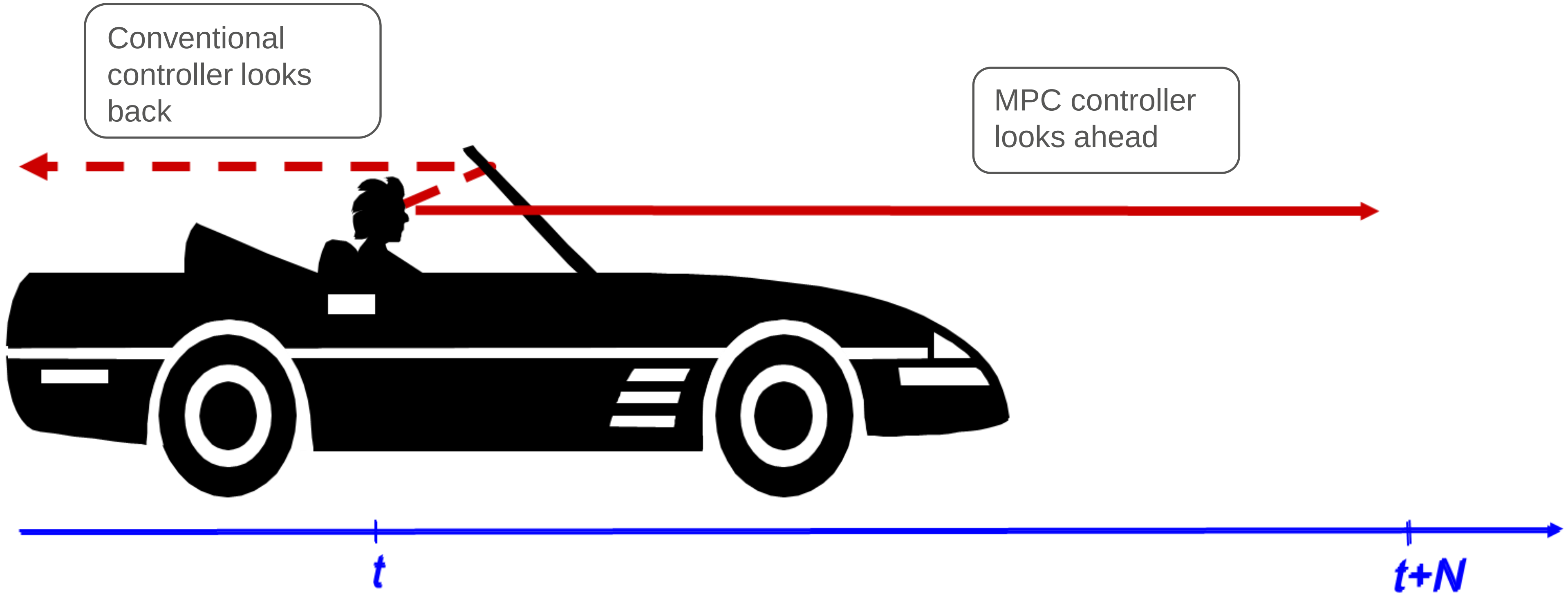
- *An agent can be defined as an entity that behaves **autonomously** within an arbitrary system in the **pursuit** of some **goals***[1]
- *A multi-agent system (MAS) is a system where multiple agents interact with each other directly, via communication acts , or indirectly, by acting on the shared environment.*[2]
- In addition, agents may decide to cooperate, to achieve a common goal, or to compete, to serve their own interests at the expense of other agents.[2]
- In particular, agents may form cooperative teams, which can in turn compete against other teams of agents.[2]

[1] M. Wooldirdge: An introduction to multiagent systems. (2009)

[2] F. Fioretto, E. Pontelli, W. Yeoh: Distributed Constraint Optimization Problems and Applications A Survey (2018)

