The 33rd Chinese Control Conference
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Active Disturbance Rejection Control: (自抗扰控制)

Methodology, Practice and Analysis

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What is
Active Disturbance Rejection Control (ADRC)?
自抗扰控制

ADRC as a potential solution has been explored in many domain of control engineering:

- **motor systems** (speed control of induction motor and permanent-magnet synchronous, noncircular turning process, etc)
- **flight control** (attitude control of space ship, high-speed vehicles, UAV, morphing aircraft, etc)
- **robotic control** （force control, uncalibrated hand-eye coordination, AUV, etc）
- **thermal process** (unstable heat conduction systems, boiler-turbine-generator systems, ALSTOM gasifier, fractional-order system, etc)
- **electromechanical systems** (induction motors, permanent magnet motors, synchronous motors, etc)
- **power electronics devices** (DC-to DC power converters, rectifiers, inverters, HVDC SMC systems, etc)
- **power systems, axial flow compressors, gasoline engines, automotive control, tension system, infinite-dimension systems, …**

ADRC in U.S.: Milestones

- ***1997: made the 1st successful ADRC hardware test on a servo mechanism***
- ***2008: $1M venture capital, grew by $5M in 2012.***
- ***2010: 1st factory implementation, 10 Parker extrusion lines (挤压机生产线) at a Parker Hannifin Extrusion Plant in North America***

(cpk: from 2.3 to >8; avg. energy saving 57%)

- ***2011: implemented ADRC in several high energy particle accelerators (高能粒子加速器) in the National Superconducting Cyclotron （超导回旋加速器） Lab in the U.S.***

- ***2011: Texas Instrument adopts ADRC; 3 patents granted.***
- ***2013: Texas Instrument released the ADRC based motion control chips***

from academic setting into industry

CCC2014

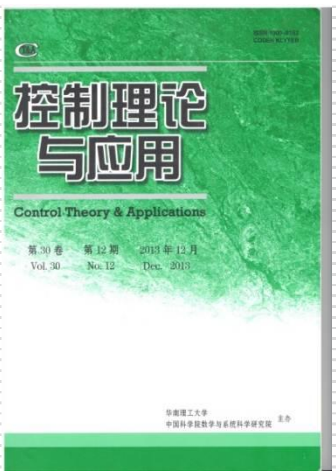
TuA22 - Invited Session: ADRC Design Techniques

TuB22 - Invited Session: Disturbance Rejection: Problems and Solutions

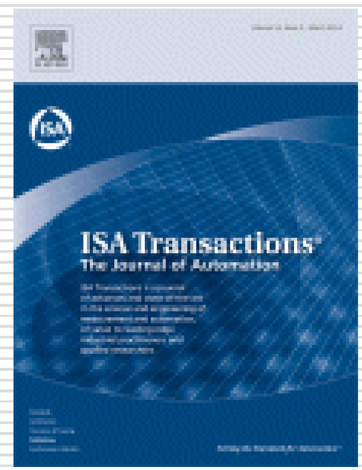
WeA22 - Invited Session: ADRC in Power Generation and Regulation

WeB22 - Invited Session: Precision Control of Mechanical Systems on ADRC

+ several regular papers



Special Issues on ADRC
Control Theory & Applications,2013



Special Issues on Disturbance
Estimation and Mitigation
ISA Transaction, 2014

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Quantum control

Outline

- Principles and methods of ADRC
- Practice
- Analysis
- Conclusions

Principles and Methods of ADRC

- **Brief history of ADRC**

Jingqing Han(1937-2008)

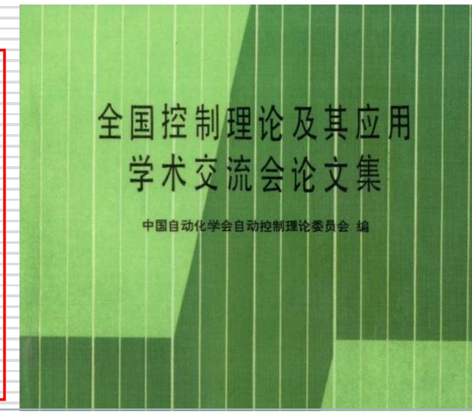
ADRC was proposed by Jingqing Han in 1990s.

One of the pioneers in control theory and applications in China

Principles and Methods of ADRC

Brief history of ADRC

The story of ADRC begins at the 1st CCC in 1979 (The 1st National Conference on Control Theory and Its Applications)



The systems, linear or nonlinear, under some conditions, can be transformed into the canonical form of cascade integrators via feedback.

-Han J. The structure of linear system and computation of feedback system, in: Proc. National Conference on Control Theory and Its Application, Academic Press, 1980

线性系统的结构与反馈系统计算

韩 京 清

（科 学 院 数 学 所）

对应于这个阵的系统叫做积分器串联系统．这是系统中最简单的系统．任意完全能控系统经适当坐标变换和状态反馈均可化成这种形式．由于反馈不改变系统的能控性，因此研究与系统的能控性有关问题，都可用对应的积分器串联形式来讨论．这种现象不仅对线性系统存在，而且在一类非线性控制系统中也成立．

Canonical form of linear and nonlinear system

The systems, linear or nonlinear, under some conditions can be transformed into the canonical form of cascade integrators via feedback.

$$\dot{x} = Ax + Bu,$$
$$y = Cx$$

$$A = \begin{bmatrix} 0 & 1 & \cdots & 0 & 0 \\ & 0 & 1 & & \\ & & \ddots & \ddots & \\ & & & 0 & 1 \\ & & & & 0 \end{bmatrix}, B = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix}$$

canonical form of linear systems

canonical form for nonlinear systems?

Canonical form of linear and nonlinear system

In 1980s-1990s, nonlinear control is a hot topic

- R.W. Brockett, Feedback invariants for nonlinear systems, 1978IFAC
- B.Jakubczyk and W.Respondek, On linearization of control systems, 1980
- B. Charlet, J.Levine, On dynamic feedback linearization, 1989

differential geometry

- M. Fliss, Generalized controller canonical forms for linear and nonlinear dynamics, 1990

differential algebra

Exact linearization via differential geometry

Isidori A., Nonlinear Control System, Springer-Verlag

Canonical form of linear and nonlinear system

Similar Idea: Exact linearization via differential geometry

The exact model is known

SISO nonlinear system $\dot{x} = f(x) + b(x)u,\ x \in R^n$

$y = h(x)$

If the relative order is *n*, then there exist:

$$\alpha(x) = -\frac{L_f^n h(x)}{L_b L_f^{n-1} h(x)},\ \beta(x) = \frac{1}{L_b L_f^{n-1} h(x)}$$

transformation: $z = T(x)$ **state feedback control** $u = \alpha(x) + \beta(x)v$

exactly linearized to a canonical form of cascade integrators

$$\dot{z} = Az + Bv,\quad y = Cz$$

$$A = \begin{bmatrix} 0 & 1 & \cdots & 0 & 0 \\ & 0 & 1 & & \\ & & \ddots & \ddots & \\ & & & 0 & 1 \\ & & & & 0 \end{bmatrix},\ B = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix},\ C = \begin{bmatrix} 1 & 0 & \cdots & 0 & 0 \end{bmatrix}$$

System with large uncertainties: how to realize the linearization?

Han: explore the problem in a completely different way

Principles and Methods of ADRC

- **Brief history of ADRC**

In the 1980s–1990s: Han further pointed out

(a) The boundary between the linear and the nonlinear system can be broken by control input.

for vast kinds of systems:

linear time-invariant or nonlinear time-varying or coupled

can be transformed into a linear decoupled chain of integrators via control input.

ADRC frame: plants no longer be distinguished by linear/nonlinear, time-varying /time invariant, coupled/decoupled

(b) For linear time-invariant system:

actively introduce special kinds of nonlinear control

for example, non-smooth feedback

to improve the performance of the closed-loop system

The original form of ADRC is nonlinear: full use the power of nonlinear feedback

This talk will focus on (a)

Principles and Methods of ADRC

- **Brief history of ADRC**

Ideas:

- **treat unknown model: a special state (named extended state by Han)**
- **design a special observer: the extended state observer (ESO), to estimate it in real time**

In such a brave stroke:

system: uncertain, nonlinear and time varying

linear chain of integrators

Next: discuss the features of ADRC by several examples

Principles and Methods of ADRC

Example 1. Consider the MIMO uncertain nonlinear time-varying system:

$$\begin{cases} \dot{X}_1 = X_2 \\ \cdots \\ \dot{X}_{n-1} = X_n \\ \dot{X}_n = D(t) + F(X,t) + B(X,t)U(t) \\ Y = X_1 \end{cases}$$

States: $X_i \in R^m (i \in \underline{n}), X = \begin{bmatrix} X_1^T & \cdots & X_n^T \end{bmatrix}$

Output to be controlled : $Y(t)$

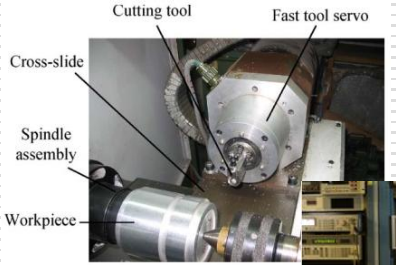
Control input: $U(t) \in R^m$

Unknown Disturbance: $D(t) \in R^m$

Uncertain dynamics: $F(X,t) \in R^m$, $B(X,t) \in R^{m\times m}$

$B(X,t) \in R^{m\times m}$ **is invertible**

Many engineering systems can be described by it:



➢The fast tool servo

Wu D., and Chen K., Design and analysis of precision active disturbance rejection control for noncircular turning process. IEEE TIE, 2009.

➢The cavity dynamics of the superconducting RF cavities

Vincent J., Morris D., Usher N., Gao Z., Zhao S., Nicoletti, A., and Zheng, Q., On active disturbance rejection based control design for superconducting RF cavities. Nuclear Instruments & Methods in Physics Research A, 2011.

➢The robot system

Su J.,etc, Task-independent robotic uncalibrated hand-eye coordination bas那么ed on the extended state observer. IEEE Transactions On Systems, Man, And Cybernetics, part B: Cybernetics, 2004.

Principles and Methods of ADRC

Example 1. Consider the MIMO uncertain nonlinear time-varying system:

$$\begin{cases} \dot{X}_1 = X_2 \\ \cdots \\ \dot{X}_{n-1} = X_n \\ \dot{X}_n = D(t) + F(X,t) + B(X,t)U(t) \\ Y = X_1 \end{cases}$$

Unknown disturbance: $D(t) \in R^m$

Uncertain dynamics: $F(X,t) \in R^m, \ B(X,t) \in R^{m\times m}$ **invertible**

For a more general nonlinear system

$$\dot{x} = f(x) + g(x)u, \ x \in R^n$$
$$y = h(x)$$

If the relative order is *n*, and the exact model is known:

exact linearization via differential geometry

If the exact model is unknown, $f(x), g(x)$ **unknown**

$$z = T(x) = \begin{bmatrix} h(x) \\ L_f h(x) \\ \vdots \\ L_f^{n-1} h(x) \end{bmatrix} = \begin{bmatrix} y \\ \dot{y} \\ \vdots \\ y^{(n-1)} \end{bmatrix} \triangleq \begin{bmatrix} z_1 \\ z_2 \\ \vdots \\ z_n \end{bmatrix} \Rightarrow \begin{cases} \dot{z}_1 = z_2 \\ \cdots \\ \dot{z}_{n-1} = z_n \\ \dot{z}_n = L_f^n h(x) + L_g L_f^{n-1} h(x) \cdot u(t) \\ y = z_1 \end{cases}$$

Uncertain dynamics: $F(X,t) \in R^m, \ B(X,t) \in R^{m\times m}$ **invertible**

Principles and Methods of ADRC

$$\begin{cases} \dot{X}_1 = X_2 \\ \cdots \\ \dot{X}_{n-1} = X_n \\ \dot{X}_n = D(t) + F(X,t) + B(X,t)U(t) \\ Y = X_1 \end{cases}$$

