Advanced Adaptive Control for Unintended System Behavior

Dr. Chengyu Cao

Mechanical Engineering
University of Connecticut
ccao@engr.uconn.edu jtang@engr.uconn.edu

Outline

☐ Part I: Challenges: Unintended System Behavior

☐ Part II: Proposed $\mathcal{L}_1$ Adaptive Control Techniques

☐ Part III: HVAC System and Control Objectives

☐ Part IV: Plans to Achieve Objectives for HVAC System

☐ Part V: Design Controllers for HVAC with GUI

☐ Part VI: Project Milestones

Challenges

In practice, engineering systems are often affected by unintended behaviors.

Causes to off-nominal situations

- ✓ disturbances,
- ✓ model uncertainties
- ✓ measurement noise
- ✓ etc.

L1 Adaptive Control

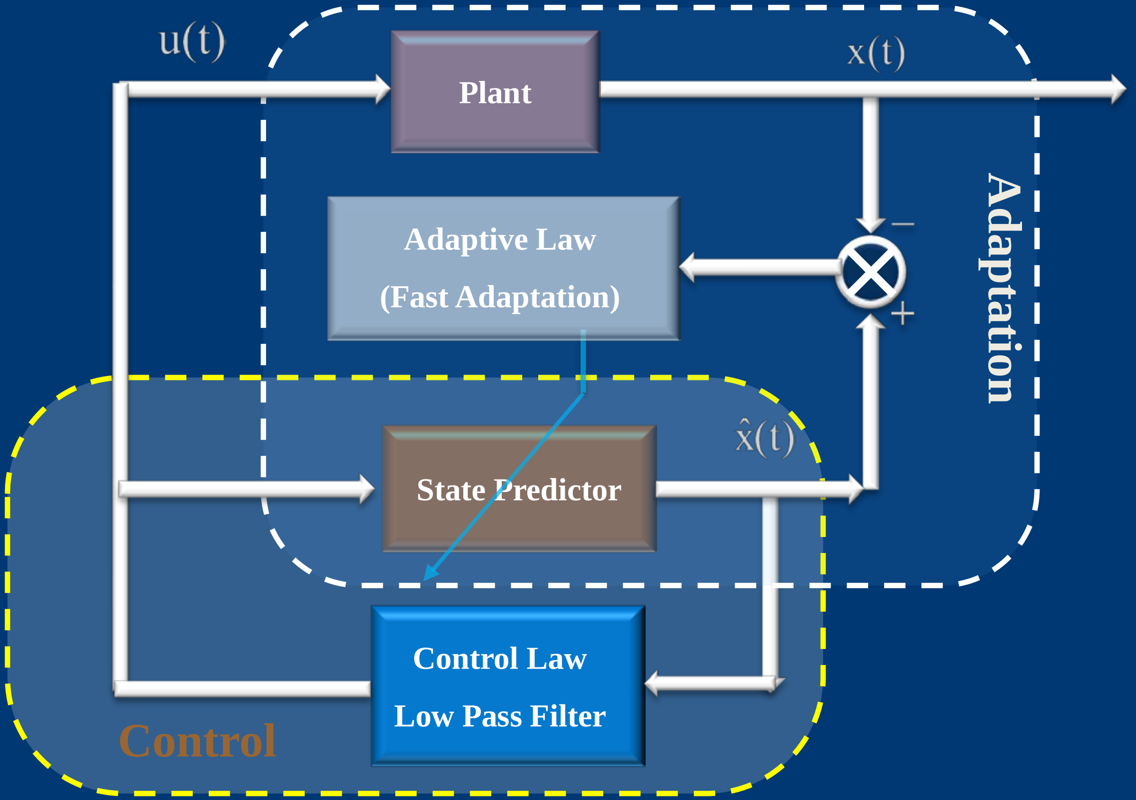
Benefits of L1 adaptive control

- improves transient performance
- handles time-varying model uncertainties and disturbances
- reduces V&V (Verification and Validation) efforts