Background of MPC control



Background of MPC control

- minimise:
  - An objective function in terms of action over the prediction horizon

$$\min_{x,u,y} J(x,u,y)$$

- subject to:
  - The dynamics of the system over the prediction horizon

$$x_{k+1} = Ax_k + Bu_k$$
$$y_k = Cx_k + Du_k$$

  - The constraints on the system

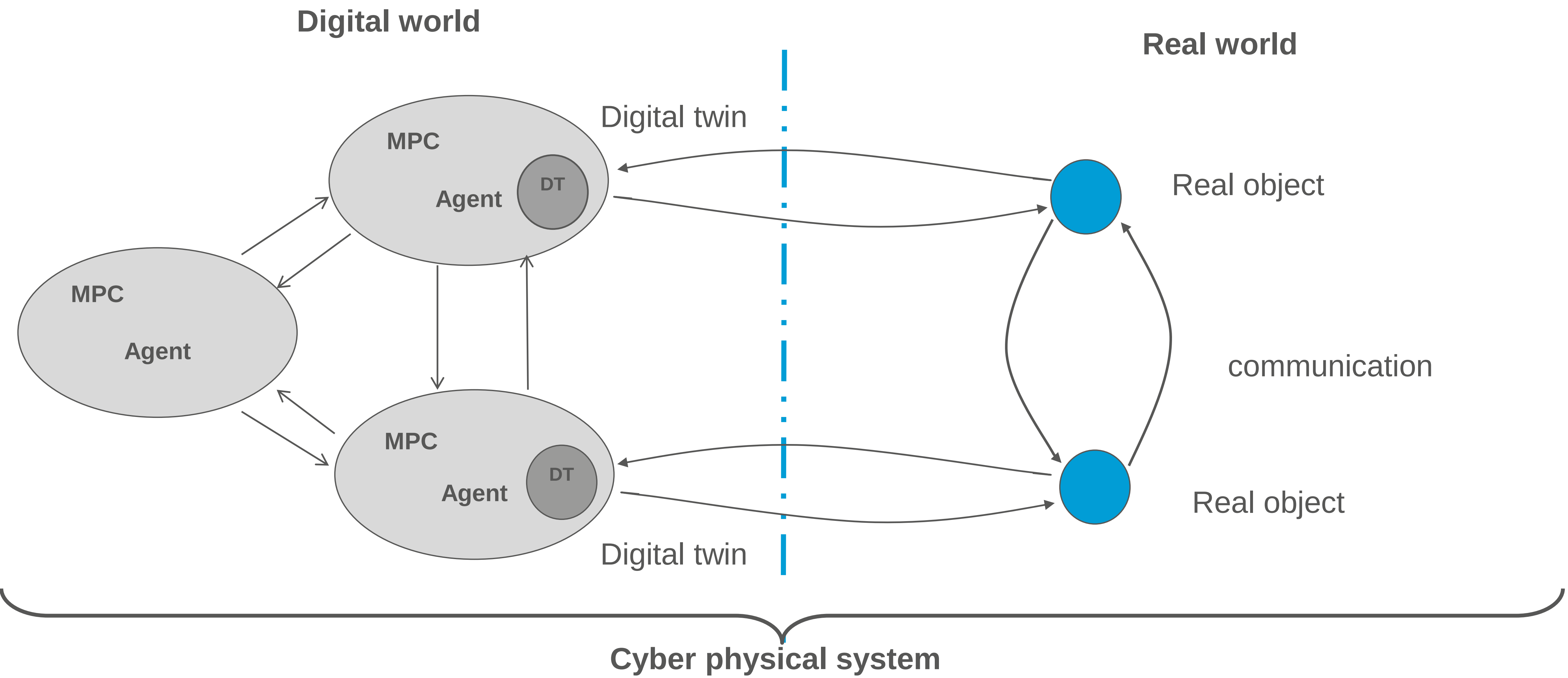
$$x_L \leq x_k \leq x_U$$
$$u_L \leq u_k \leq u_U$$
$$y_L \leq y_k \leq y_U$$