$\bar{B}(t)$ **Estimation for** $B(X,t)$, $\bar{B}(t)$ **is invertible.**

canonical form of cascade integrators

$$\begin{cases} \dot{X}_1 = X_2 \\ \cdots \\ \dot{X}_{n-1} = X_n \\ \dot{X}_n = \bar{B}(t)U(t) \end{cases}$$

difference between the original system and its canonical form

$$X_{n+1} = D(t) + F(X,t) + \left[B(X,t) - \bar{B}(t) \right] U(t)$$

"extended state" or "total disturbance"

External disturbance — **Internal disturbance (nonlinear, time-varying, coupled)**

$$\begin{cases} \dot{X}_1 = X_2 \\ \cdots \\ \dot{X}_{n-1} = X_n \\ \dot{X}_n = X_{n+1} + \bar{B}(t)U(t) \end{cases}$$

Canonical form + total disturbance

Principles and Methods of ADRC

$$\begin{cases} \dot{X}_1 = X_2 \\ \cdots \\ \dot{X}_{n-1} = X_n \\ \dot{X}_n = X_{n+1} + \bar{B}(t)U(t) \end{cases}$$

Canonical form + total disturbance

Extended state observer(ESO) (Han, 1995)

actively estimate the "total disturbance"

$$\begin{cases} \dot{\hat{X}}_1 = \hat{X}_2 - G_1(\hat{X}_1 - Y) \\ \cdots \\ \dot{\hat{X}}_n = \hat{X}_{n+1} - G_n(\hat{X}_1 - Y) + \bar{B}(t)U(t) \\ \dot{\hat{X}}_{n+1} = -G_{n+1}(\hat{X}_1 - Y) \end{cases} \Longrightarrow \begin{array}{l} \hat{X}_1 \to Y \\ \cdots \\ \hat{X}_n \to X_n (= Y^{(n-1)}) \\ \hat{X}_{n+1} \to X_{n+1} \end{array}$$

- **The order of ESO = the order of the plant +1**
- $G_i(\hat{X}_1 - Y)$ **nonlinear function to be designed**

Principles and Methods of ADRC

Canonical form + total disturbance

$$X_{n+1} = D(t) + F(X,t) + \left[B(X,t) - \bar{B}(t)\right]U(t)$$

$$\begin{cases} \dot{X}_1 = X_2 \\ \cdots \\ \dot{X}_{n-1} = X_n \\ \dot{X}_n = X_{n+1} + \bar{B}(t)U(t) \end{cases}$$

ADRC (Han,1998)

ESO (1995)

$$\begin{array}{l} \hat{X}_1 \to Y \\ \cdots \\ \hat{X}_n \to X_n (= Y^{(n-1)}) \\ \hat{X}_{n+1} \to X_{n+1} \end{array}$$

$$U(t) = -\bar{B}^{-1}(t)\hat{X}_{n+1} + U_0(Y, \hat{X}_2, \cdots \hat{X}_n)$$

Compensate for total uncertainty — **Control for canonical system**

Strong Robustness — **Desired Performance**

$$\begin{cases} \dot{X}_1 = X_2 \\ \cdots \\ \dot{X}_{n-1} = X_n \\ \dot{X}_n = \bar{B}(t)U_0(\bullet) \end{cases}$$

The methodology of ADRC is developed (1990s)

New meaning for the concept of disturbance rejection

Principles and Methods of ADRC

$$\begin{cases} \dot{X}_1 = X_2 \\ \cdots \\ \dot{X}_n = D(t) + F(X,t) + B(X,t)U(t) \\ Y = X_1 \end{cases}$$

$$\begin{cases} \dot{X}_1 = X_2 \\ \cdots \\ \dot{X}_{n-1} = X_n \\ \dot{X}_n = X_{n+1} + \bar{B}(t)U(t) \end{cases}$$

$$X_{n+1} = D(t) + F(X,t) + \left[B(X,t) - \bar{B}(t)\right]U(t)$$

ADRC law

ESO
$$\begin{cases} \dot{\hat{X}}_1 = \hat{X}_2 - G_1(\hat{X}_1 - Y) \\ \cdots \\ \dot{\hat{X}}_n = \hat{X}_{n+1} - G_n(\hat{X}_1 - Y) + \bar{B}(t)U(t) \\ \dot{\hat{X}}_{n+1} = -G_{n+1}(\hat{X}_1 - Y) \end{cases}$$

$$U(t) = -\bar{B}^{-1}(t)\hat{X}_{n+1} + U_0(Y, \hat{X}_2, \cdots \hat{X}_n)$$

Han turned his attention to an even significant problem:

design the control law

without an exact mathematical model

control of uncertain systems / disturbance rejection

the most fundamental issue in control science / engineering

control of uncertain systems / disturbance rejection

one of the most fundamental issue in control science / engineering

Uncertainty / disturbance (new meaning)

- **Internal Uncertainty**
  - **Parameters**
  - **Dynamics**
- **External Disturbance**

•feedback control
•Adaptive control
•Robust control
•Embedded model control (EMC)
•Sliding mode control
•Model free control(M. Fliess, Z.G. Han)
•Feedback capability

•PID control
•Invariance principle (IP)
•Internal model principle (IMP)
•Disturbance-accommodation control (DAC)
•Disturbance observer based control (DOBC)
•Nonlinear output regulator theory
•……

ADRC:
- a vast range of uncertainties/disturbances
- transient/steady performance
- simplicity in engineering implementation

Extended discussion: the capability of ADRC for uncertainties by some examples

Principles and Methods of ADRC

Example 1: MIMO uncertain nonlinear time-varying system:

$$\begin{cases} \dot X_1 = X_2 \\ \cdots \\ \dot X_n = D(t) + F(X,t) + B(X,t)U(t) \\ Y = X_1 \end{cases}$$

$$\begin{cases} \dot X_1 = X_2 \\ \cdots \\ \dot X_{n-1} = X_n \\ \dot X_n = X_{n+1} + \bar B(t)U(t) \end{cases}$$

$$X_{n+1} = D(t) + F(X,t) + \left[B(X,t) - \bar B(t)\right]U(t)$$

ADRC law

ESO

$$\begin{cases} \dot{\hat X}_1 = \hat X_2 - G_1(\hat X_1 - Y) \\ \cdots \\ \dot{\hat X}_n = \hat X_{n+1} - G_n(\hat X_1 - Y) + \bar B(t)U(t) \\ \dot{\hat X}_{n+1} = -G_{n+1}(\hat X_1 - Y) \end{cases}$$

$$U(t) = -\bar B^{-1}(t)\hat X_{n+1} + U_0(Y, \hat X_2, \cdots \hat X_n)$$

$$\begin{cases} \dot X_1 = X_2 \\ \cdots \\ \dot X_{n-1} = X_n \\ \dot X_n = \bar B(t)U_0(\bullet) \end{cases}$$

Can ADRC only deal with the uncertainties of matched condition ?

Principles and Methods of ADRC

Example 2. Consider the system with unmatched condition:

$$\begin{cases} \dot{x}_1 = f_1(t, x_1, x_2, D(t)) \\ \dot{x}_2 = f_2(t, x_1, x_2, D(t)) + b(t, x_1, x_2)u \\ y = x_1 \end{cases}$$

States: $x_i \in R(i=1,2)$

Output to be controlled: $y(t)$,

Control input: $u(t) \in R$

Uncertain dynamics: $f_i(t, x_1, x_2)(i=1,2)$, $b(t, x_1, x_2)$

$b(t, x_1, x_2)$ **is invertible**

Unknown Disturbance: $D(t) \in R^p$

Uncertainty $f_1(t, x_1, x_2, D(t))$ **: not satisfy the matched condition**

---

flight control system

$$\begin{cases} \dot{\alpha} = \omega_z - a_{11}(t)\alpha + a_{10}(t) \\ \dot{\omega}_z = u - u^* + a_{21}(t)\alpha + a_{22}(t)\omega_z \\ y = \alpha \end{cases}$$

Angle of attack: α,

Angular rate: ω_z.

Uncertain aero-dynamic parameters: $a_{10}, a_{11}, a_{21}, a_{22}$

Unknown disturbance: u^* **wind**

Principles and Methods of ADRC

Example 2. Consider the system with unmatched condition:

$$\begin{cases} \dot{x}_1 = f_1(t, x_1, x_2, D(t)) \\ \dot{x}_2 = f_2(t, x_1, x_2, D(t)) + b(t, x_1, x_2)u \\ y = x_1 \end{cases}$$

Define $\bar{x}_1 = x_1, \ \ \bar{x}_2 = f_1(t, x_1, x_2, D(t)),$

$\bar{b}(t)$ $\quad \dfrac{\partial f_1}{\partial x_2} \neq 0$

$$\begin{cases} \dot{\bar{x}}_1 = \bar{x}_2 \\ \dot{\bar{x}}_2 = \dfrac{\partial f_1}{\partial t} + \dfrac{\partial f_1}{\partial x_1} f_1(t, x_1, x_2, D(t)) + \dfrac{\partial f_1}{\partial x_2} f_2(t, x_1, x_2, D(t)) + \dfrac{\partial f_1}{\partial D}\dot{D}(t) + \dfrac{\partial f_1}{\partial x_2} b(t, x_1, x_2)u \\ y = \bar{x}_1 \end{cases}$$

$$\begin{cases} \dot{\bar{x}}_1 = \bar{x}_2 \\ \dot{\bar{x}}_2 = \bar{b}(t)u \end{cases}$$

canonical form of cascade integrators

$$\bar{x}_3 = \frac{\partial f_1}{\partial t} + \frac{\partial f_1}{\partial x_1} f_1(t, x_1, x_2, d_1(t)) + \frac{\partial f_1}{\partial x_2} f_2(t, x_1, x_2, d_2(t)) + \frac{\partial f_1}{\partial D}\dot{D}(t) + \left(\frac{\partial f_1}{\partial x_2} b(t, x_1, x_2) - \bar{b}(t)\right)u$$

"total disturbance"

Principles and Methods of ADRC

$$\begin{cases} \dot{x}_1 = f_1(t, x_1, x_2, D(t)) \\ \dot{x}_2 = f_2(t, x_1, x_2, D(t)) + b(t, x_1, x_2)u \\ y = x_1 \end{cases} \quad \Rightarrow \quad \begin{cases} \dot{\bar{x}}_1 = \bar{x}_2 \\ \dot{\bar{x}}_2 = \bar{x}_3 + \bar{b}(t)u \\ y = \bar{x}_1 \end{cases}$$

total disturbance

$$\bar{x}_3 = \frac{\partial f_1}{\partial t} + \frac{\partial f_1}{\partial x_1} f_1(t, x_1, x_2, d_1(t)) + \frac{\partial f_1}{\partial x_2} f_2(t, x_1, x_2, d_2(t)) + \frac{\partial f_1}{\partial D}\dot{D}(t) + \left(\frac{\partial f_1}{\partial x_2} b(t, x_1, x_2) - \bar{b}(t)\right)u$$

ADRC

ESO

$$\begin{cases} \dot{\hat{x}}_1 = \hat{x}_2 - g_1(\hat{x}_1 - y) \\ \dot{\hat{x}}_2 = \hat{x}_3 - g_2(\hat{x}_1 - y) + \bar{b}(t)u(t) \\ \dot{\hat{x}}_3 = -g_3(\hat{x}_1 - y) \end{cases}$$

$$u(t) = -\bar{b}^{-1}(t)\hat{x}_3 + u_0(y, \hat{x}_2)$$

compensate for total disturbance ($-\bar{b}^{-1}(t)\hat{x}_3$)

achieve the performance of the canonical system ($u_0(y, \hat{x}_2)$)

$$\begin{cases} \dot{\bar{x}}_1 = \bar{x}_2 \\ \dot{\bar{x}}_2 = \bar{b}(t)u_0(\bullet) \end{cases}$$

From the point of control, $\bar{x}_3(\bullet)$ **:needed to be estimated and compensated for**

no need to estimate $f_1(t, x_1, x_2, D(t))$

Principles and Methods of ADRC

The essence of ADRC: estimate the "total uncertainty" via ESO

- **uncertainty or disturbance: if not influence the output to be controlled**
  not needed to estimate and reject it.
- **disturbance: affects the output**
  can definitely be observed from the output

The extended state or the "total disturbance" is always observable.