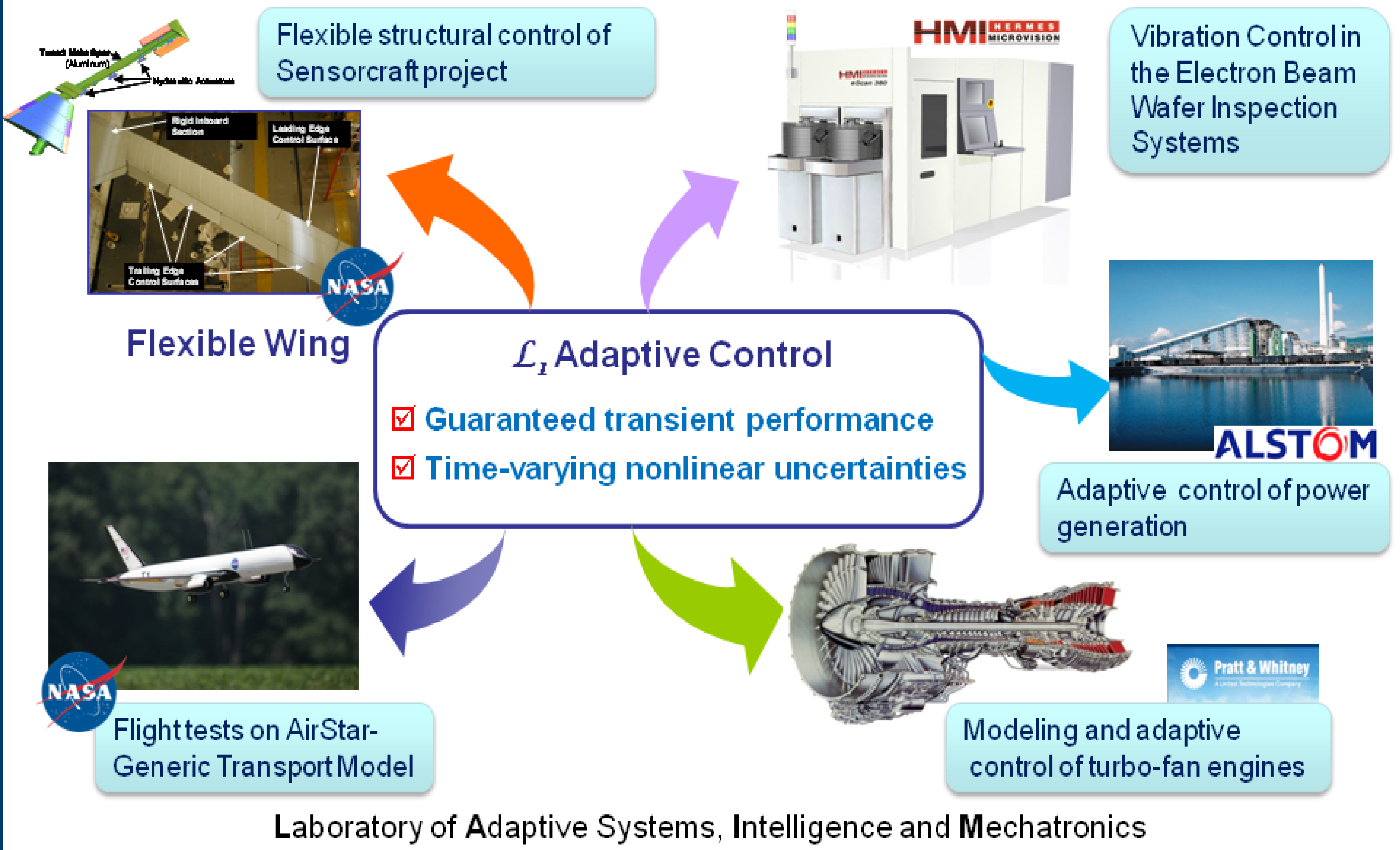
$\mathcal{L}_1$ Adaptive Control Structure

❑ Features:

- ➢ Handles time-varying parameters and uncertainties
- ➢ Allows for fast and robust adaptation
- ➢ Improves transient performance and tracking performance