  - The initial state of the system at the beginning of the current control cycle

$$x_{k=0} = x_0$$

E.F. Camacho and C. Bordons, Model Predictive Control, Springer, 1999

Relation between digital agents and digital twins



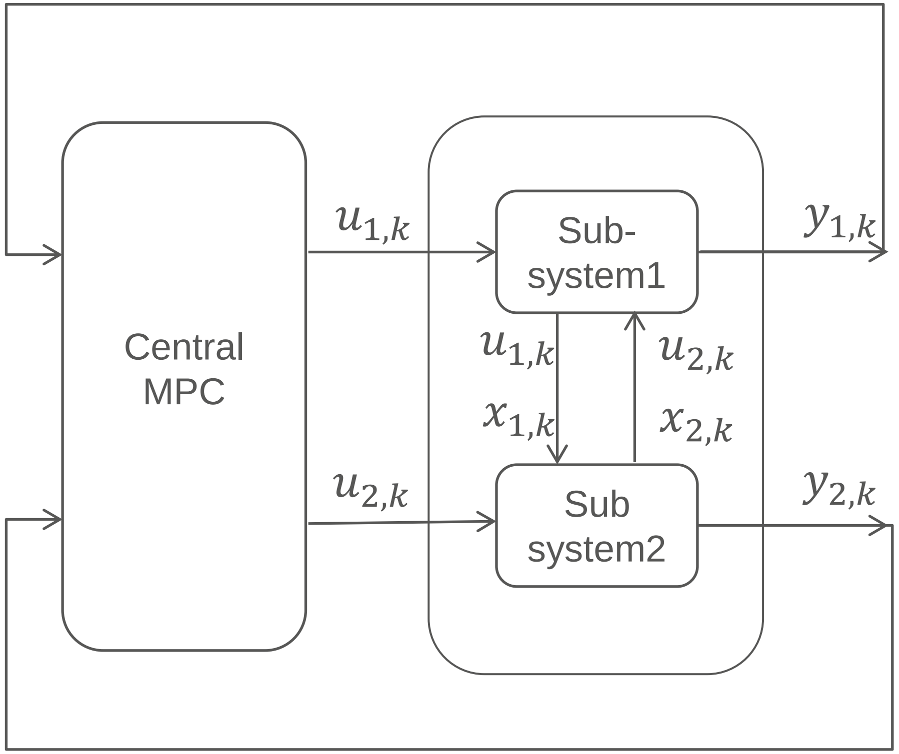
Different set up of the MPC system

- **Centralized:** Subsystem communicates with a centralized MPC that performs computation and sends new commands
- **Decentralized**: purely local MPC, i.e. no communication between local MPC controller (agents)
- **Hierarchical:** MPC where computations are done by MPCs that communicate with other MPCs at a higher level in a hierarchical structure, eventually leading to a centralized controller
- **Distributed:** local MPC controls local subprocess where each MPC communicates with its neighbours, but there is not a central controller

Daniel K. Molzahn, Florian Dörfler, Henrik Sandberg, Steven H. Low, Sambuddha Chakrabarti, Ross Baldick,Javad Lavaei
A Survey of Distributed Optimization and Control Algorithms for Electric Power Systems,
IEEE TRANSACATION ON SMART GRID, VOL 8,NO . NOVEMBER 2017

Central MPC architecture

Centralized: Subsystem communicates with a centralized MPC that performs computation and sends new commands



- Model: Interacting subsystems

$$G_1 := \begin{cases} x_{1,k+1} = A_{11}x_{1,k} + B_{11}u_{1,k} + A_{12}x_{2,k} + B_{12}u_{2,k} \\ y_{1,k} = C_1 x_{1,k} \end{cases}$$

$$G_2 := \begin{cases} x_{2,k+1} = A_{22}x_{2,k} + B_{22}u_{2,k} + A_{21}x_{1,k} + B_{21}u_{1,k} \\ y_{2,k} = C_2 x_{2,k} \end{cases}$$

- Cost function

$$J = \sum_{k=t}^{t+N-1} \frac{1}{2}\left({\|x_k\|^2}_Q + {\|u_k\|^2}_R \right) + \frac{1}{2} [\![{\|x_{t+N}\|^2}_R]\!]$$