Example 2. Consider the system with unmatched condition:

$$\begin{cases} \dot{x}_1 = f_1(t, x_1, x_2, D(t)) \\ \dot{x}_2 = f_2(t, x_1, x_2, D(t)) + b(t, x_1, x_2)u \\ y = x_1 \end{cases}$$

$$\begin{cases} \dot{\bar{x}}_1 = \bar{x}_2 \\ \dot{\bar{x}}_2 = \dfrac{\partial f_1}{\partial t} + \dfrac{\partial f_1}{\partial x_1} f_1(t, x_1, x_2, D(t)) + \dfrac{\partial f_1}{\partial x_2} f_2(t, x_1, x_2, D(t)) + \dfrac{\partial f_1}{\partial D}\dot{D}(t) + \dfrac{\partial f_1}{\partial x_2} b(t, x_1, x_2) u \\ y = \bar{x}_1 \end{cases}$$

"total disturbance"

$$\bar{x}_3 = \frac{\partial f_1}{\partial t} + \frac{\partial f_1}{\partial x_1} f_1(t, x_1, x_2, d_1(t)) + \frac{\partial f_1}{\partial x_2} f_2(t, x_1, x_2, d_2(t)) + \frac{\partial f_1}{\partial D}\dot{D}(t) + \left(\frac{\partial f_1}{\partial x_2} b(t, x_1, x_2) - \bar{b}(t)\right) u$$

Principles and Methods of ADRC

ADRC: deal with a large class of uncertain nonlinear systems

$$\begin{cases} \dot{X}_1 = F_1(t, X_1, X_2, D(t)) \\ \cdots \\ \dot{X}_{n-1} = F_{n-1}(t, X_1, \cdots, X_n, D(t)) \\ \dot{X}_n = F_n(t, X_1, \cdots, X_n, D(t), U(t)) \\ Y = X_1 \end{cases}$$

States: $X_i \in R^m (i \in \underline{n}), X = \begin{bmatrix} X_1^T & \cdots & X_n^T \end{bmatrix}$

Output: $Y(t)$

Control input: $U(t) \in R^m$

Unknown disturbance: $D(t) \in R^p$

Uncertain dynamics: $F_i(t, X_1, \cdots, X_{i+1}) \in R^m$,

$\frac{\partial F_i}{\partial X_{i+1}} (i \in \underline{n-1}), \frac{\partial F_n}{\partial U}$, **nonsingular**

covers many practical nonlinear systems

can be generalized to

Example 2. Consider the system with unmatched condition:

$$\begin{cases} \dot{x}_1 = f_1(t, x_1, x_2, D(t)) \\ \dot{x}_2 = f_2(t, x_1, x_2, D(t)) + b(t, x_1, x_2)u \\ y = x_1 \end{cases}$$

Principles and Methods of ADRC

ADRC: deal with a large class of uncertain nonlinear systems :

$$\begin{cases} \dot{X}_1 = F_1(t, X_1, X_2, D(t)) \\ \cdots \\ \dot{X}_{n-1} = F_{n-1}(t, X_1, \cdots, X_n, D(t)) \\ \dot{X}_n = F_n(t, X_1, \cdots, X_n, D(t), U(t)) \\ Y = X_1 \end{cases}$$

States: $X_i \in R^m (i \in \underline{n}), X = \begin{bmatrix} X_1^T & \cdots & X_n^T \end{bmatrix}$

Output: $Y(t)$

Control input: $U(t) \in R^m$

Unknown disturbance: $D(t) \in R^p$

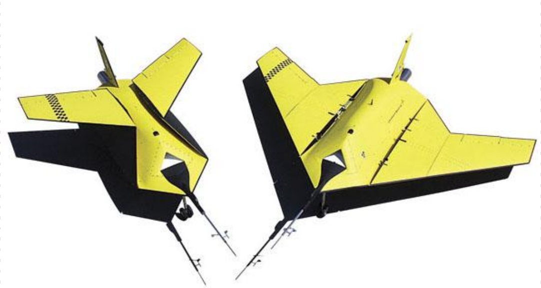
Uncertain dynamics: $F_i(t, X_1, \cdots, X_{i+1}) \in R^m$,

$\frac{\partial F_i}{\partial X_{i+1}} (i \in \underline{n-1}), \frac{\partial F_n}{\partial U}$, **nonsingular**

$Y = X_1 \in R^m \longleftrightarrow U(t) \in R^m$

$Y = X_1 \in R^p \longleftrightarrow U(t) \in R^q$ $q > p$ **Over-actuated**

Compound control:
lateral jets and aerodynamic fins



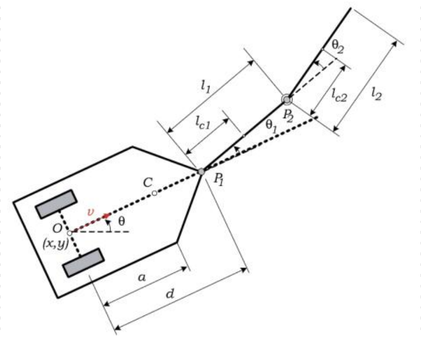
Morphing aircraft

$V(t) (\in R^m)$ → $U(t) (\in R^q)$

ADRC + optimization and allocation

Principles and Methods of ADRC

$Y = X_1 \in R^p \longleftrightarrow U(t) \in R^q$ $q < p$ **Under-actuated**



wheeled mobile manipulators

Furuta pendulum

Flat output + ADRC

- *the number of flat outputs = the number of control inputs.*
- *all system variables can be expressed by the flat outputs.*
- *avoid of zero dynamics problems*
- *physically significant*

ADRC makes sense in an input output framework.
The input output model of a flat system is nicely set up for ADRC.

•*Sira-Ramirez,H., Agrawal, S.K., Differentially Flat Systems, Marcel Dekker, Inc., 2004*
•*Fliess, M., Levine, J., etc. Flatness and defect of nonlinear systems: introductory theory and examples, Int.J.Control, 61(6),1327-1361,1995*

Principles and Methods of ADRC

ADRC can be used to deal with a large class of uncertainty nonlinear systems :

$$\begin{cases} \dot{X}_1 = F_1(t, X_1, X_2, D(t)) \\ \cdots \\ \dot{X}_{n-1} = F_{n-1}(t, X_1, \cdots, X_n, D(t)) \\ \dot{X}_n = F_n(t, X_1, \cdots, X_n, D(t), U(t)) \\ Y = X_1 \end{cases}$$

Unknown disturbance: $D(t) \in R^p$

Uncertain dynamics: $F_i(t, X_1, \cdots, X_{i+1}) \in R^m,$

$\frac{\partial F_i}{\partial X_{i+1}} (i \in \underline{n-1}), \frac{\partial F_n}{\partial U},$ **nonsingular**

$Y = X_1 \in R^m$

$\updownarrow$

$U(t) \in R^m$

$Y = X_1 \in R^p \longleftrightarrow U(t) \in R^q$ $q > p$ **Over-actuated** — **ADRC + optimization and allocation**

$Y = X_1 \in R^p \longleftrightarrow U(t) \in R^q$ $q < p$ **Under-actuated** — **Flat output + ADRC**

ADRC

a new paradigm for

- **control of nonlinear uncertain systems**
- **disturbance rejection**

Principles and Methods of ADRC

Two-degrees-of-freedom controller design

Two-channel principle (双通道设计)

ADRC $U(t) = -\bar{B}^{-1}(t)\hat{X}_{n+1} + U_0(Y, \hat{X}_2, \cdots \hat{X}_n)$

Compensate for the total uncertainty
- **stability**

replaces "I"

Performance:
- **quick**
- **Smooth**
- **high precision**

generalized PD $U_0(Y, \hat{\dot{Y}}, \cdots, \hat{Y}^{(n-1)})$

- **Invariance principle (IP)**
- **DOBC**
- **PID control (PD+I)**
- **……**

Performance:

- **stability:** disturbance rejection
- **transient:** quick, smooth, high-precision

From PID to ADRC: replaces PID, the hugely successful control mechanism

Principles and Methods of ADRC

Grand and ambitious scheme

- **From PID to ADRC**
- **control of uncertain systems, the fundamental problem in control science**

Doubts:

- **Is it really able to handle the vastly uncertain nonlinear systems in practice?**
- **Is its way of rejecting the "total disturbance" too rude to get high precision control?**
- **What's the theoretical base for this idea?**
- **……**

Principles and Methods of ADRC

theoretical justification: lagging behind for quite some time

Ambition to deal with vast uncertainties
The uncertain systems: nonlinear, time-varying, MIMO
The disturbance signal: discontinuous
The feedback: in general nonlinear structure

Great ambition: equally matched by the great challenge in theoretical analysis

quite attractive to applied researchers

Much applied research has been carried out by groups across the globe in a diverse range of engineering disciplines.

Successes roll in from many application fronts.

Outline

- Principles and methods of ADRC
- Practice
- Analysis
- Conclusions

Practice

ADRC as a potential solution has been explored in many domain of control engineering:

- **motor systems** (speed control of induction motor and permanent-magnet synchronous, noncircular turning process, etc)
- **flight control** (attitude control of space ship, high-speed vehicles, UAV, morphing aircraft, etc)
- **robotic control** （force control, uncalibrated hand-eye coordination, AUV, etc）
- **thermal process** (unstable heat conduction systems, boiler-turbine-generator systems, ALSTOM gasifier, fractional-order system, etc)
- **electromechanical systems** (induction motors, permanent magnet motors, synchronous motors, etc)
- **power electronics devices** (DC-to DC power converters, rectifiers, inverters, HVDC SMC systems, etc)
- **power systems, axial flow compressors, gasoline engines, automotive control, tension system, infinite-dimension systems, …**

Practice

- **motion control**
  - **The experiments on the precision motion control in numerical-controlled machining**
  - **TI's SpinTACTM MOTION Control Suite**
- **flight control**

  achieve effective control of a complex system with vast range of uncertainties/disturbances
- **More in some ADRC groups around the world**

motion control

Motion control applications: almost every sector of industry

regulate mechanical motions: position, velocity, acceleration

Newtonian Law of motion

$$\ddot{y} = f(y, \dot{y}, d) + bu$$

y: position output
u: force input generated by the actuator
d: external disturbance
$f(\bullet)$: all other forces except u,
nonlinear friction, the gear backlash, torque disturbance, etc
b: torque constant

Requirements: high speed and high precision of tracking

ADRC

ESO

$$\begin{cases} \dot{\hat{x}}_1 = \hat{x}_2 - \beta_{01} \bullet fal(\hat{x}_1 - y, \alpha_1, \delta_1) \\ \dot{\hat{x}}_2 = \hat{x}_3 - \beta_{02} \bullet fal(\hat{x}_1 - y, \alpha_2, \delta_2) + b_0 u \\ \dot{\hat{x}}_3 = -\beta_{03} \bullet fal(\hat{x}_1 - y, \alpha_3, \delta_3) \end{cases}$$

$$fal(e, \alpha_1, \delta_1) = \begin{cases} \dfrac{e}{\delta^{1-\alpha}} = ke, |e| \le \delta \\ |e|^{\alpha} sign(e), |e| > \delta \end{cases}$$

$$U(t) = -b_0^{-1}\hat{x}_3 + k_1(r - y) + k_2(\dot{r} - \hat{x}_2)$$

compensate for the total uncertainty

control law for the canonical form system

Strong Robustness

Transient performance

replaces "I"

PD

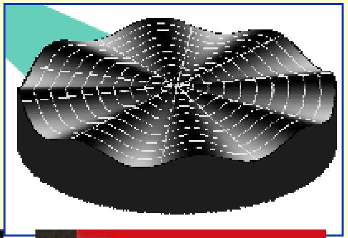
motion control-1

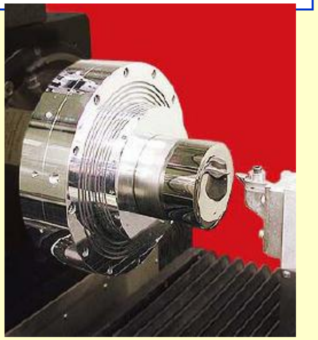
The first successful motion control test was done by Han at Cleveland State University in 1997.

