Distributed model predictive control of compressor systems

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Introduction: Outline

Introduction
- Compressor Systems
- Conventional Control
- MPC Approaches

Modelling
- Compressor Systems

MPC
- Overview
- Formulation
- Implementation

Results
- Control Performance
- Computational Performance

Conclusion

Introduction: Compressor Systems

Industrial Applications

- Used often in natural gas installations
- Very energy-intensive process
  - Small improvements in efficiency $\Longrightarrow$ large energy/capital savings
- Complex system from control perspective
  - Highly non-linear
  - Multivariable, highly coupled
  - Hard input constraints and rate constraints
  - Unstable regimes (surge, stall)
- Highest efficiencies often near surge line

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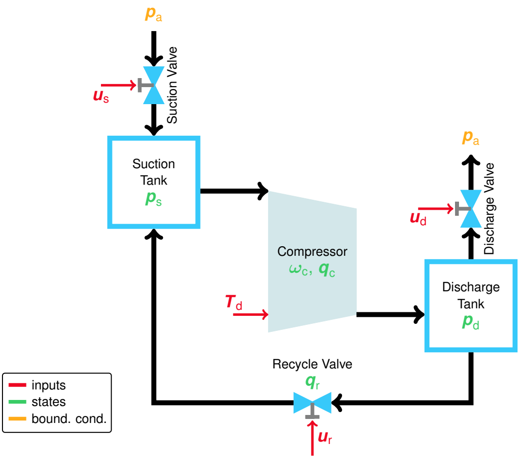
Increasing control performance can significantly reduce costs

Introduction: Compressor Systems

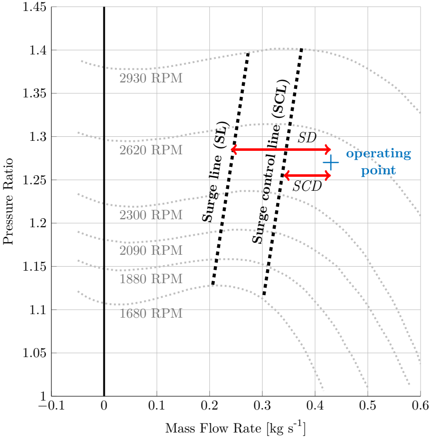
Compressor Dynamics



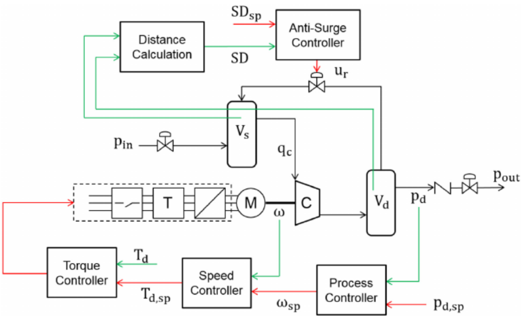
- Atmospheric pressure at boundary
- Controlled inputs: u_r and T_d
- Outputs: SD and p_d
- Disturbances: u_s and u_d

Introduction: Compressor Systems

Surge Distance



Introduction: Conventional Control



- Separate process and anti-surge controllers (ASC)
- Loop decoupling and anti-windup terms
- Potential of electric drivers not fully utilized

Potential for increased performance with multivariable control

Introduction: MPC Approaches

Advantages:

- Combine process control and ASC
- Use fast response of electric drivers to improve ASC performance
- Treat constraints explicitly

Disadvantages:

- Increased computation time – especially for large systems
- Centralized control $\Longrightarrow$ difficult to implement in industrial setting

Introduction: MPC Approaches

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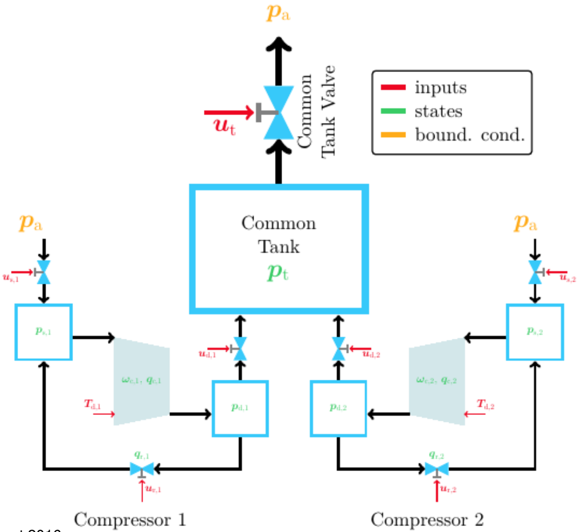
Use distributed MPC to decrease computation time

