Active Uncertainty Compensation Based Control
With Applications to Energy Systems

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Content

- Background
- Theoretical development
- Experimental Applications
- Conclusions
Problem Formulation

- **Motion Control**
  - Target Tracking
  - Accurate model
  - Strong Nonlinearity

- **Process control**
  - Stable Operation
  - Modelling Error
  - Time-delay

- **Energy Control**
  - Objectives
    - Frequent Load Tracking
    - Disturbance Rejection
  - Difficulties
    - Dynamic Nonlinearity
    - Modelling Uncertainty
    - Various Disturbances
  - Intractable Dynamics
    - Time-delay
    - Non-minimum phase
    - Multivariable couplings

Background
Insights on Uncertainty

Tsien questions the basic assumption of the modern control theory that ‘the properties and characteristics of the system to be controlled were always assumed to be known’ and points out that, in reality, ‘large unpredictable variations of the system properties may occur.’


“If there is no uncertainty in the system, the control or the environment, feedback control is largely unnecessary.”


“In fact, robustness to model uncertainty was broadly one of the major shortcomings of early model-based state-space theories. That this was true even in adaptive control.”
# Background

## State-of-the-art of the uncertainty compensation methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Time</th>
<th>Author</th>
<th>Model Used</th>
<th>Limitation</th>
</tr>
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<tbody>
<tr>
<td>Passive</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>2DOF-PID</td>
<td>1985</td>
<td>M. Araki, et al</td>
<td>First Order Plus Dead time model</td>
<td>Any Process</td>
</tr>
<tr>
<td>Active</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Active Disturbance Rejection Control</td>
<td>1998</td>
<td>Han, J.Q</td>
<td>Cascaded Integrators</td>
<td>Minimum-phase</td>
</tr>
<tr>
<td>Uncertainty and disturbance Estimator</td>
<td>2004</td>
<td>Zhong, QC and Rees</td>
<td>State Space model</td>
<td>Stable processes</td>
</tr>
</tbody>
</table>
Active Uncertainty Compensation Based Control (AUCBC)

- **Energy Uncertainties**
  - Renewable intermittency
  - Frequent load changes
  - Parameter perturbation
  - Uncertain dynamics
  - Fuel variation
  - Heat transfer deterioration
  - ......................

- **Uncertainty Estimation**
- **Uncertainty Compensation**

- **Background**
  - Renewable intermittency
  - Frequent load changes
  - Parameter perturbation
  - Uncertain dynamics
  - Fuel variation
  - Heat transfer deterioration

- **Set-point Tracking**

- **Uncertainty**: the dynamics beyond the nominal linear model

- **Basic idea**
Content

- Background
- Theoretical development
- Experimental Applications
- Conclusions
Theoretical development

- Two-degrees-of-freedom (2DOF) PI control
- Extension of AUCBC to time-delay
- Extension of AUCBC to unstable system
- Extension of AUCBC to non-minimum phase
- Extension of AUCBC to multivariable processes
Single-degrees-of-freedom (1DOF) PI control

- A passive compensation structure

\[
\begin{align*}
r(s) + e(s) & \rightarrow G_c(s) \rightarrow u(s) + \rightarrow G_P(s) \rightarrow y(s) \\
d(s) & \rightarrow d(s)
\end{align*}
\]

Set-point tracking

Disturbance Rejection

Very sluggish!!
Two-degrees-of-freedom (2DOF) PI control

A passive compensation structure

First-order-plus-time-delay, FOPTD Model

\[ G_p(s) = \frac{K}{1+Ts} e^{-Ls}, \quad G_c(s) = k_p + \frac{k_i}{s}, \quad F(s) = \frac{bT_i s + 1}{T_i s + 1} \]

\[ u(t) = k_p [(br - y) + \frac{1}{T_i} \int_0^t (r - y) dt], \quad 0 < b \leq 1 \]
Optimization of PI parameters for disturbance rejection