Applications



Flexible structural control of Sensorcraft project

Flexible Wing

Vibration Control in the Electron Beam Wafer Inspection Systems

$\mathcal{L}_1$ Adaptive Control

- ☑ Guaranteed transient performance
- ☑ Time-varying nonlinear uncertainties

Adaptive control of power generation

Flight tests on AirStar-Generic Transport Model

Modeling and adaptive control of turbo-fan engines

Laboratory of Adaptive Systems, Intelligence and Mechatronics

Application of $\mathcal{L}_1$ in Flight Control

NASA:

AirSTAR

$\mathcal{L}_1$ adaptive controller

- closes the loop for 14 minutes
- finishes all the scenarios successfully

Fort Pickett, VA, April 2010, 14th flight of AirStar

Limitations in L1 Adaptive Control

- The benefit of L1 adaptive control

$$\lim_{\Gamma\to\infty}\left(u_{ad}(t)-u_r(t)\right)=0, \qquad \forall t\geq 0;$$

$$\lim_{\Gamma\to\infty}\left(x(t)-x_r(t)\right)=0, \qquad \forall t\geq 0 \;.$$

- However, $\Gamma \propto 1/T$, but T is limited by hardware sampling rate
- To overcome this limitation, we can introduce additional estimation schemes with memorizing mechanism

Problem Formulation

Consider a SISO system

$$\dot{x}(t) = A_K x(t) + b\, u_K(t) + \sigma(t),$$

$$y(t) = c^{\bullet}\, x(t), \qquad x(0) = x_0 = 0$$

- x: system state
- u_K: control input
- σ: uncertainty
- y: output
- A_K, b, c: known system matrices

- If A_K is controllable, there exists K such that $A_K - bK^T$ is Hurwitz.
- Then we can rewrite the system as

$$\dot{x}(t) = Ax(t) + b\, u(t) + \sigma(t)$$

- $A = A_K - bK^T$ is
- $u = u_K + K^T x(t)$

- The control objective is for y to track a given reference signal, r.

Adaptive Law/State Predictor

- The state predictor is designed to mimic the system dynamics

$$\dot{\hat{x}}(t) = Ax(t) + b\,u(t) + \sigma(t) + \sigma_b(t)$$

$$\hat{y}(t) = c^{\bullet}\,x(t)$$

  - $\hat{\sigma}_b$ is the memorizing mechanism term
  - $\hat{\sigma}$ is time-varying disturbance
- The adaptive law for $\hat{\sigma}$ is obtained by writing the error dynamics, $\dot{\tilde{x}} = \dot{\hat{x}} - \dot{x}$, discretizing, substituting $\hat{\sigma}(iT)$, and solving for $\tilde{x}((i+1)T) = 0$
  - i: number of elapsed time steps
  - T: duration of time step

Adaptive Law

$\hat{\sigma}$ is generated by the standard piecewise-constant adaptive law,

$$\hat{\sigma}(iT) = -\left[\int_0^T \Phi(T-\tau)d\tau\right]^{-1} \Phi(T)\tilde{x}(iT)$$

$$\Phi(T) = e^{AT}, \qquad \left(\Gamma = -\left[\int_0^T \Phi(T-\tau)d\tau\right]^{-1} \Phi(T)\right)$$

$\hat{\sigma}_b$ is generated by the feedback law,

$$\hat{\sigma}_b(t) = D(s)(\sigma(t) + \sigma_b(t))$$

$D(s)$ is a low-pass filter.