From left:
Han Jingqing, Jiang Fangjun, Zhiqiang Gao

Precision Motion Control in Numerical-Controlled Machining (Since 2000)

Machining of non-symmetric surfaces

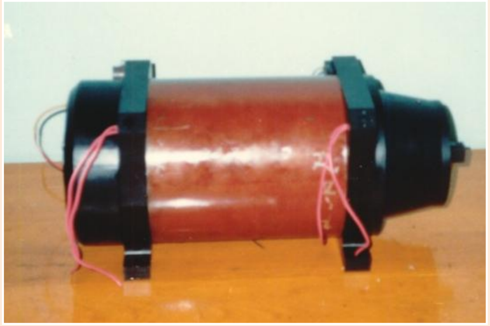
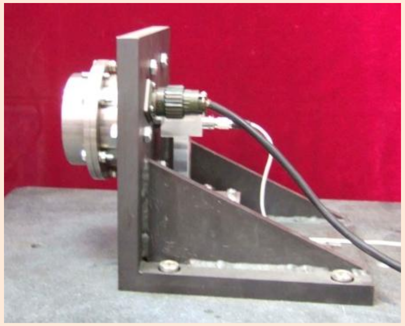





Precision noncircular turning
精密非圆车削

Ultra-precision Non-rotational symmetric turning
超精密非轴对称车削

Fast Tool Servo

Precision tracking motion is required for an FTS

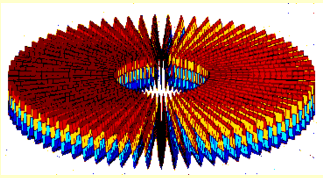
- ❈High accuracy(±5μm, ±0.02μm)
- ❈High acceleration（20g, 200g)
- ❈Disturbance rejection to cutting force and vibration(切削力、工艺系统振动)

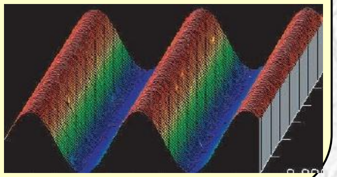
Experiments of Diamond Turning Sinusoidal Micro-structured Surfaces
正弦微结构表面超精密车削实验

FTS turning of sinusoidal surface (1D, 2D) of oxygen-free copper workpieces

1-D Sinusoidal Surface

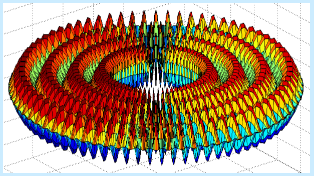
$$z_1 = A\sin(n\theta)$$

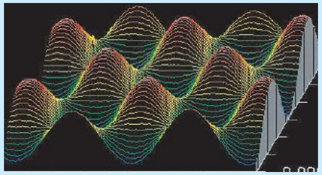


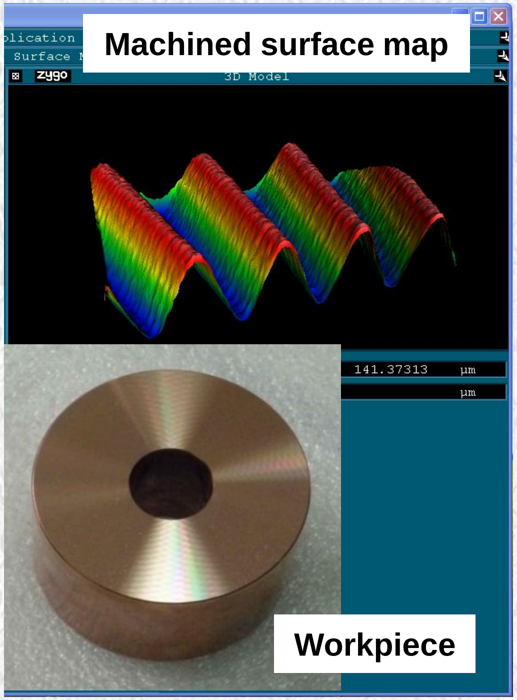


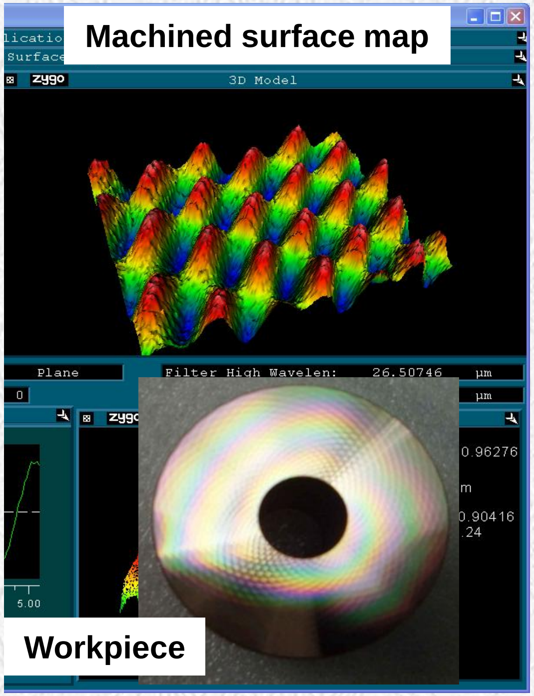
2-D Sinusoidal Surface

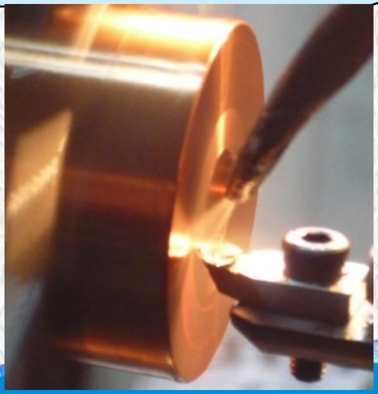
$$z_2 = \sin(2\pi mr)\cdot A\sin(n\theta)$$











Results:

Surface roughness(表面粗糙度):

Ra 33 nm(1D), Ra 28 nm(2D)

Group of Zhiqiang GAO at CSU

ADRC in U.S.: Milestones

- *1997: Prof. Han visited CSU; made the 1st successful ADRC hardware test on a servo mechanism*
- *2003: linear, parameterized ADRC, patent app.*
- *2008: $1M venture capital, grew by $5M in 2012.*
- *2010: 1st factory implementation, 10 Parker extrusion lines (挤压机生产线) at a Parker Hannifin Extrusion Plant in North America*

  (cpk: from 2.3 to >8; avg. energy saving 57%)
- *2011: implemented ADRC in several high energy particle accelerators (高能粒子加速器) in the National Superconducting Cyclotron （超导回旋加速器） Lab in the U.S.*
- *2011: Texas Instrument adopts ADRC; 3 patents granted.*
- ***2013: Texas Instrument New Motion Control Chips***

from academic setting into industry

motion control

TEXAS INSTRUMENTS 德州仪器

- ➢*2011: Texas Instrument adopts ADRC; 3 patents granted.*
- ➢*2013: Texas Instrument New Motion Control Chips*

TMS320F28052M
TMS320F28054M
TMS320F28068M
TMS320F28069M

TI Home > Semiconductors > Microcontrollers (MCU) > Performance MCUs > Real-time Control

TMS320F28052M (ACTIVE) ☆☆☆☆☆ No reviews yet.

Piccolo Microcontroller with InstaSPIN-MOTION

TMS320F2805x Piccolo™ Microcontrollers (Rev. B)

TMS320F2805x Piccolo MCU Silicon Errata (Rev. B)

TMS320F2805xM InstaSPIN-MOTION Technical Reference Manual

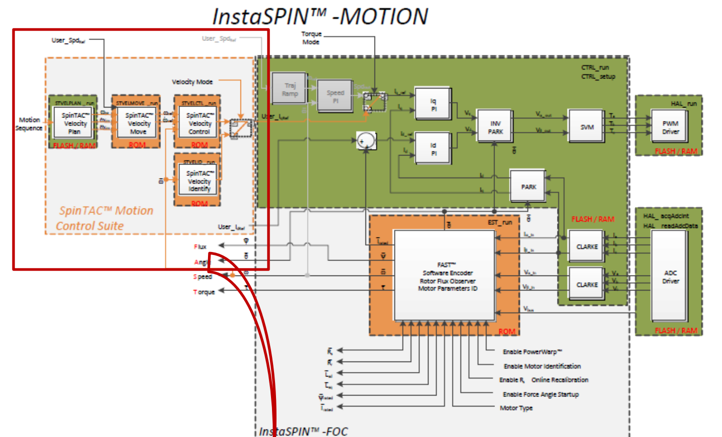


Figure 1. InstaSPIN-MOTION = C2000 F2805xM MCU + FAST Software Sensor (optional) + Auto-Tuned Inner-Torque Controller + SpinTAC Motion Control Suite

Manual: application examples, performance evaluating

CONTROL

SpinTAC Control is an advanced speed and position controller featuring Active Disturbance Rejection Control (ADRC), which proactively estimates and compensates for system disturbance, in real-time.

replace PID with ADRC

Practice

- motion control
  - The experiments on the high-precision machining process
  - TI's SpinTACTM MOTION Control Suite
- flight control

  achieve effective control of a complex system with vast range of uncertainties/disturbances
- More in some ADRC groups around the world

Attitude Control of Aerodynamic Flight

(rockets, missiles, hypersonic vehicles)

$$\begin{bmatrix}\dot{\vartheta}\\ \dot{\psi}\\ \dot{\gamma}\end{bmatrix}=\begin{bmatrix}0 & \cos\gamma & -\sin\gamma\\ 0 & \sin\gamma/\cos\vartheta & \cos\gamma/\cos\vartheta\\ 1 & \sin\gamma tg\vartheta & \cos\gamma tg\vartheta\end{bmatrix}\begin{bmatrix}\omega_x\\ \omega_y\\ \omega_z\end{bmatrix},\qquad I=\begin{bmatrix}I_x & -I_{xy} & -I_{xz}\\ -I_{xy} & I_y & -I_{yz}\\ -I_{xz} & -I_{yz} & I_z\end{bmatrix}$$

$$\begin{bmatrix}\dot{\omega}_x\\ \dot{\omega}_y\\ \dot{\omega}_z\end{bmatrix}=I^{-1}\begin{bmatrix}0 & \omega_z & -\omega_y\\ -\omega_z & 0 & \omega_x\\ \omega_y & -\omega_x & 0\end{bmatrix} I \begin{bmatrix}\omega_x\\ \omega_y\\ \omega_z\end{bmatrix}+I^{-1}\frac{1}{2}\rho V^2 SL\begin{bmatrix}m_x(Ma,h,\alpha,\beta,W(t),\delta_x,\delta_y,\delta_z)\\ m_y(Ma,h,\alpha,\beta,W(t),\delta_x,\delta_y,\delta_z)\\ m_z(Ma,h,\alpha,\beta,W(t),\delta_x,\delta_y,\delta_z)\end{bmatrix},$$

Parametric uncertainties — **Uncertain dynamics** — **Disturbance (wind)** — **control input**

I **inertia matrix**

ρ **density of air (near space: changes drastically)**

$(\vartheta \quad \psi \quad \gamma)$ **attitude angles**

$(\omega_x \quad \omega_y \quad \omega_z)$ **angular velocity**

$(\delta_x \quad \delta_y \quad \delta_z)$ **control surface: aileron, elevator and rudder**

aerodynamic moment coefficients:

$m_i(i=x,y,z)$: **nonlinear functions of** $(Ma,h,\alpha,\beta,W(t),\delta_x,\delta_y,\delta_z)$

changes drastically, described by a table, with uncertainties

(α,β) **attack angle, sideslip angle** **when** (α,β) **large the dynamics of the three axes: heavily coupled**

Design $(\delta_x \quad \delta_y \quad \delta_z)$ **such at** $(\vartheta \quad \psi \quad \gamma)$ **track the attitude command** $(\vartheta^* \quad \psi^* \quad \gamma^*)$