Two-degrees-of-freedom (2DOF) PI control

In the presence of step input of disturbance $d$:

Performance Objective:

$$IAE = \int_{0}^{\infty} |r(t) - y(t)| \, dt,$$

Robustness Constraints:

$$M_s = \max_{\omega} |S(i\omega)| = \max_{\omega} \left| \frac{1}{1 + G_p(i\omega)G_c(i\omega)} \right| \leq 1.6$$
Two-degrees-of-freedom (2DOF) PI control

Conventional graphical method

\[ G_c(s) = k_p + \frac{k_i}{s}, \]

Procedures:
- Sweep \( w \) from 0 to infinity;
- Draw MS contour lines under each \( w \);
- Find the peak of the envelope;

Deficiency:
- Difficult to use and understand;
- Time-consuming

New Solution

I. Propose new robustness index: Relative delay margin \( R_{dm} = \frac{\varphi_m}{\omega_{gc} L} = \frac{\varphi_m}{a} \)

II. Coordinate Transformation

III. Analyze and optimization under the new coordinate system

\[
\begin{align*}
k_p K &= \frac{T}{L} \sin(\varphi_m + a) - \cos(\varphi_m + a) \\
k_i KL &= a \sin(\varphi_m + a) + \frac{T}{L} a^2 \cos(\varphi_m + a)
\end{align*}
\]
Two-degrees-of-freedom (2DOF) PI control

Optimization under the new constraint and coordinates: $\left(\phi_m, a\right)$

In the presence of step input of disturbance $d$:

**Performance Objective:**

$$IAE = \int_0^\infty |r(t) - y(t)| \, dt,$$

**Robustness Constraints:**

$$R_{dm} = \frac{\phi_m}{a} \leq 1.6$$

---

![Mapping Diagram](image)

- $a + \arctan\left(\frac{aT}{L}\right) + \phi_m = \pi$
- $a = 0$
- $\phi_m = 0$
- $R_{dm} = 1.63$

$k_i$

$k_p$
Optimization under the new constraint and coordinates: \( (\varphi_m, a) \)

<table>
<thead>
<tr>
<th>In the presence of step input of disturbance ( d ):</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance Objective:</td>
</tr>
<tr>
<td>( IAE = \int_{0}^{\infty}</td>
</tr>
<tr>
<td>Robustness Constraints:</td>
</tr>
<tr>
<td>( R_{dm} = \frac{\varphi_m}{a} \leq 1.6 )</td>
</tr>
</tbody>
</table>

Analytical solution: **Lagrange multiplier method**

\[
\frac{d}{da} \left[ a \sin((r_{dm} + 1)a) + \frac{T}{L} a^2 \cos((r_{dm} + 1)a) \right] = 0
\]

Theoretical development

- Two-degrees-of-freedom (2DOF) PI control
- Extension of Active UCBC to time-delay

Modify
Uncertainty compensation in time-delay process

Time-delay modification

Input synchronization

**Original plant**
\[ G_p(s) = \frac{K}{1 + T_s} e^{-L_s} \]

**Ideal plant**
\[ G_{EP} \approx \frac{1}{s} e^{-L_s} \]

Extended State Observer, ESO

1. \[ \dot{x} = Ax + Bu + Eh \]
2. \[ y = c^T x \]
3. \[ h \text{ is unknown uncertainty} \]

\[ z = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \\ h \end{bmatrix} \]

\[ \dot{z} = A_e z + B_e u + H(y - \hat{y}) \]
\[ \hat{y} = c_e^T z \]

Estimation error feedback
Control design based on the ideal plant

For the ideal plant

\[ G_{EP} \approx \frac{1}{s} e^{-Ls} \]

\[ G_{OP}(s) \approx \frac{k_p}{s} e^{-Ls} \]

\[ G_{CL}(s) = \frac{y(s)}{r(s)} = \frac{k_p}{s + k_p e^{-Ls}} e^{-Ls} \approx \frac{k_p}{s + k_p (1 - Ls)} e^{-Ls} = \frac{1}{1 + \frac{1}{k_p - L}} e^{-Ls} \]

\[ G_{CL}^d(s) = \frac{1}{1 + \lambda Ls} e^{-Ls} \]