Update Law for Memory Term

- $D(s)$ has the form

$$D(s) = \frac{a}{s+a}$$

- The feedback law for $\hat{\sigma}_b$ can be solved to obtain

$$\hat{\hat{\sigma}}_b(t) = \sigma(t)\frac{a}{s}$$

Control Law

The control law consists of 3 parts,

$$u(t) = u_1(t) + u_2(t) + u_3(t)$$

- u_1 is designed to drive y to r in the absence of uncertainties
- u_2 and u_3 are designed to cancel the effects of matched and unmatched components of uncertainties respectively
- Matched and unmatched components determined by

$$\begin{bmatrix} \hat{\sigma}_1 \\ \hat{\sigma}_2 \end{bmatrix} = \begin{bmatrix} b & \bar{b} \end{bmatrix}^{-1} (\hat{\hat{\sigma}} + \sigma_b)$$

  - $\bar{b}$ is the nullspace of b^{T}
  - $\hat{\sigma}_1$ is the matched component
  - $\hat{\sigma}_2$ is the unmatched component

The matched component can be cancelled by simply choosing it's opposite

$$u_2(t) = -\hat{\sigma}_1(t)$$

u_1 is determined by dynamic version of the state predictor, omitting the uncertainty terms

$$u_1(t) = -\frac{1}{cA^{-1}b} r(t)$$

The matched component can be cancelled by simply choosing it's opposite

$$u_3(t) = -C_2(s) \frac{c(sI - A)^{-1}\bar{b}}{c(sI - A)^{-1}b} \hat{\sigma}_2(t)$$

Simulations

Two simulation examples are presented for
Small T, $T = 0.0001$ seconds
Large T, $T = 0.01$ seconds

Both cases are tested with and without memorizing mechanism present in the controller

Controller A: $\hat{\sigma}_b(t) = \sigma(t)\frac{a}{s}$

Controller B: $\hat{\sigma}_b(t) = 0$

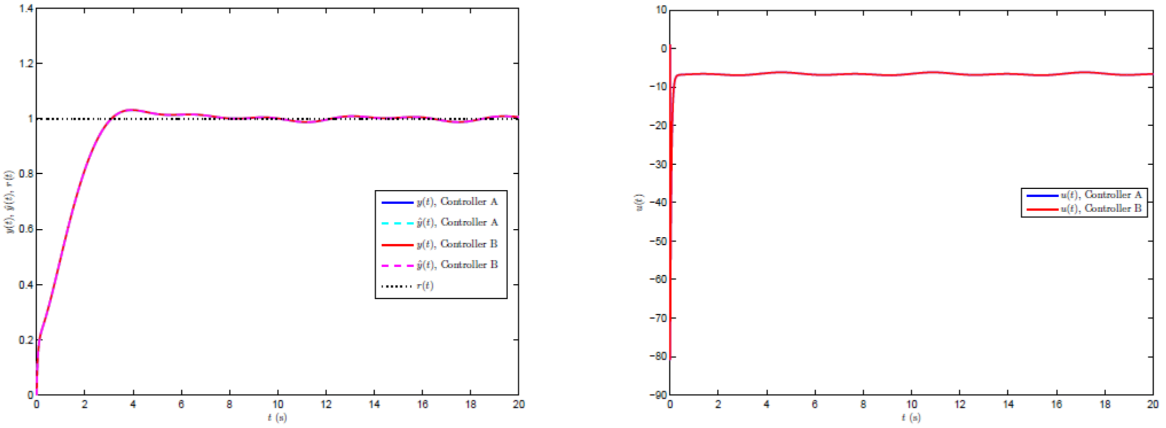
Simulation for $T = 0.0001$ seconds

Both controllers perform identically

Output prediction matches real output

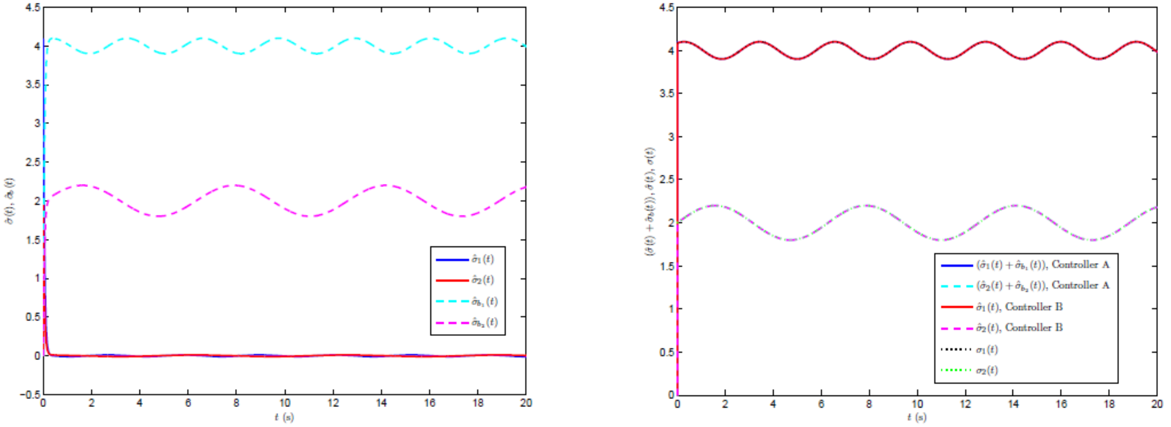
Uncertainty estimations are identical for both controllers