Attitude Control

$$\begin{bmatrix}\dot{\vartheta}\\ \dot{\psi}\\ \dot{\gamma}\end{bmatrix} = \begin{bmatrix}0 & \cos\gamma & -\sin\gamma\\ 0 & \sin\gamma/\cos\vartheta & \cos\gamma/\cos\vartheta\\ 1 & \sin\gamma tg\vartheta & \cos\gamma tg\vartheta\end{bmatrix}\begin{bmatrix}\omega_x\\ \omega_y\\ \omega_z\end{bmatrix}, \qquad I = \begin{bmatrix} I_x & -I_{xy} & -I_{xz}\\ -I_{xy} & I_y & -I_{yz}\\ -I_{xz} & -I_{yz} & I_z\end{bmatrix}$$

$$\begin{bmatrix}\dot{\omega}_x\\ \dot{\omega}_y\\ \dot{\omega}_z\end{bmatrix} = I^{-1}\begin{bmatrix}0 & \omega_z & -\omega_y\\ -\omega_z & 0 & \omega_x\\ \omega_y & -\omega_x & 0\end{bmatrix} I \begin{bmatrix}\omega_x\\ \omega_y\\ \omega_z\end{bmatrix} + I^{-1}\frac{1}{2}\rho V^2 SL\begin{bmatrix} m_x(Ma,h,\alpha,\beta,W(t),\delta_x,\delta_y,\delta_z)\\ m_y(Ma,h,\alpha,\beta,W(t),\delta_x,\delta_y,\delta_z)\\ m_z(Ma,h,\alpha,\beta,W(t),\delta_x,\delta_y,\delta_z)\end{bmatrix},$$

Parametric uncertainties

Uncertain dynamics

Disturbance (wind)

control input

Control: keep a stable flight under the vast uncertainties

The fundamental scientific problem

control of systems with large uncertainties and complex structure

(nonlinear, time-varying and coupled)

Attitude Control

Backstepping **Physical knowledge**

$$\begin{bmatrix}\dot{\vartheta}\\ \dot{\psi}\\ \dot{\gamma}\end{bmatrix}=\begin{bmatrix}0 & \cos\gamma & -\sin\gamma\\ 0 & \sin\gamma/\cos\vartheta & \cos\gamma/\cos\vartheta\\ 1 & \sin\gamma tg\vartheta & \cos\gamma tg\vartheta\end{bmatrix}\begin{bmatrix}\omega_x\\ \omega_y\\ \omega_z\end{bmatrix},\quad \omega^*=\begin{bmatrix}0 & \cos\gamma & -\sin\gamma\\ 0 & \sin\gamma/\cos\vartheta & \cos\gamma/\cos\vartheta\\ 1 & \sin\gamma tg\vartheta & \cos\gamma tg\vartheta\end{bmatrix}^{-1}K_1\left(\begin{bmatrix}\vartheta^*\\ \psi^*\\ \gamma^*\end{bmatrix}-\begin{bmatrix}\vartheta\\ \psi\\ \gamma\end{bmatrix}\right)$$

$$\begin{bmatrix}\dot{\omega}_x\\ \dot{\omega}_y\\ \dot{\omega}_z\end{bmatrix}=I^{-1}\begin{bmatrix}0 & \omega_z & -\omega_y\\ -\omega_z & 0 & \omega_x\\ \omega_y & -\omega_x & 0\end{bmatrix}I\begin{bmatrix}\omega_x\\ \omega_y\\ \omega_z\end{bmatrix}+I^{-1}\frac{1}{2}\rho V^2 SL\begin{bmatrix}m_x(Ma,h,\alpha,\beta,W(t),\delta_x,\delta_y,\delta_z)\\ m_y(Ma,h,\alpha,\beta,W(t),\delta_x,\delta_y,\delta_z)\\ m_z(Ma,h,\alpha,\beta,W(t),\delta_x,\delta_y,\delta_z)\end{bmatrix}$$

$$\triangleq H(I,\rho,V,Ma,h,W(t),\omega,\alpha,\beta,U),$$

$$\omega \triangleq \begin{bmatrix}\dot{\omega}_x\\ \dot{\omega}_y\\ \dot{\omega}_z\end{bmatrix}\qquad U=\begin{bmatrix}\delta_x\\ \delta_y\\ \delta_z\end{bmatrix}$$

measurable

$\frac{\partial H(\cdot)}{\partial U}$ **nonsingular**

$$F(t)\triangleq H(I,\rho,V,Ma,h,W(t),\omega,\alpha,\beta,U)-B_0(t)U$$

total disturbance

$$B_0(t)=I_0^{-1}\frac{1}{2}\rho_0 V_0^2 S_0 L_0 M_0(t)$$

$$\dot{\omega}=F(t)+B_0(t)U$$

$$\dot{\omega}=U_1$$

ADRC

$$U=B_0^{-1}(V)(-Z_2+U_1)$$

$$U_1=K_2(\omega^*-\omega)$$

Linear ESO

$$\begin{cases}\dot{Z}_1=Z_2-\beta_1(Z_1-\omega)+B_0(t)U,\\ \dot{Z}_2=-\beta_2(Z_1-\omega)\end{cases}$$

$$Z_1\to\omega$$

$$Z_2\to F(t)$$ ***total disturbance***

A completely new method in attitude control

Huang Y., Xu K.K., Han J., Lam J. Flight control design using extended state observer and non-smooth feedback. In: Proc. the 40th IEEE Conference on Decision and Control, Orlando, USA, 2001, pp.223–228.

Attitude Control

$$\begin{bmatrix}\dot{\omega}_x\\ \dot{\omega}_y\\ \dot{\omega}_z\end{bmatrix} = I^{-1}\begin{bmatrix}0 & \omega_z & -\omega_y\\ -\omega_z & 0 & \omega_x\\ \omega_y & -\omega_x & 0\end{bmatrix} I \begin{bmatrix}\omega_x\\ \omega_y\\ \omega_z\end{bmatrix} + I^{-1}\frac{1}{2}\rho V^2 SL \begin{bmatrix} m_x(Ma,h,\alpha,\beta,W(t),\delta_x,\delta_y,\delta_z)\\ m_y(Ma,h,\alpha,\beta,W(t),\delta_x,\delta_y,\delta_z)\\ m_z(Ma,h,\alpha,\beta,W(t),\delta_x,\delta_y,\delta_z)\end{bmatrix}$$

$$\triangleq H(I,\rho,V,Ma,h,W(t),\omega,\alpha,\beta,U),$$

$$\dot{\omega} = F(t) + B_0(t)U$$

$$\dot{\omega} = U_1$$

Linear ESO

$$\begin{cases}\dot{Z}_1 = Z_2 - \beta_1(Z_1 - \omega) + B_0(t)U,\\ \dot{Z}_2 = -\beta_2(Z_1 - \omega)\end{cases}$$

$$Z_1 \to \omega$$

$$Z_2 \to F(t)$$ ***total disturbance***

$$U = B_0^{-1}(V)(-Z_2 + U_1)$$

traditional methods (small perturbation theory)

- **set point designs, a large set of linear time-invariant systems**
- **longitudinal motion, lateral motion**

A completely new method in attitude control

Since 1999, thousands of simulation tests on different kinds of flight vehicles (rockets, missiles, hypersonic vehicles)

fast dynamic response, suitable for a vast range of uncertainties

Since 2012, successfully flight tests on some kinds of missiles.

convincingly shown that ADRC can achieve effective control of a complex system in the absence of a detailed and accurate mathematical model

Practice

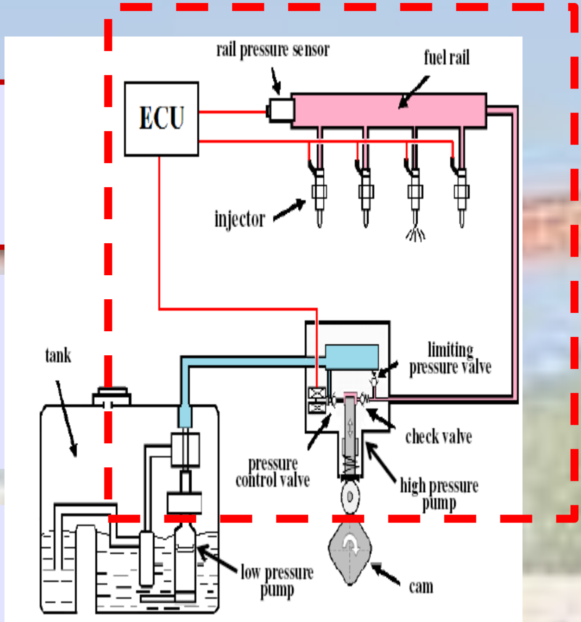
- **motion control**
  - **The experiments on the high-precision machining process**
  - **TI's SpinTACTM MOTION Control Suite**
- **flight control**

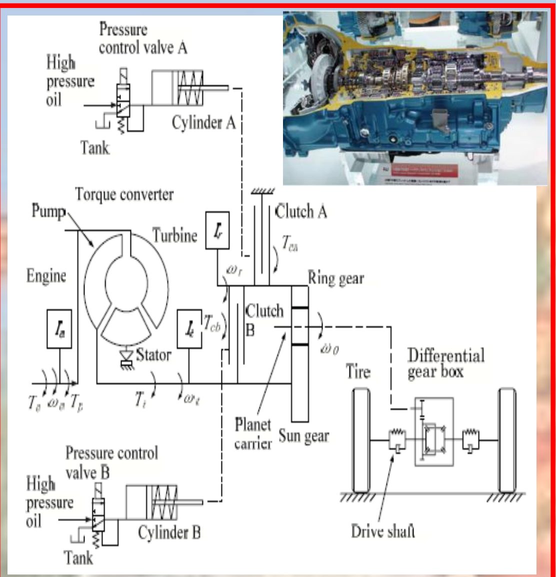
  achieve effective control of a complex system with vast range of uncertainties/disturbances
- **More in some ADRC groups around the world**

Group of Hong CHEN at Jilin Univ., China

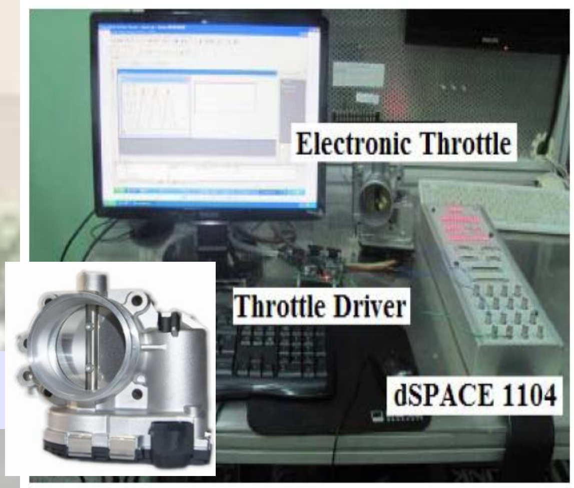
ADRC in Automotive control （汽车控制）

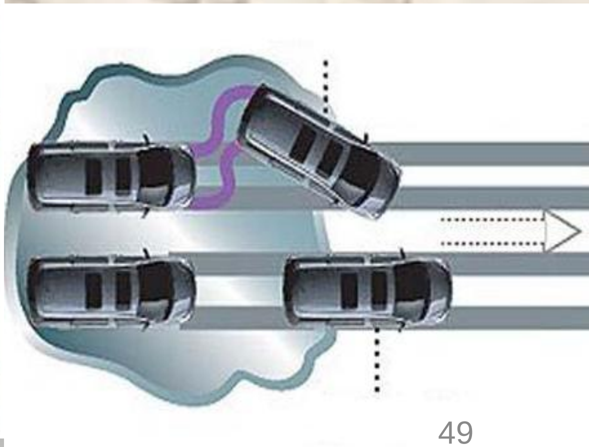
- Common rail pressure control in (Gasoline Direct Injection, GDI) engine (缸内直喷汽油机)
- Clutch slip control for Automatic Transmission
- Electronic throttle control
- Traction control system for motor-in-wheel electric vehicle
- Idle speed control for engine





Schematic graph of automatic transmission





ADRC in Automotive Control

Lei Yuan, Hong Chen, Bingtao Ren. **The Design of TCS Controller for Four Wheel Independent-Drive Electric Vehicle Based on ADRC.** CCDC 2014, Changsha China.