Distributed MPC architecture

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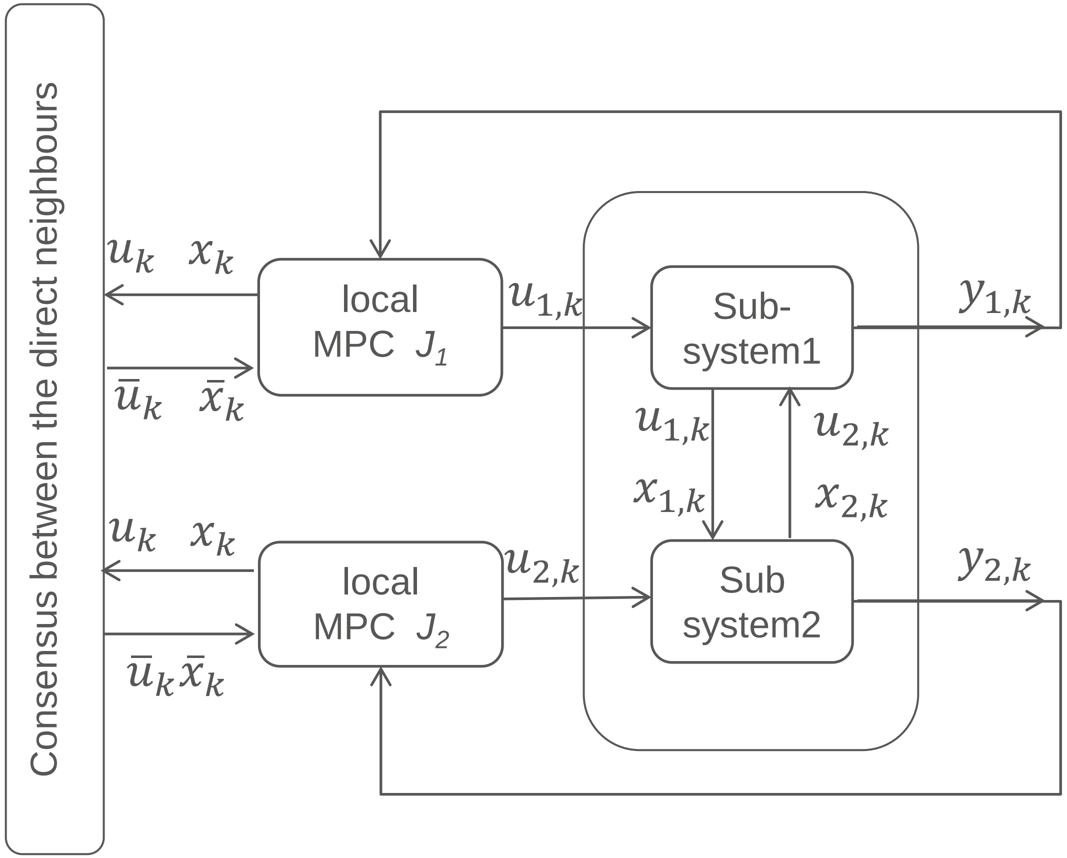
Distributed: cooperative consensus based DMPC



- Model: Interacting subsystems

$$G_1 := \begin{cases} x_{1,k+1} = A_{11}x_{1,k} + B_{11}u_{1,k} + A_{12}x_{2,k} + B_{12}u_{2,k} \\ y_{1,k} = C_1 x_{1,k} \end{cases}$$

$$G_2 := \begin{cases} x_{2,k+1} = A_{22}x_{2,k} + B_{22}u_{2,k} + A_{21}x_{1,k} + B_{21}u_{1,k} \\ y_{2,k} = C_2 x_{2,k} \end{cases}$$