Both match real uncertainty



(a) Tracking performance and output prediction

(b) Time-history of $u(t)$



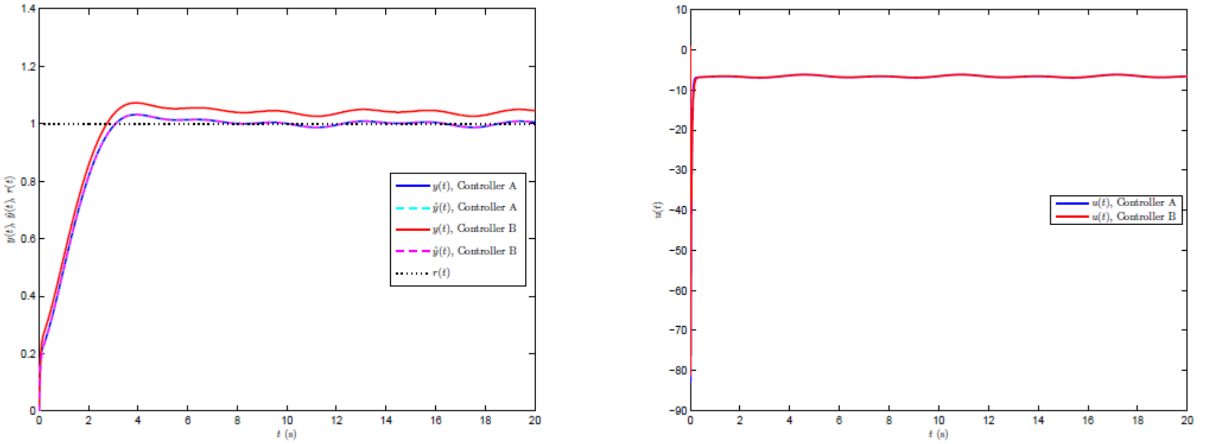
(c) Time-history of $\hat{\sigma}(t)$ and $\hat{\sigma}_b(t)$ for Controller A

(d) Total uncertainty approximation

Simulation for $T = 0.01$ seconds

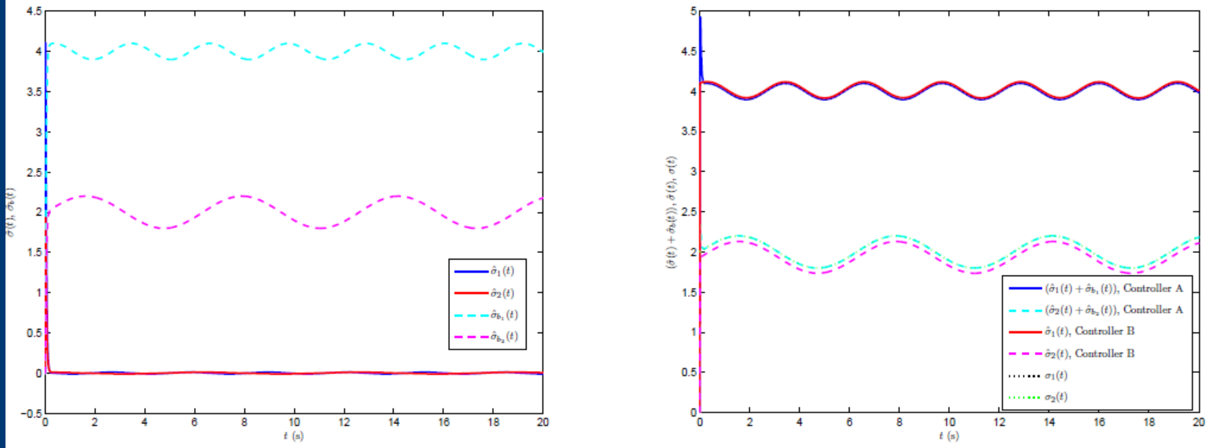
Controller B displays a significant steady-state error, while Controller A tightly matches the reference