刘奇芳，宫洵，胡云峰，陈虹. **缸内直喷汽油机的自抗扰轨压跟踪控制器设计. 控制理论与应用**. Vol. 30, No. 12, 2013

Qifang Liu, Xun Gong, Yunfeng Hu, Hong Chen. **Active Disturbance Rejection Control of Common Rail Pressure for Gasoline Direct Injection Engine**. ACC 2013, Washington DC USA.

Yanan Fan, Yunfeng Hu, Pengyuan Sun, Hong Chen. **Electronic Throttle Controller Design Using Sliding Mode Control with Extend State Observer**. SICE Annual Conference 2013, Nagoya Japan.

Xun Gong, Qifang Liu, Yunfeng Hu, Hong Chen. **Idle Speed Controller Design for SI Engine based on ADRC**. MSC 2012, Dubrovnik Croatia.

Yunfeng Hu, Qifang Liu, Bingzhao Gao, Hong Chen. **ADRC Based Clutch Slip Control for Automatic Transmission**. CCDC 2011, Mianyang China.

Group of Prof. Lei GUO at Beihang Univ., China

Control for Systems with Multiple Disturbances

多源干扰系统控制理论及应用

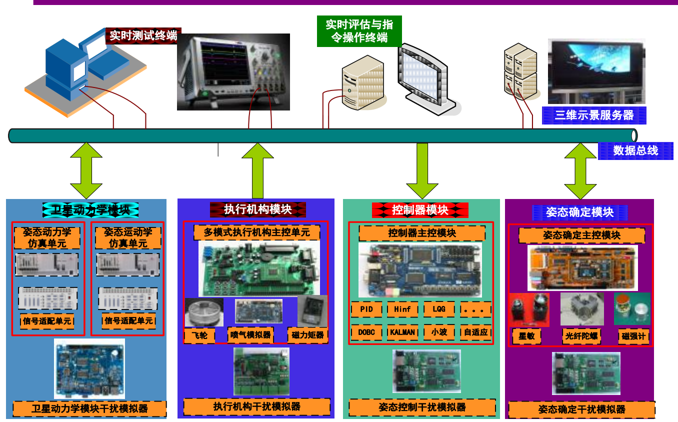
Theory: Composite hierarchical anti-disturbance control

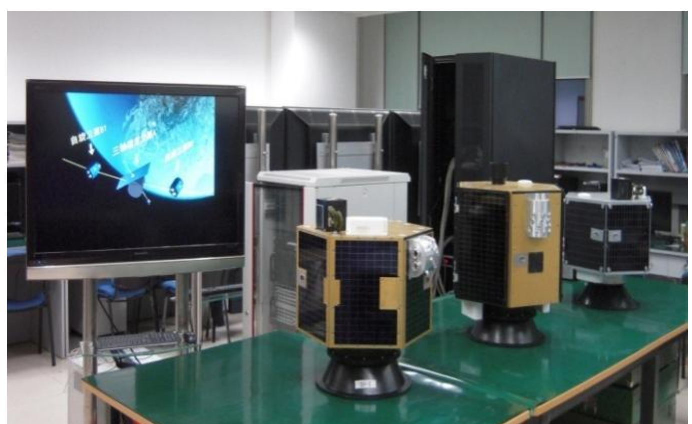
复合分层抗干扰控制《ADRC: one of the inner loops》

Applications: Anti-Disturbance based navigation and control technology for spacecrafts

飞行器抗干扰导航与控制系统技术

- **Smart sensing and fusion technology in environment with multiple disturbances**
  多源干扰环境智能感知与信息融合技术
- **Anti-Disturbance based landing control technology for deep space planetary exploration**
  深空探测行星抗干扰着陆控制技术
- **Distributed formation network and cooperation control technology for satellites**
  多星分布式编队组网和协同控制技术
- **Analysis, test and evaluation technology of multiple disturbance rejection for spacecraft**
  航天器多源干扰分析、测试与评估技术

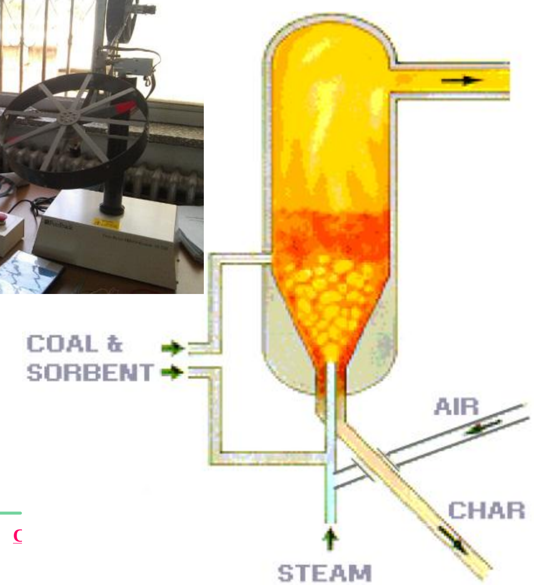


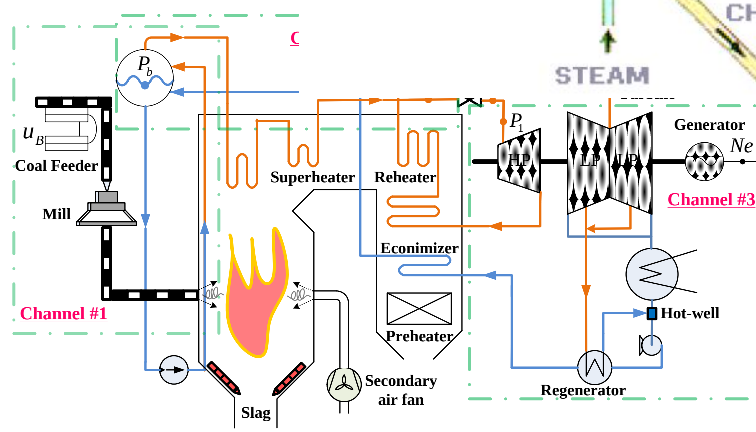


Group of Donghai LI at Tsinghua University, China

ADRC for the Thermal Process and Other Industrial Processes

- boiler-turbine unit, hydroturbine governor
- HVDC system
- power plant ball mill, coordinated control of static phase shifter and excitation system
- unstable heat conduction system
- boiler-turbine-generator system
- ALSTOM Gasifier Benchmark
- fractional-order systems
- ADRC tuning aided by existing PID/PI
- model-aided ADRC design
- inverse decoupling ADRC design
- EOTF–based ADRC design
- ADRC-enhanced input shaping design





ADRC在电力系统中的应用研究

[1]刘翔,姜学智,李东海,万静芳,薛亚丽. 火电单元机组机炉协调自抗扰控制[J]. 控制理论与应用,2001,S1:149-152.
[2]刘翔,姜学智,李东海. 水轮发电机组调速系统的自抗扰控制[J]. 清华大学学报(自然科学版),2001,10:69-73.
[3]余涛,沈善德,李东海,朱守真. 高压直流输电系统的自抗扰控制方法[J]. 电力系统自动化,2002,22:22-26+52.
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[5]余涛,沈善德,李东海,朱守真. 静止移相器和发电机励磁系统的自抗扰协调控制[J]. 中国电机工程学报,2003,09:1-5.

- 分布参数系统(**heat conduction system**)

Dong Zhao,Donghai Li, Yanzhen Chang, Youqing Wang. Numerical Simulation and Linear Active Disturbance Rejection Control of Unstable Heat Conduction Systems, System Simulation and Scientific Computing, Communications in Computer and Information Science2012, pp 35-46

- 机炉电协调(**boiler-turbine-generator system**)

T. Yu, K.W. Chan, J.P. Tong, B. Zhou, D.H. Li, Coordinated robust nonlinear boiler-turbine-generator control systems via approximate dynamic feedback linearization, Journal of Process Control, Volume 20, Issue 4, April 2010, Pages 365-374.

- ALSTOM气化炉

Chun-E Huang, Donghai Li, Yali Xue, Active disturbance rejection control for the ALSTOM gasifier benchmark problem, Control Engineering Practice, Volume 21, Issue 4, April 2013, Pages 556-564

- 分数阶系统

Mingda Li, Donghai Li, Jing Wang, Chunzhe Zhao, Active disturbance rejection control for fractional-order system, ISA Transactions, Available online 8 February 2013, ISSN 0019-0578, 10.1016/j.isatra.2013.01.001.

- 既有PID参数转化为ADRC参数

Chunzhe Zhao, Donghai Li, Control design for the SISO system with the unknown order and the unknown relative degree, ISA Transactions, in press

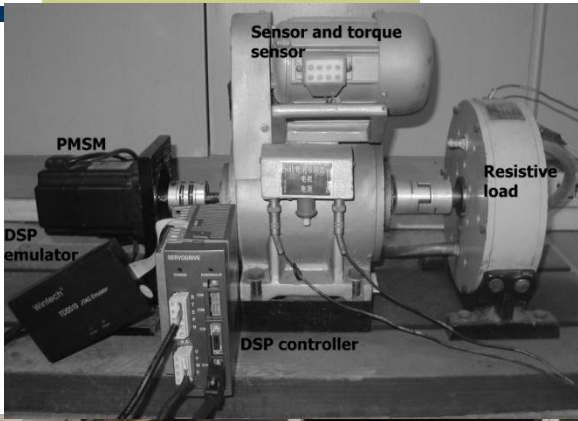
- 模型辅助ADRC设计

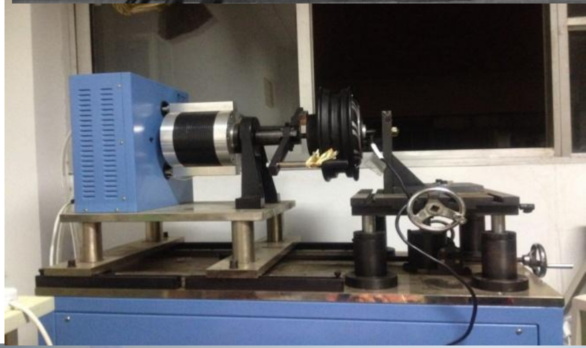
Sun Li. Junyi Dong. Donghai Li. Xi Zhang. DEB-oriented Modelling and Control of Coal-Fired Power Plant. The 19th World Congress of IFAC. (Accepted)

- 逆解耦ADRC设计:董君伊，清华大学热能工程系，硕士学位论文，2014
- 基于等效开环传递函数的ADRC设计(**EOTF–based ADRC design**)

Qian Liu, Donghai Li, Wen Tan, Design of Multi-Loop ADRC Controllers Based on the Effective Open-Loop Transfer Function Method, Accepted by CCC 2014.

Group of Shihua LI at Southeast Univ. , China





ADRC for Mechatronic Systems (机电一体化):

- PMSM System
- Power Converters
- MAGLEV System

ADRC Digital Implementation and Industrial Application:

- Digital implementation in product at ESTUN Automation Company
- Earn more then 100 million RMB benefits for ESTUN Automation Company

ADRC Design and Analysis:

- Mismatched Disturbance
- Compensation Design
- Performance Analysis

Southeast University
Mechatronic Systems Control Lab

Group of Shihua Li at SEU, China

ADRC Design and Analysis:

S. Li, J. Yang, W.H Chen, X. Chen. Generalized extended state observer based control for systems with mismatched uncertainties, *IEEE Trans. on Industrial Electronics*, 2012, 59(12), 4792-4802.

S. Li, J. Yang, W.H Chen, X. Chen. *Disturbance Observer Based Control: Methods and Applications*. CRC Press, 2014.

ADRC for Mechatronic Systems:

Z. Liu, S. Li. Adaptive speed control for permanent magnet synchronous motor system with variations of load inertia, *IEEE Trans. on Industrial Electronics*, 2009, 56(8), 3050-3059.

H. Liu, S. Li. Speed Control for PMSM Servo System Using Predictive Functional Control and Extended State Observer. *IEEE Trans. on Industrial Electronics*, 2012, 59(2), 1171-1183.

