Development and Application of Advanced Process Control for UKy CO$_2$ Capture Pilot-Plant

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Overview

• Background
  – Motivation | Objectives
  – CCSI’s APC Framework Toolset
  – UKy-CAER CO\textsubscript{2} Capture Pilot-Plant Facility

• Project Plan / Status

• Past Accomplishments
  – Identify “most-influential” I/O variables
  – Develop dynamic reduced models
  – Offline “simulation-based” control studies

• Current Activity / Accomplishments
  – Integration with pilot-plant DCS
  – Implement real-time APC

• Results

• Summary
Motivation / Contribution to CCSI²

• Industrial APC Ain’t Easy
  – Computational cost
  – Need for accurate and fast real-time prediction models
  – APC / NMPC module costs - $$$
  – Non-generic, embedded within DCS

• New Contribution
  – NMPC-based industrial control
    • Optimal dynamic operation
  – Exploit more-efficient third-party solvers (MATLAB – sparse matrix calculations, IPOPT, etc.)
Why Advanced Process Control (APC) Framework?

- Integrated framework for optimal control of CO$_2$ capture processes
- Efficient dynamic transition to desired set-point and mitigation of process uncertainties
- Enables to protection of intellectual data by serving as a “black-box” surrogate dynamic-model
- Leverage “fast” D-RMs from CCSI’s D-RM Builder as predictive models to optimize control-moves towards cost-effective transient response in face of process constraints

APC Framework Features

- Constrained **Nonlinear Model Predictive Control** (NMPC) using DAB-Net D-RM model
- Constrained **Multiple-Model Predictive Control** (MMPC) based on multiple linear state-space “model-bank”
- Unscented Kalman Filter (UKF)-based state-estimation
Background

• University of Kentucky’s CCS Project
  – Center for Applied Energy Research (CAER)
    • Other Participants: LG&E/KU, Hitachi, EPRI, etc.
  – 2 MWth (0.7 MWe) slip stream test facility
  – At E. W. Brown Generating Station
    • Louisville Gas & Electric (LG&E) and Kentucky Utilities (KU)
    • In Harrodsburg, KY, 30 miles from UKy-CAER
  – Sponsors
    • DOE/NELT ($14.55 Million)
    • Kentucky Department of Energy Development and Independence
    • Carbon Management Research Group (Consortium)
  – Catch and release program

• Opportunity: improve control responses time | residence time in solvent/desiccant loops
CAER’s CO₂ Capture Test Facility

LG&E/KU Brown Station

CO₂ Capture Facility

Existing Control System

- Emerson’s DeltaV system
- All standard PID Controllers (w/ 2-3 cascade loops)
- Currently uses 170 process variables
  - Maximum 250 variables from the license
- Over 20 manipulated input variables
- Solvent residence time: ~30 min through the loop; scope for improvement
Project Status/Plan

• Assess control requirements
• Operability and controllability analysis
  • Identify relevant I/O process variables
  • Design step-change sequence
  • Run step-tests
    – Keep low-level PID controllers unchanged
• Build D-RM for the system
  • Validate approach on secondary-stripping column sub-section
  • Develop D-RM for entire plant
    – Testing data | Validation data
• Evaluate APC methodology for online real-time control
  • Validate APC approach using offline “plant” based on D-RM – demonstrated benefits
  • Integrate CCSI’s APC Framework w/ pilot-plant’s DCS
  • Closed-loop identification based on historical data
• Implement real-time nonlinear MPC
  • Controller tuning and validation (preliminary)
  • Demonstrate operational improvement over existing methods
CAER’s CO₂ Capture Process

• Three loops
  – Flue gas pretreatment loop
  – Amine solvent loop
  – Liquid desiccant loop

• Solvent loop design
  – Single absorber with intercooler
  – 2 strippers
    • Primary stripper
    • Secondary air stripper

• Cooling tower/liquid desiccant loop design
  – Removing moisture in humid air by liquid desiccant
Relevant Process Variables

- **Manipulated Inputs (MV)**
  - Solvent flow rate
  - Primary stripper pressure
  - Reboiler steam flowrate
  - Flow rate of air to secondary stripper
  - Cooling air flowrate
  - Desiccant flowrate
  - Rich-solvent heater steam flowrate
  - CO$_2$ concentration of flue gas to absorber (disturbance)

- **Output / Controlled Variables (CV)**
  - Percentage of CO$_2$ captured
  - Temperatures of product streams of individual columns
  - Compositions of product streams
Previous “offline” Control Studies

CO₂ concentration disturbance in inlet flue gas (14% to 16%) at t = 0

NMPC Objective function

\[
\min_{\Delta u_1, ..., \Delta u_M} \sum_{p=1}^{M} \left( \left( CO_{2p}^{SP} - CO_{2p} \right) w_p \left( CO_{2p}^{SP} - CO_{2p} \right) \right) + \left( Stm_{M}^{nub} + Stm_{M}^{RHB} \right) + \sum_{m=1}^{M} \Delta u_m^T w_m \Delta u_m
\]