Uncertainty estimations more accurate for Controller A than Controller B



(a) Tracking performance and output prediction

(b) Time-history of $u(t)$



(c) Time-history of $\hat{\sigma}(t)$ and $\hat{\sigma}_b(t)$ for Controller A

(d) Total uncertainty approximation

Conclusions

- $\mathcal{L}_1$ adaptive control uses high gain adaptive law (fast adaptation) to increase performance
- Adaptive gain is inversely proportional to hardware sampling time
- Sampling time is limited by hardware
- Memorizing mechanism is shown to improve performance for larger sampling times

Proposed $\mathcal{L}_1$ Adaptive Control Techniques

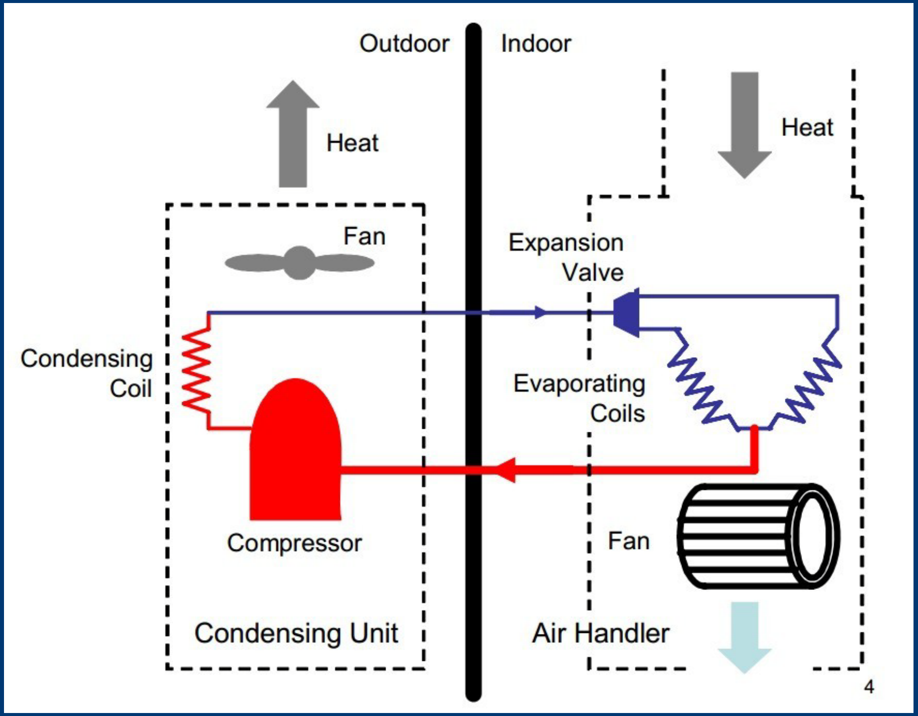
1. Extend the System Coverage of the $\mathcal{L}_1$ Adaptive Controller
   - Output feedback control for nonlinear system
   - $\mathcal{L}_1$ adaptive control design will be further extended under the output feedback framework for more challenging problems

2. Reduce Tuning Efforts of the $\mathcal{L}_1$ Adaptive Controller
   - Design a low-pass filter with minimized tuning efforts such that the controller has the adaptability for arbitrarily large nonlinear time-varying uncertainties without redesign parameters

3. Relax Hardware Requirements
   - $\mathcal{L}_1$ adaptive control with memorizing technique would give the ability to maintain performance with increased integration step-size

UTC Application: HVAC System

Rooftop AC: possible application platform



The Electrical System of an Air Conditioner (Kosterev 2007)

* Nonlinear uncertainties
* Changing and unknown operating condition
* Etc.