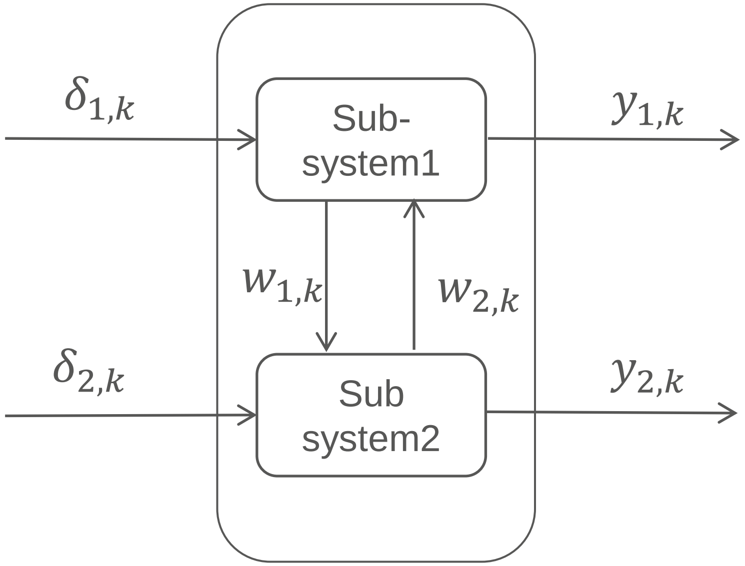
- Assuming the cost function is separable $J = \rho_1 J_1 + \rho_2 J_2$
- Extent the cost function

$$J_1 = \sum_{k=t}^{t+N-1} \frac{1}{2}\left(\|x_k\|_Q^2 + \|u_k\|_R^2\right) + \frac{1}{2}\left(\|x_k\|_R^2\right) +$$

$$+ \sum_{k=t}^{t+N-1} \gamma_k^T \left(\begin{bmatrix} x_k \\ u_k \end{bmatrix} - \begin{bmatrix} \bar{x}_k \\ \bar{u}_k \end{bmatrix} \right) + \frac{\varrho}{2} \left(\left\| \begin{bmatrix} x_k \\ u_k \end{bmatrix} - \begin{bmatrix} \bar{x}_k \\ \bar{u}_k \end{bmatrix} \right\|^2 \right)$$

Ramin Rostami, Giuliano Costantini, Daniel Görges ADMM-Based Distruted Model Predictive Control, Primal and Dual Approaches, 2017 IEEE 56th Annual Conference on Decision and Control (CDC), December 12-15, Melbourne Australia

Distributed MPC architecture



- Model: Interacting subsystems (optimal flow problem)

$$G_1 := \begin{cases} x_{1,k+1} = A_{11}x_{1,k} + B_{11}\delta_{1,k} + B_{12}w_{2,k} + E_1 v_{1,k} \\ y_{1,k} = C_1 x_{1,k} \end{cases}$$

$$G_2 := \begin{cases} x_{2,k+1} = A_{22}x_{2,k} + B_{22}\delta_{2,k} + B_{21}w_{1,k} + E_2 v_{2,k} \\ y_{2,k} = C_2 x_{2,k} \end{cases}$$