80% reduction in settling time

Less (~5%) steam duty
Industrial Implementation: D-RM development

- Reboiler Steam Flowrate
- RHR Steam Flowrate
- Desiccant Flowrate
- Cooling Tower Air Flowrate
- L/G
- CO2 Capture
- Primary HX Overhead Temp

D-RM Building Process

- Configure Relevant I/O Variables
- Configure I/O Ranges & Time Dependency
- Prepare Training / Validation Input Sequence
- Conduct Process / Plant Step-Tests for Training / Validation Scenario
- Integrate D-RM with APC
- Predict Response / Show Regression Error With Plots
- Generate D-RM Based on Plant Results
- Uncertainty Quantification Analysis

D-RM in Form of MATLAB Code

Mean and Covariances Predicted By UKF

MATLAB Plot Showing Predicted Output vs. Plant Response

Training Sequence

Configuring I/O Variable Selection

Configuring Inputs/Outputs

I/O Variable Selection

MATLAB Plot Showing Predicted Output vs. Plant Response

CCSI
National Energy Technology Laboratory
Lawrence Livermore National Laboratory
Los Alamos National Laboratory
Pacific Northwest National Laboratory
West Virginia University
U.S. Department of Energy
Results – System Identification / D-RM Building

5 Input Variables
Results – System Identification / D-RM Building

D-RM tracks the pilot-plant response well with slight offset for validation data

Primary Control Variable – Minimize settling times

Critical Constraint Variable – Values above 139°F leads to solvent leakage from stack (closely monitored)

2 Output Variables
Industrial APC Implementation

Real-time exchange of values, events, R/W state

MATLAB

Emerson DeltaV DCS

APC

D-RM

Setpoints

Measured Process Variables (inputs, states, outputs)

Controller Outputs

MATLAB Emerson DeltaV DCS

Real-time exchange of values, events, R/W state
Integration with pilot-plant DCS

- **OPC (OLE for Process Control) Protocol**
  - Identify existing Emerson Delta-V OPC server on pilot-plant DCS
  - Create OPC client within CCSI APC Framework
  - Establish connection from client to server
  - Identify process variables tags (r/w permissions) available on server – PLC/charm names
  - Create read-only PV tags and writable remote setpoint (SP) tags on client
  - Conduct step-tests on relevant remote SP and validate PV with DCS historian

- **Develop event callbacks routines for solving real-time control optimization problem**
- **Establish real-time communication at each sampling “clock” time**
Results – Real-time APC (preliminary study)

Study Details
- 3 input – 2 output
- CO₂ concentration disturbance in inlet flue gas (14% to 16%) at t = 600 min
- Control objective

\[
\min_{\Delta u_1:...:\Delta u_M} J = \sum_{p=1}^{P} (CO_{2}^{SP} - CO_{2}^{TP})^T w_y (CO_{2}^{TP} - CO_{2}^{SP}) + \sum_{m=1}^{M} \Delta u_m^T w_u \Delta u_m
\]

- Sampling-time = 1 min
- Prediction Horizon = 2 hr
- Control Horizon = 10 steps
## Summary

### Performance Improvement

<table>
<thead>
<tr>
<th>UKy/CAER existing control</th>
<th>APC Framework</th>
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<tr>
<td>No automated control of CO₂ capture</td>
<td>Optimal setpoint tracking of CO₂ possible using NMPC</td>
</tr>
<tr>
<td>Rely on overhead T high-alarm visual feeds to rectify solvent loss to stack.</td>
<td>Overhead T monitored and predicted via model. Take necessary steps before violating constraints</td>
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<tr>
<td>Square I/O system required for multiple single-input-single-out controllers – e.g. CO₂ capture may only be paired with reboiler-steam flow</td>
<td>One output may optimally be controlled by two or more sensitive inputs – e.g. both reboiler and RHR steam contribute to controlling CO₂ capture</td>
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<td>Fixed control parameters leading to sub-optimal performance when operating far from “tuned” regime</td>
<td>NMPC with Kalman Filter updates the model based on extent of plant-model mismatch</td>
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Summary

Demonstrated CCSI’s APC Tools applicability and benefits in CO₂ capture plant

– Identified most-influential pilot plat’s PV
– Developed dynamic reduced-order model (D-RM)
– Demonstrated ability to interface with existing pilot-plant DCS using industry-standard OPC
– Implement real-time APC for CO₂ capture SP tracking with temperature constraint

Future Work

– Refine existing D-RM through closed-loop identification using historical data
– Implement plant-wide APC with economic optimization and demonstrate benefits over existing control methods
Acknowledgement

- University of Kentucky’s CAER Team
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  - Control Room Operators: Len, Marshall, Otto
- OPC Foundation
  - Provide educational material for efficient OPC implementation
- Matrikon OPC Team
  - Provide test-bench for OPC communication offline
- MATLAB OPC Toolbox
  - Provide OPC client interface for APC-DeltaV communication
Disclaimer

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