Uncertainty compensation in time-delay process

\[ b_0 = \frac{K}{T} \; ; \; \omega_o = \frac{k_o}{T} \; ; \; k_p = \frac{1}{k_e (\lambda + 1) L} \]
Uncertainty compensation in time-delay process

Simulation verification

\[ G_P(s) = \frac{1.895}{3.201s + 1} e^{-0.961s} \]

Frequency response comparison between the compensated plant and ideal plant

Performance comparison
Theoretical development

- Two-degrees-of-freedom (2DOF) PI control
- Extension of AUCBC to time-delay
- Extension of AUCBC to unstable system
Uncertainty compensation in unstable process

Modified Uncertainty and Disturbance Estimator

System model

\[ \dot{x} = (A + F)x + Bu(t - L) + d(t) \]

Control law

\[ U(s) = B^+(A_mX + B_mC - AX) - B^+K_eE + UDE \]

where:
- \( B^+ \) is the Moore-Penrose pseudoinverse of \( B \)
- \( A_m \) and \( B_m \) are matrices derived from the system
- \( C \) is the output matrix
- \( A \) is the system matrix
- \( X \) is the state vector
- \( K_e \) is the feedback gain
- \( E \) is the uncertainty matrix
- \( UDE \) is the uncertainty disturbance estimator
- \( s \) is the Laplace variable
- \( A = sI - A \) is the characteristic equation

The diagram illustrates the system with the following components:
- Virtual Plant \( \Sigma : (A, B) \)
- Artificial Delay \( e^{-\tau s} \)
- UDE and Feedback Stabilization \( B^+K_eE \)
- External disturbance \( d \)
- Controlled Process \( \Sigma : (A + F, B) \)
- Artificial Delay \( e^{-Ls} \)
- State Feedback \( Bu \)
- Output Feedback \( y_v \)
- \( x_v \) inputs
- 28
Modified Uncertainty and Disturbance Estimator

Stability analysis

**Theorem:** the closed-loop MUDE control system is stable if and only if

\[-\frac{1}{T} < K_e < \frac{1}{\tau} \alpha \sin(\alpha) - \frac{1}{T} \cos(\alpha)\]  

(1)

where, \( \alpha \) is the solution of the equation,

\[\tan(\alpha) = -\frac{T}{\tau} \alpha\]  

(2)

in the interval \((0, \pi)\).

The proof detail is referred to

Simulation verification: Unstable with time delay

\[ G(s) = \frac{3.433}{103.1s - 1} e^{-20s} \]

<table>
<thead>
<tr>
<th>Method</th>
<th>IAE_{TP}</th>
<th>IAE_{DR}</th>
<th>( M_T )</th>
<th>( M_S )</th>
<th>Settling time</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSP</td>
<td>26.6</td>
<td>30.2</td>
<td>2.3</td>
<td>2.4</td>
<td>200s</td>
</tr>
<tr>
<td>FSP</td>
<td>20.0</td>
<td>37.1</td>
<td>3.2</td>
<td>2.8</td>
<td>280s</td>
</tr>
<tr>
<td>MUDE</td>
<td>20.0</td>
<td>27.6</td>
<td><strong>2.0</strong></td>
<td><strong>2.3</strong></td>
<td>180s</td>
</tr>
</tbody>
</table>

Theoretic development

- Two-degrees-of-freedom (2DOF) PI control
- Extension of AUCBC to time-delay
- Extension of AUCBC to unstable
- Extension of AUCBC to Non-minimum phase (NMP)
Uncertainty compensation in NMP process

NMP Process Description

\[ G_P(s) = \prod_{i} \frac{s - z}{(1 + s / p_i)^{n+1}} \]

- Right-half Plane (RHP) zero in TF.
- Initial inverse response in step response.