S. Li, M. Zhou, X, Yu. Design and Implementation of Terminal Sliding Mode Control Method for PMSM Speed Regulation System. *IEEE Trans. on Industrial Informatics*, 2013, 9(4): 1879 – 1891.

ADRC for Control Systems of the Gravure Printing Machine

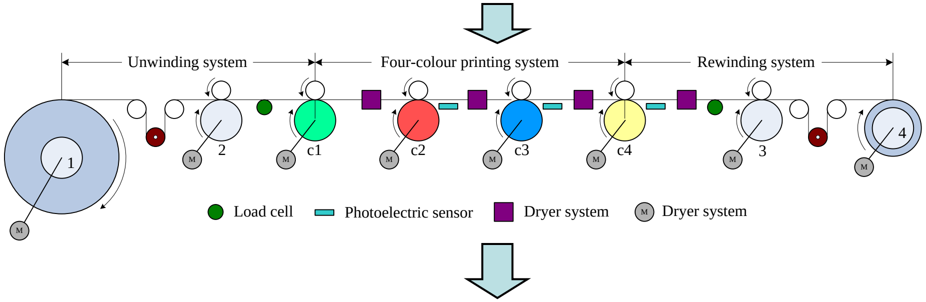
照相凹版印刷机

Control systems in gravure printing machines

- ●Tension control system（张力控制系统）
  - ➢Unwinding system
  - ➢Rewinding system
- ●Register control system（套准控制系统）

Features of the control systems

- ●Nonlinear
- ●Strong-coupling
- ●Strong disturbance
- ●Multi-input multi-output

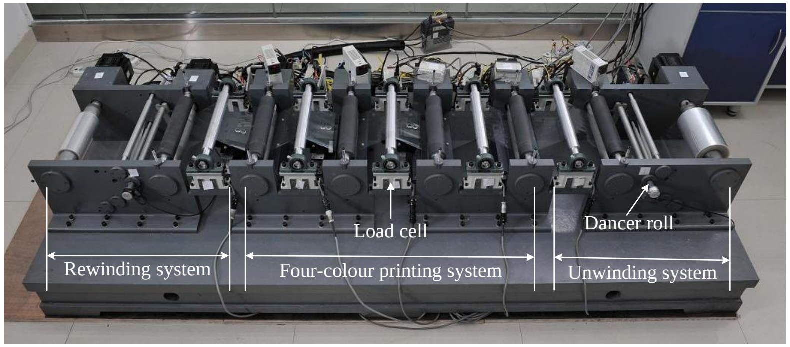


ADRC decoupling controllers

- ●Unwinding controller
- ●Rewinding controller
- ●Register controller

Feed-forward ADRC controller

- ●Register controller



ADRC for the tension control systems

- Shanhui Liu, Xuesong Mei, et al. A Decoupling Control Algorithm for Unwinding Tension System Based on Active Disturbance Rejection Control[J]. Mathematical Problems in Engineering, 2013, vol. 2013, Article ID 439797, 18 pages .
- Shanhui Liu, Xuesong Mei, et al. Tension controller design for unwinding tension system based on active disturbance rejection control. 2012 IEEE International Conference on Mechatronics and Automation, Chengdu, China, Aug. 5-8, 2012: 1798-1803.
- Shanhui Liu, Xuesong Mei, Li'e Ma, Hao You, Zheng Li. Active Disturbance Rejection Decoupling Controller Design for Roll-to-roll Printing Machines. 2013 IEEE Third International Conference on Information Science and Technology, Yangzhou, China, Mar. 23-25, 2013: 111-116.

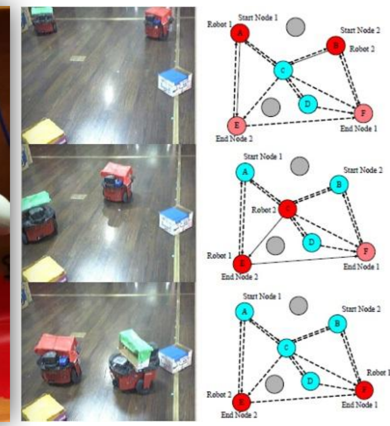
ADRC for the register control systems

- Shanhui Liu, Xuesong Mei, Kui He, et al. Active disturbance rejection decoupling control for multi-color register system in gravure printing machine[J]. Control Theory & Applications, 2014(Accepted).

Group of Jianbo Su at Shanghai Jiaotong Univ. China

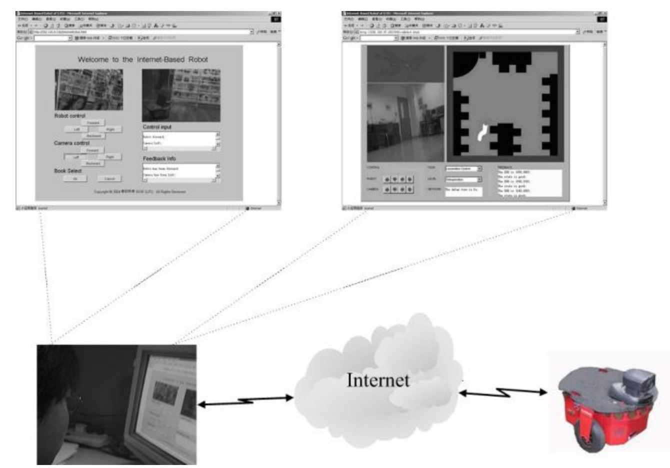
ADRC for uncalibrated visual servoing systems

- Robot manipulator to track a dynamic object in 3-D space
- Humanoid robot to perform Chinese calligraphy
- Multi mobile robot formation control with obstacle avoidance



Analysis of ADRC

- Convergence ability and convergence speed for the uncalibrated robotic visual servoing
- Stability for internet-based robot visual servoing control with random time-delay
- Parameter tuning in robotic visual servoing



Performance comparison of ADRC and DOB based robotic visual servoing control

ADRC for uncalibrated visual servoing systems

1. Jianbo Su, et al., “Nonlinear visual mapping model for 3-D visual tracking with uncalibrated eye-in-hand robotic system”, ***IEEE Transactions on Systems, Man, and Cybernetics, Part B: Cybernetics***, Vol.34, No.1, pp.652-659, Feb., 2004.
2. Jianbo Su, et al., “Task-independent robotic uncalibrated hand-eye coordination based on the extended state observer”, ***IEEE Transactions on Systems, Man, and Cybernetics, Part B: Cybernetics***, Vol.34, No.4, pp. 1917-1922, Aug., 2004.
3. Jianbo Su, et al., “Calibration-free robotic eye-hand coordination based on an auto disturbance-rejection controller”, ***IEEE Transactions on Robotics***, Vol.20, No.5, pp. 899-907, Oct., 2004.
4. Jianbo Su, et al., “Uncalibrated hand/eye coordination based on auto disturbance rejection controller”, ***Proceedings of IEEE Conference on Decision and Control***, pp.923-924, Dec., 2002.
5. Hongyu Ma, Jianbo Su, “Uncalibrated robotic 3-D hand-eye coordination based on the extended state observer”, ***Proceedings of IEEE International Conference on Robotics and Automation***, pp.3327-3332, Sept. 2003.
6. 苏剑波，邱文彬，“基于自抗扰控制器的机器人无标定手眼协调”，**自动化学报**，第29卷第2期，pp.161-167，2003年3月
7. 马红雨，苏剑波，“基于耦合ADRC原理的机器人无标定手眼协调”，**机器人**，第25卷第1期，pp.39-43，2003年1月

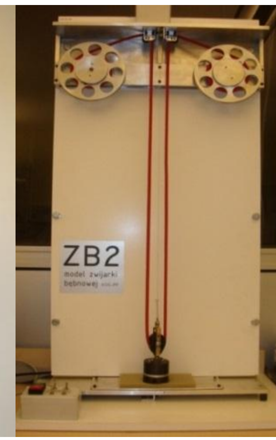
Analysis of ADRC

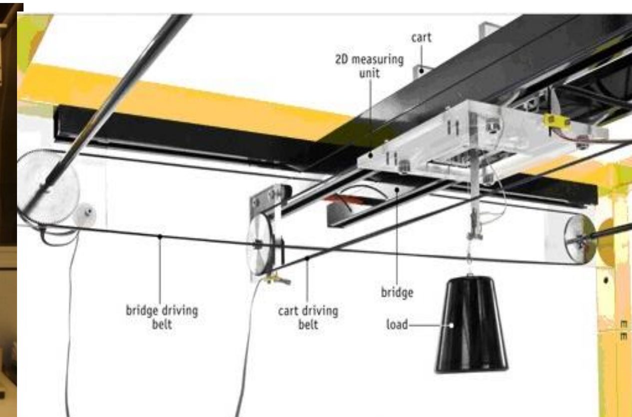
1. Jianbo Su, “Convergence analysis for the uncalibrated robotic hand-eye coordination based on the unmodeled dynamics observer”, ***Robotica***, Vol.28, No.4, pp. 597-605, July, 2010.
2. Xueqiao Hou, Jianbo Su, “New approaches to internet based intelligent robotic system”, ***Proceedings of IEEE International Conference on Robotics and Automation***, pp.3363 -3368, April, 2004.
3. 高振东，“网络环境中的机器人视觉伺服及融合控制”，上海交通大学博士学位论文，2007

Group of Rafal MADONSKI at PUT, Poland

ADRC for industry-inspired systems

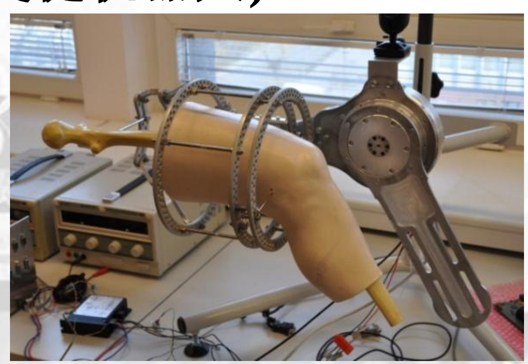
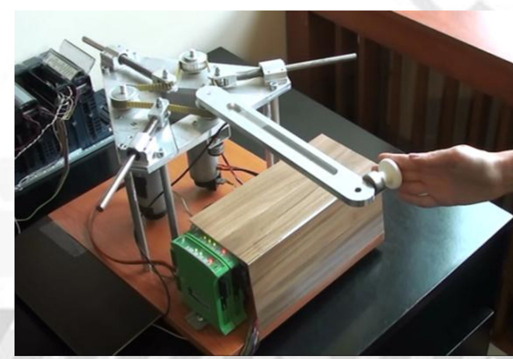
- manipulators
- reel-to-reel systems（卷盘）
- gantry cranes （吊车）
- water managements systems



ADRC in rehabilitation robotics (复健机器人)

- robotic-enhanced limb rehabilitation trainings
- flexible-joint manipulators

Analysis on ADRC

ADRC for industry-inspired systems

R. Madonski, et al., **Application of active disturbance rejection controller to water supply system**, CCC, 2014

M. Przybyla, et al., **Active Disturbance Rejection Control of a 2DOF manipulator with significant modeling uncertainty**, Bulletin of the Polish Academy of Sciences, 2012

R. Madonski, et al., **Application of Active Disturbance Rejection Control to a reel-to-reel system seen in tire industry**, Proc. of CASE, 2011

ADRC in rehabilitation robotics

R. Madonski, et al., **Application of a disturbance-rejection controller for robotic-enhanced limb rehabilitation trainings**, ISA Transactions, 2013

M. Kordasz, R. Madonski, et al., **Active Disturbance Rejection Control for a flexible-joint manipulator**, Proc. of RoMoCo, 2011

Analysis of ADRC

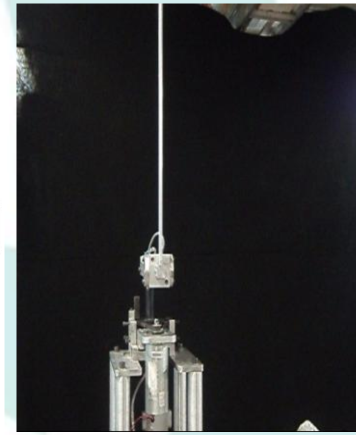
M. Nowicki, R. Madonski, **Disturbance rejection through virtual extension of the system - geometric approach**, Proc. of the IFAC World Congress, 2014