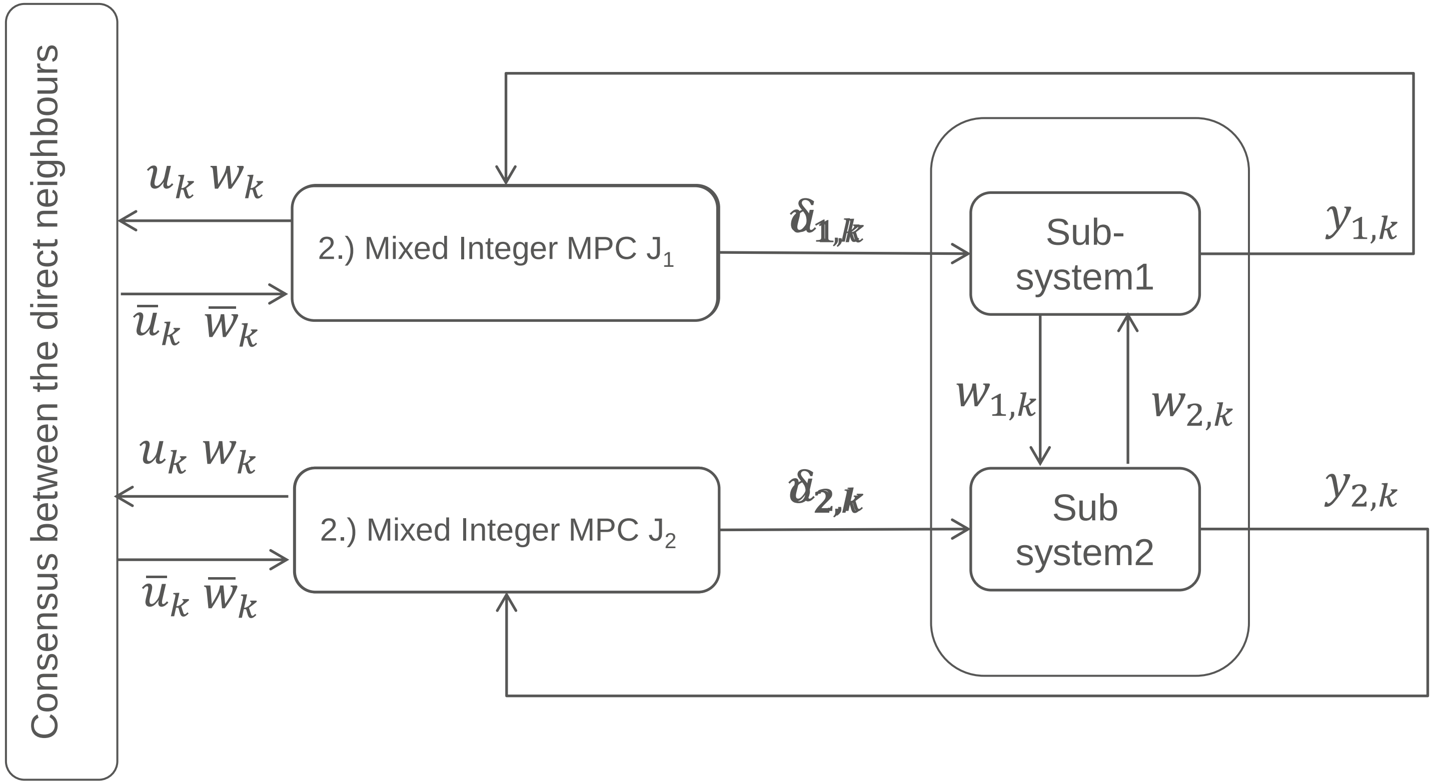
Coupling boundary conditions

$$F_2 w_{2,k} - F_1 w_{1,k} = 0$$

C. A. Hans , P. Braun J. Rausch , L. Grüne Hierarchical Distributed Model Predictive Control of Interconnected Microgrids, IEEE Transaction s on Sustainable Energy 2018

Distributed MPC architecture

w_k



- Main loop:
  1. Solve the local relaxed MPC's J_1 and J_2 in parallel where $\delta_{1,k}$ is continues
  2. Send u_k and w_k to the central unit and find a consensus
  3. Send $\bar{u}_k$ and $\bar{w}_k$ to the local MPC's
  4. Repeat unit converged
- Mixed integer update:

  Solve the local mixed integer MPC J_1 and J_2 by using the solution of loop 1-4 as a starting point and where $\delta_{1,k}$ is now discreet

C. A. Hans , P. Braun j.Rausch , L. Grüne Hierarchical Distributed Model Predictive Control of Interconnected Microgrids, IEEE Transaction on Sustainable Energy 2018

Applications

- Interconnected micro grids
- Drinking water networks
- Steam networks
- Natural gas networks
- Off gas networks in steelworks

All these applications belong to the class of optimal flow problems.

Conclusion

Distributed algorithms have advantages over centralized approaches:

- Agents share a limited amount of information => increase of cybersecurity
- Flexible => can be extended
- Robustness with respect to failure
- Parallel computation => faster
- suitable for very big problems
- potential to respect privacy of data

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Thank you for your attention!

Dr.-Ing. Andreas Wolff
Senior Expert Automation
Downstream Automation
Andreas.Wolff@bfi.de
+49 175 5268085