Bed Temperature response in Fluidized bed combustor

Combined feed-forward and AUCBC solution

- **AUCBC**: Enforce the NMP plant behave like nominal
- The feed-forward control produces the optimal set-point tracking.
Uncertainty compensation in NMP process

Algorithm basics:

- AUCBC: Enforce the NMP plant behave like nominal
- MESO is designed based on Canonical form

\[
\begin{align*}
\dot{x} &= A_e \dot{x} + B_e u + H (y - \hat{y}) \\
\hat{y} &= c_e^T \dot{x}
\end{align*}
\]

\[
A_e = \begin{bmatrix} A_0 & B_0 \\ 0 & 0 \end{bmatrix}, \quad B_e = \begin{bmatrix} B_0 \\ 0 \end{bmatrix}, \quad A_o = \begin{bmatrix} 0 & 1 & \cdots & \cdots & 1 \\ \vdots & \cdots & \cdots & \cdots & \cdots \\ 0 & \cdots & \cdots & \cdots & 1 \\ -a_0 & -a_1 & \cdots & \cdots & -a_{n-1} \end{bmatrix}, \quad B_o = \begin{bmatrix} \beta_1 \\ \beta_2 \\ \vdots \\ \beta_n \end{bmatrix}, \quad c_o^T = [1 \ 0 \ \cdots \ 0]
\]

- Feed-forward control produces the optimal set-point tracking

\[
u_1(t) = \begin{cases} 
(e^{z(t-t_0)} - 1) r a_{us}, & t \in [t_0, t_1) \\
r, & t \in [t_1, \infty)
\end{cases}
\]

\[
t_1 = t_0 + \frac{\ln(1/a_{us} + 1)}{z}
\]
Uncertainty compensation in NMP process

Convergence analysis:

**Theorem 1**: Assuming (i) \( q \) is bounded, i.e., \( |q(t)| \leq \delta \), (ii) \( \bar{A} \) is Hurwitz and (iii) \( \sum_{1}^{n-1} a_i \beta_{i-1} + \beta_n \neq 0 \), then the estimation error \( \varepsilon \) is bounded, i.e., there exist a constant \( \sigma_i > 0 \) and a finite \( T_1 > 0 \) such that \( |\varepsilon_i(t)| \leq \sigma_i \), \( i = 1, 2, \cdots, n+1 \), \( \forall t \geq T_1 > 0 \).

Furthermore, \( \sigma_i = O\left(\frac{1}{l_{n+1}}\right) \).

\[
\bar{A} = A_e - Hc_e^T = \begin{bmatrix}
-h_1 & 1 & \beta_1 \\
\vdots & \ddots & \vdots \\
-h_{n-1} & 1 & \beta_2 \\
-a_0 - h_n & -a_1 & \cdots & -a_{n-1} & \beta_n \\
-h_{n+1} & 0 & 0 & \cdots & 0
\end{bmatrix} = \begin{bmatrix}
\Lambda \\
-h_{n-1} \\
0
\end{bmatrix} \begin{bmatrix}
\gamma \\
0
\end{bmatrix}
\]

\[
\bar{A}^{-1} = \begin{bmatrix}
0 & -\frac{1}{h_{n+1}} \\
\gamma^{-1} & -\frac{1}{h_{n+1}} \gamma^{-1} \Lambda
\end{bmatrix}
\]

Li Sun, Donghai Li, Zhiqiang Gao, Zhao Yang and Shen Zhao. Combined feedforward and model-assisted active disturbance rejection control for non-minimum phase system. **ISA Transactions**, 2016, 64: 24-33.
Simulation verification