HVAC System

HVAC system design is based on the principles of thermo dynamics, fluid mechanics, and heat transfer.

Sub-systems of Commercial Rooftop

☐ Refrigeration Sub-system
☐ Heating Sub-system
☐ OD Air Economizer/Ventilation Sub-system

Modeling of HVAC

For the control of HVAC system, nominal models are needed.

Complete dynamic model include

- ☐ RTU
- ☐ air-distribution systems
- ☐ building zones
- ☐ etc.

Model uncertainty and disturbances are significant.

Multiple Control Loops

Actuator	Control target
Compressor	Supply air temperature
Supply air fan	Supply air duct pressure
Exhaust fan	Pressure of one selected zone
Zone damper	Zone temperature

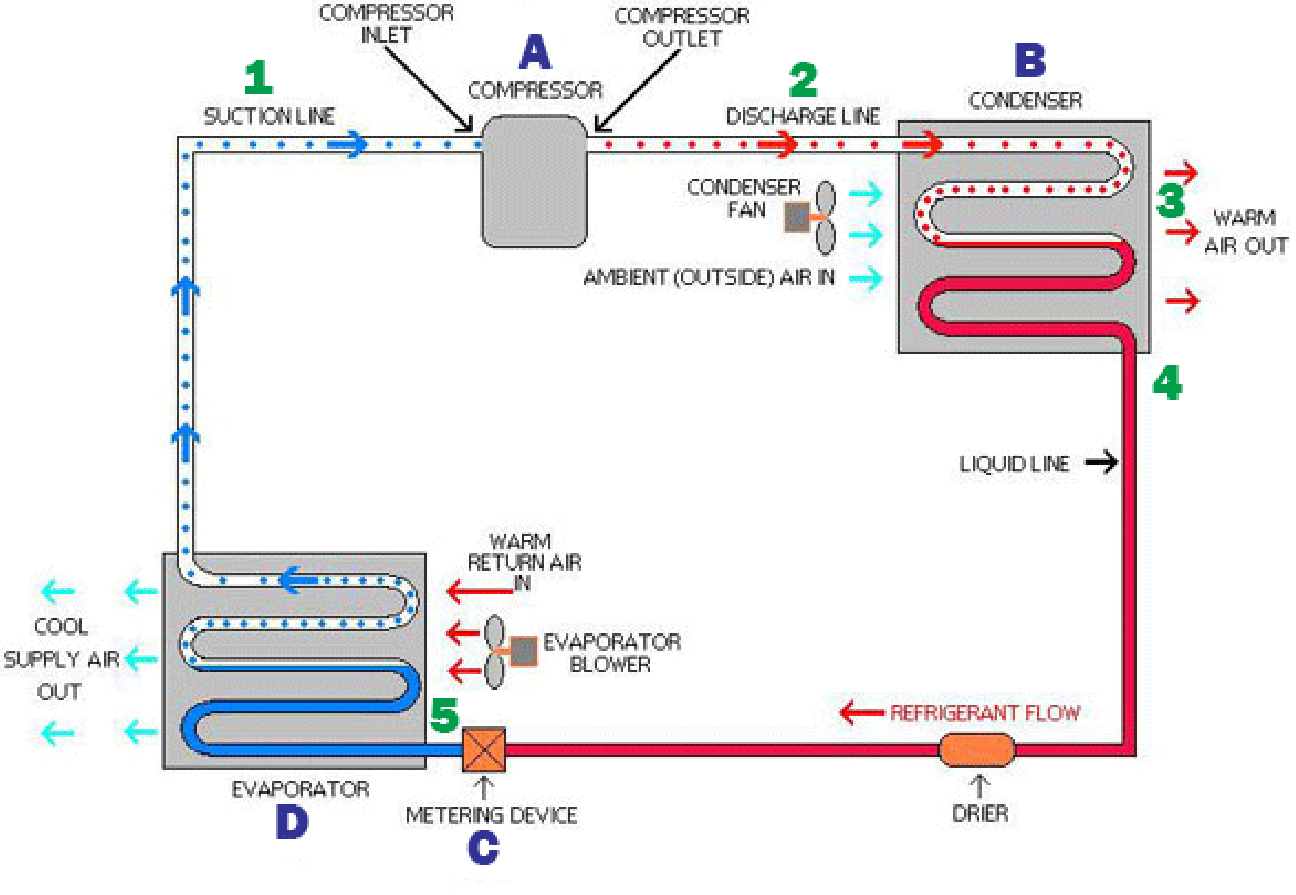
Control Objectives for HVAC System

- Performance in off-nominal situations
  - Maintain performance under different environments and off-nominal situations

- System protection
  - Prevent component damages

- Energy Conservation
  - Minimize electricity consumption

Protection: Compressor



- pumps the refrigerant gas up to a high pressure and temperature.
- enters a condenser and condenses into its liquid phase.
- evaporates and returns to the compressor, and repeats the cycle.

Protection

Overheating protection

❑ Long time running of the system;
❑ Too high temperature of the environment;
❑ Short circuit

Overcooling protection

❑ Too low temperature of the environment;

Over-current protection

❑ Long time running of the system;
❑ Too low voltage;
❑ Short circuit

Solutions: Performance

Applying proposed $\mathcal{L}_1$ adaptive control to HVAC System:

✓ Maintain system performance with unintended system behavior caused by changing environmental conditions and equipment degradation.

✓ Handle unintended equipment behavior in case of component faults

✓ ReduceV&V efforts

Solution: Energy Conservation

Model based performance seeking control

- Adaptive control handles model uncertainties and unintended system behavior
- Model based performance seeking utilizing redundant actuations

Solution: Protection

Protections

↓

Signal constraints need to be maintained

↓

Maintain input/output constraints

Solution: Protection (continued)