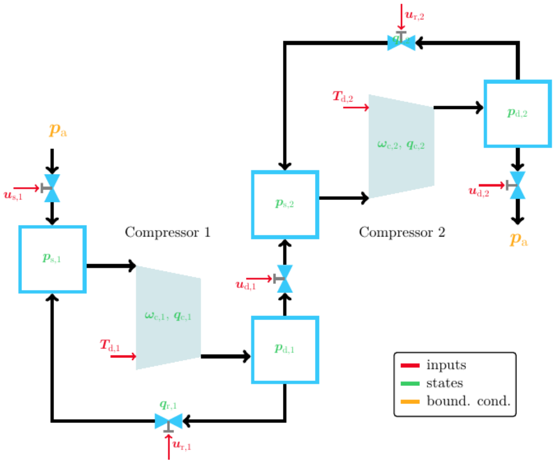
Modelling: Outline

Modelling: Compressor Systems

Parallel System



Modelling: Compressor Systems
Serial System



MPC: Outline

MPC: Overview
Control Approaches

3 control approaches used:

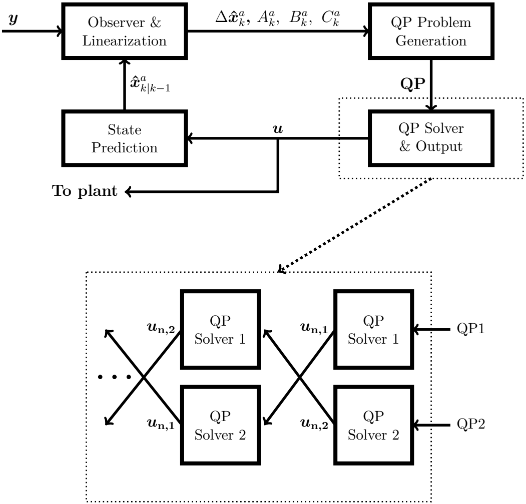
- Centralized control: used as benchmark
- Distributed control: split controller into two subcontrollers
  - Cooperative control: single cost function
  - Non-cooperative control: individual cost functions

Outputs controlled: (all 3, centralized/cooperative)

- Parallel system: p_{t}, SD_1, SD_2
- Serial system: $p_{\mathrm{d},1}$, SD_1, $p_{\mathrm{d},2}$, SD_2

MPC: Overview

Algorithm



MPC: Formulation

- Quadratic cost function

$$J = \sum_{i=1}^{p} \left(\Delta y_i - \Delta y_i^{\text{ref}} \right)^{\mathsf{T}} W_y \left(\Delta y_i - \Delta y_i^{\text{ref}} \right) + \sum_{i=1}^{m} (\Delta u_i)^{\mathsf{T}} W_u (\Delta u_i)$$

- Linearized, discretized, augmented formulation

$$\begin{aligned} \text{s.t. } \Delta \hat{\boldsymbol{x}}^a_{k+i+1} &= A^a_k \Delta \hat{\boldsymbol{x}}^a_{k+i} + B^a_k \Delta \boldsymbol{u}^a_{k+i} + \boldsymbol{f}_{\mathrm{d},k} \\ \Delta \boldsymbol{y}_k &= C^a_k \Delta \hat{\boldsymbol{x}}^a_k \end{aligned}$$

- Input constraints (absolute value and rate)

$$\begin{aligned} \text{s.t. } \Delta U_{\min} \leq \Delta U &\leq \Delta U_{\max} \\ \Delta U_{\mathrm{r,min}} \leq A_{\mathrm{rate}} \Delta U &\leq \Delta U_{\mathrm{r,max}} \end{aligned}$$

MPC: Formulation

Quadratic Program

$$\arg\min_{U} \ \frac{1}{2}\Delta U^{\mathsf{T}} \ H \ \Delta U + g^{\mathsf{T}} \Delta U$$
$$\text{s.t. } \Delta U_{\text{min}} \leq \Delta U \leq \Delta U_{\text{max}},$$

- Dense formulation $\implies$ replace ΔY terms using model

$$\Delta Y_k = S_{U_k} \Delta U_k + S_{x_k} \Delta \hat{\boldsymbol{x}}_k^a + S_{f_k} \boldsymbol{f}_{\text{d},k}$$
$$\Downarrow$$
$$H = 2\left(W_u + S_{U_k}^{\mathsf{T}} \ W_y \ S_{U_k}\right)$$
$$g = 2\left(\Delta \hat{\boldsymbol{x}}_k^a S_{x_k}^{\mathsf{T}} + \boldsymbol{f}_{\text{d},k} S_{f_k}^{\mathsf{T}} - \Delta Y_k^{\text{ref}}\right) W_y S_{U_k}.$$