Actual plant

\[ G'(s) = \frac{123.853 \times 10^4 (-s + 3.5)}{(s^2 + 6.5s + 42.25)(s + 45)(s + 190)} \:
\]

Nominal model

\[ G(s) = \frac{144.86 (-s + 3)}{s^2 + 6.5s + 42.25} \:
\]
Theoretical development

- Two-degrees-of-freedom (2DOF) PI control
- Extension of AUCBC to time-delay
- Extension of AUCBC to unstable
- Extension of AUCBC to Non-minimum phase (NMP)
- Extension of AUCBC to Multivariable process
Uncertainty compensation in Multivariable process

Multivariable Control

Conventional
Decentralized
Solution

Simple but unsatisfactory

Conventional
Decoupling
Control

Poor Robustness
AUCBC Solution Idea:
• Considering the couplings as a kind of uncertain disturbance for each single loop, as well as other uncertainties.
• Design disturbance observer to estimate the lumped uncertainties.
• Compensate the estimated term in the inner loop.
• The outer-loop controllers are designed individually.
Equivalent block diagram transformation

Uncertainty compensation in Multivariable process
Equation

\[
\begin{align*}
G(s) &= \frac{g_{11}}{\tilde{g}_{11}} \quad Q_1(s) = \frac{g_{12}}{\tilde{g}_{11}} \\
\tilde{g}_{11} &= \frac{Q_2(s)}{g_{21}} = \frac{\tilde{g}_{21}}{g_{22}} \\
\end{align*}
\]

Conclusion: The proposed AUCBC Solution can be equivalent to the conventional inverted decoupling, but with robustness significantly improved!!!

Laboratory verification

Experimental platform

Performance

Fig. 17. Tracking performances under different strategies

Li Sun, Junyi Dong, Donghai Li, Kwang Y. Lee. A Practical Multivariable Control Approach Based on Inverted Decoupling and Decentralized Active Disturbance Rejection Control. Industrial & Engineering Chemistry Research, 2016, 55(7): 2008-2019. (Citation: 53)
Content

- Background
- Theoretical development
- Experimental Applications
- Conclusions
AUCBC configuration in various DCS

ABB
Emerson
Matlab

GE
Test Platform

Test results

Bumpless Transfer & Anti-saturation
Application Examples

- Water level control in a 1000MW power plant
- Temperature Control in a 300MW power plant
- Fuel cell control
Application in power plant regenerator
The experimental controlled output agrees well with the theoretic trajectory!
Experimental Applications

Application in superheated steam temperature cascaded control
Experimental Applications

Application in superheated steam temperature cascaded control

AUCBC parameter tuning: MOPSO

\[ J_2(A) \prec J_2(D) \]

\[ J_1(A) < J_1(D) \]

\[ \forall \]

MOPSO Algorithm

Repository

Start

Initialize

Simulation & Evaluation

Dominance Sorting

Non-dominant solutions

Update \( g_{\text{best}} \)

Update \( p_{i}^{\text{best}} \)

Density Evaluation

Leader Selection

Based on Eq. (21)-(22)

Update \( g_{i}^{\text{best}} \)

Update \( i^{th} \) particle

\[ i < N \]

\[ \text{Terminate?} \]

Swarm Moved Solutions

NO

YES

End

\[ i = i + 1 \]

Max Generation

M particles

Search space

Model in Section 2

Update best \( i \)

Update best \( g \)

\[ i = 0 \]
Long-term running data statistics under different controls

Fuel cell control (500W)

Experimental Applications

Stack temperature control (500W)

Compressor Movements

Content

Background

Theoretical development

Experimental Applications

Conclusions
Conclusion

- Uncertainty is universal, inevitable and essential for control;
- A new computation algorithm is developed for PI optimization.
- The data-driven uncertainty compensation method is extended to time-delay, unstable, NMP and multivariable processes.
- Several successful applications in power plants and fuel cells
- More application examples and theoretic details can be found:


Thank you for your attention!

Q&A