Incorporate input/output constraints protection in L1 adaptive control

Input constraints → Direct implementation

Output constraints → Model based prediction and optimization

↓

Prerequisite: Get rid of unintended system behavior

Software Toolbox with GUI

User

Specifies
System Information

Interface

Structure,
time-delay,
uncertainties bound,
measurement noise
and performance
requirement

Software Toolbox

Memorizing Technique
(Relax hardware
requirement)

Deadzone
(Handle noise and
time-delay)

Filter Bandwidth
Adaptation
(Reduce tuning effort)

Output Feedback
(Extend coverage)

Give the control design for this specific system and ***provide*** quantification for possible V&V analysis.

GUI Interface

Guide the users through design process with enough information and explanation.

- Step 1:

  System information: (Nominal plant architecture -- Chosen from pre-defined classes that $\mathcal{L}_1$ adaptive controller can handle).

  -- User can pick one option which is most close to the system.

- Step 2:

  Under this architecture, input nominal information of plants.

- Step 3:

  Uncertainty information. (bounds, etc.)

- Step 4:

  Other information. (measurement noise, etc.)

Software Toolbox

After the information collection is done through the interface.

❖ Software toolbox system will generate a controller automatically with a few tuning parameters.

❖ Next step, controller needs to be tuned and tested.

The parameters would be tuned based on guidance.

Rooftop Air Conditioners

1. Analysis system and get generic modeling of the rooftop AC.
   - Compressor unit model, dynamic behavior and etc.
   - States: running & installed

2. Collect high-frequency problems and study the impacts to control system and energy saving.
   - Sensor failure, economizer, thermostats and etc.

3. Using design tool-box for rooftop AC control system and testing the controller.

Project Milestones

1

- Generic modeling of interested system (Rooftop AC)

2

- Software Toolbox

3

- Reports and slides of theoretical results

4

- Experiments and tests of adaptive control on the model

1881

Department of Mechanical Engineering

Thank you!

University of Connecticut