- Solve using `qpOASES` active-set solver

MPC: Formulation

Distributed MPC

- One sub-controller for each compressor

$$\Delta Y_k = S_{U_k} \Delta U_k + S_{x_k} \Delta \hat{\boldsymbol{x}}_k^a + S_{f_k} \boldsymbol{f}_{\mathrm{d},k} + S_{U_k^{\mathrm{ot}}} \Delta U_k^{\mathrm{ot}}$$

$$\Downarrow$$

$$H_{\mathrm{dist.}} = H_{\mathrm{cent.}}$$

$$g_{\mathrm{dist.}} = g_{\mathrm{cent.}} + \Delta U_k^{\mathrm{ot}} \, S_{U_k^{\mathrm{ot}}}^{\mathsf{T}} W_y \, S_{U_k}$$

- Iterate, exchanging solution info between sub-controllers, to converge to optimal solution
- Two types of DMPC controller
  - Cooperative controller: common cost function (weight outputs from both compressors)
  - Non-cooperative controller: individual cost functions (weight outputs from single compressor)

MPC: Implementation

General

- Use Dormand-Prince (`ode45`) algorithm for simulation
- Perform state estimation using static observer

Simulink

- Use `Embedded MATLAB` to implement MPC controllers
- Set up for C code generation, for deployment on embedded hardware

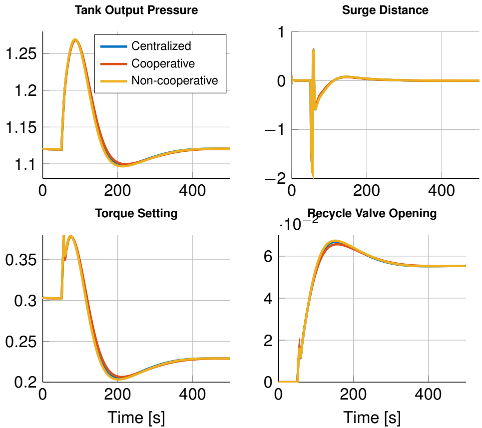
C++

- Linear algebra performed with `Eigen` library
- Use knowledge of augmented matrices to speed up QP generation (store dense and sparse sections of matrix separately)

Results: Outline

Results: Control Performance

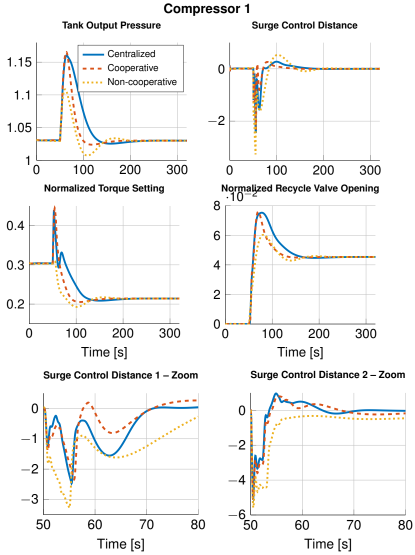
Parallel System



Control performance identical for DMPC

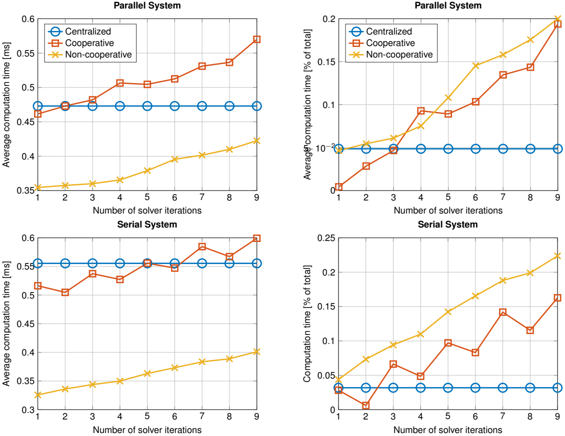
Results: Control Performance

Serial System



- Cooperative performance similar to centralized
- Non-cooperative has poorer anti-surge control performance

Results: Computational Performance



Most time used for QP generation (< 10% for QP solving)

Non-cooperative approach better to reduce computation time

Conclusion: Outline

Conclusion: Outline

Distributed MPC can reduce computational cost

- Cooperative control: minimal reduction
- Non-cooperative: significant reduction (fewer outputs $\implies$ faster QP generation)
- QP generation has larger effect than QP solver

. . . but performance is decreased in some cases

- Cooperative control very similar to centralized
- Non-cooperative control shows reduced ASC performance in serial case

Conclusion: Outline

Future Work

- Improve computational efficiency
  - Reduce number of states for prediction matrix generation
  - Use more efficient linear algebra implementation
- Investigate convergence of non-cooperative controller
  - Effect of noise/model mismatch
  - Effect of model parameters (tank sizes etc.)
- Experimental tests

Questions?