R. Madonski, et al., **High-gain disturbance observer tuning seen as a multicriteria optimization problem,** Proc. of Mediterranean Conf. on Control and Autom. (MED), 2013

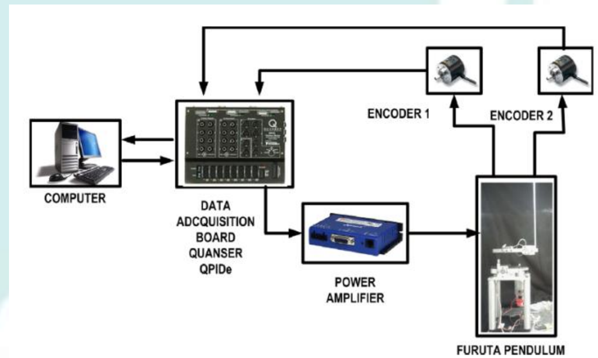
R. Madonski, P. Herman, **Model-Free Control or Active Disturbance Rejection Control? On different approaches for attenuating the perturbation,** Proc. of Mediterranean Conf. on Control and Automation (MED), 2012

R. Madonski, P. Herman, **Method of sensor noise attenuation in high-gain observers - experimental verification on two laboratory systems,** Proc. of Intern. Symposium on Robotic and Sensors Environments (ROSE), 2012

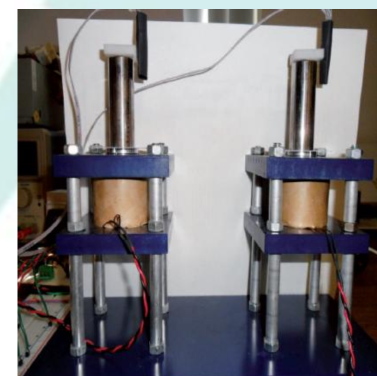
Group of H. SIRA-RAMIREZ at CINVESTAV, Mexico （The Center for Research and Advanced Studies of the National Polytechnic Institute ）



Linear ADRC of underactuated mechanical Systems



- The PVTOL example
- Variable length pendulum
- Inverted pendulum on a cart
- Furuta pendulum



Hardware Validations of the Concept of ADRC

- The Omni-directional mobile robot
- A simple pendulum
- Induction motor control
- Leader-follower control of Thomson’s jumping rings

Linear ADRC of underactuated mechanical Systems

M. Ramirez-Neria, H. Sira-Ramirez, R. Garrido-Moctezuma, A. Luviano- Ju_arez "Linear Active Disturbance Rejection Control of Underactuated Systems: The case of the Furuta Pendulum" *ISA Transactions* (accepted for publication, to appear)

Hardware Validations of the Concept of ADRC

H. Sira-Ramirez, C. Lopez-Uribe and M. Velasco-Villa, "Linear Observer-Based Active Disturbance Rejection Control of The Omnidirectional Mobile Robot" *Asian Journal of Control*, Vol. 15, No. 1, pp. 51-63, January, 2013.

H. Sira Ramirez, F. Gonzalez Montañez, J. Cortes Romero, A. Luviano-Juarez "State observers for active disturbance rejection in induction motor Control" in AC Motors control - Advanced Design Techniques and Applications, F. Giri, Editor, John Wiley and Sons, Ltd. Hoboken, N.J., USA, 2014 (available since sept. 2013).

M. Ramirez-Neria, J. L. Garcia-Antonio, H. Sira-Ramirez, M. Velasco-Villa, R. Castro-Linares. "An Active Disturbance Rejection Control of Leader-Follower Thomson's Jumping Rings", Journal of Control Theory and Applications. Vol. 30, No. 12, pp. 1563-1571, December 2013.

Group of S. E. TALOLE
at Defence Institute of Advanced Technology, India

- ◆Extended state observer based robust control of wing rock motion for combat aircraft
- ◆Extended state observer-based robust pitch autopilot design for tactical missiles
- ◆Extended-State-Observer-Based Control of Flexible-Joint System With Experimental Validation
- ◆Extending the Operating Range of Linear Controller by Means of ESO
- ◆Performance Analysis of Generalized Extended State Observer in Tackling Sinusoidal Disturbances
- ◆Robust Height Control System Design for Sea-Skimming Missiles
- ◆Robust Roll Autopilot Design for Tactical Missiles
- ◆Sliding Mode Observer for Drag Tracking in Entry Guidance

Group of Wen TAN at North China Electric Power Univ., China

ADRC for Load Frequency Control of Power Systems （电力系统负荷频率控制）

- Analysis of LADRC for LFC
- LADRC design for LFC in deregulated environments

ADRC for Boiler-Turbine Units

- Multivariable ADRC

ADRC for Systems with Nonlinearity

- Anti-windup scheme for LADRC

Simulation and Control Platform for Power Systems with Renewable Energy

<u>ADRC for Boiler-Turbine Units</u>

- G. N. Lou, W. Tan, Q.L. Zhen, ***Linear active disturbance rejection control for the coordinated system of drum boiler-turbine units***, Proc. of the CSEE, 2011,
- W. Tan, J. X. Fan, C. F. Fu, ***Linear active disturbance rejection controllers for boiler-turbine units***, CCC, 2013

<u>ADRC for Load Frequency Control of Power Systems</u>

- W. Tan, ***Load frequency control: Problems and solutions***, CCC, 2011
- J. X. Fan, W. Tan, C. F. Fu, ***Analysis and tuning of linear active disturbance rejection controllers for load frequency control of power systems***, CCC, 2013
- W. Tan, H. Zhou, ***Linear active disturbance rejection control for load frequency control of power systems***, Control Theory & Applications, 2013
- W. Tan, Y. C. Hao, D. H. Li, ***Load frequency control in deregulated environments via active disturbance rejection***, submitted to Int. J. Electrical Power & Energy Systems, 2014

<u>ADRC for Systems with Nonlinearity</u>

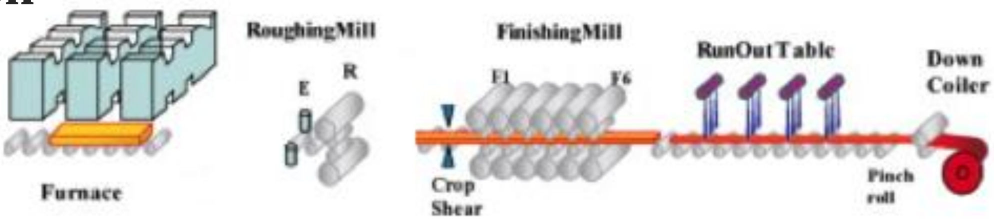
- H. Zhou, W. Tan, ***Anti-windup schemes for linear active disturbance rejection control***, submitted to Control Theory & Applications, 2014

University of Science and Technology Beijing

Group of Lijun WANG at USTB, China

- Monitoring automatic gauge control system with large time-delay
  (大时滞厚度自动监控系统)

- Hot strip width and gauge regulation
  (热连轧板宽板厚调节)



- Hydraulic automation position control system for rolling mills (轧钢厂)

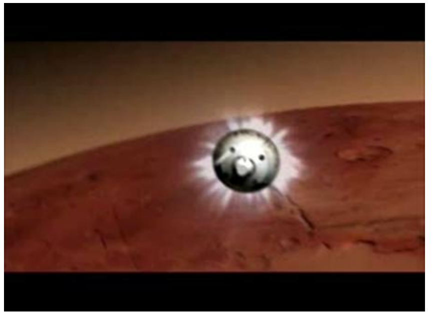
- Time-delay
  - Lijun Wang, Chaonan Tong, Qing Li, Yixin Yin, Zhiqiang Gao, Qinling Zheng. Practical active disturbance rejection solution for monitoring automatic gauge control system with large time-delay. Control Theory and Applications, 2012, 29(3): 368-374.
  - Lijun Wang, Qing Li, Chaonan Tong, Yixin Yin. Overview of active disturbance rejection control for systems with time-delay. Control Theory and Applications, 2013, 30(12): 1520-1532.
- Multivariable coupling
  - Lijun Wang, Chaonan Tong, Qing Li, Yixin Yin, Zhiqiang Gao, Qinling Zheng. A practical decoupling control solution for hot strip width and gauge regulation based on active disturbance rejection. Control Theory and Applications, 2012, 29(11): 1471-1478.
- High-order
  - Lijun Wang, Chaonan Tong, Qing Li, Yixin Yin, Zhiqiang Gao, Qinling Zheng. Disturbance rejection in hydraulic automation position control system for rolling mills. Proceedings of the 32th Chinese Control Conference, CCC 2013, 2013: 5498-5503.

ADRC in Weapon System

- Tank gun control system
- Tracking of axis of firepower of unmanned turret

ADRC for Aerospace

- Mars entry guidance

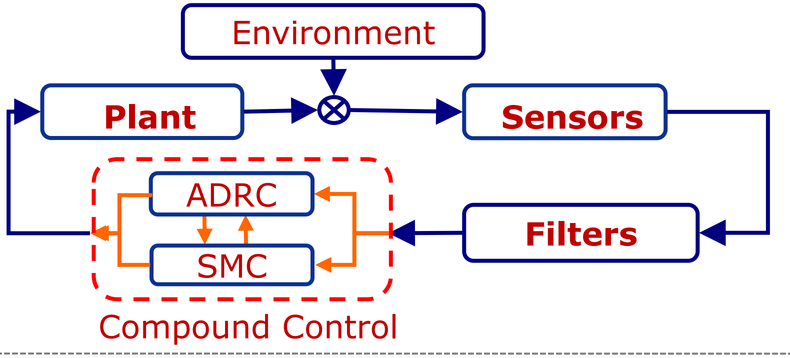


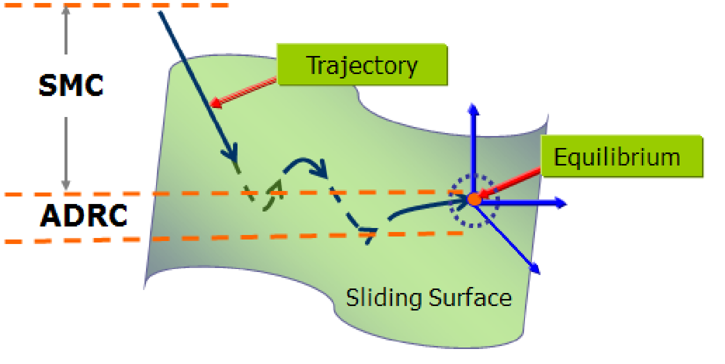
Application of Compound Control

- ADRC and SMC

Analysis of ADRC

- Uncertain multivariable systems with time-delay
- Control of power plant with a single loop





Analysis of ADRC

Y. Q. Xia, P. Shi, G.-P. Liu, D. Rees, "Active disturbance rejection control for uncertain multivariable systems with time-delay," ***IET Contr. Theory Appl.***, 2007, 1(1):75-81.

Y. Q. Xia, B. Liu, M. Y. Fu, "Active disturbance rejection control for power plant with a single loop," ***Asian Journal of Control***, 2012, 14(1):239-250.

ADRC in Weapon System

Y. Q. Xia, L. Dai, M. Y. Fu, et al., "Application of active disturbance rejection control in tank gun control system ," ***Journal of the Franklin Institute***, 2014, 351(4):2299−2314.

L. Ye, **Y. Q. Xia**, et al., "Active disturbance rejection control for tracking of axis of firepower of unmanned turret," ***Contr. Theory and Appl.***, Accepted , 2014.

ADRC for Aerospace

Y. Q. Xia, R. F. Chen, F. Pu, L. Dai. "Active disturbance rejection control for drag tracking in mars entry guidance," ***Advances in Space Research***, 2014, 53(5):853–861.

Application of Compound Control

Y. Q. Xia, M. Y. Fu, *Compound control methodology for flight vehicles*, **Springer**, 2013 (ISBN:978-3-642-36840-0).

Y. Q. Xia, Z. Zhu, et al., "Attitude tracking of rigid spacecraft with bounded disturbances," ***IEEE Trans. Industrial Electronics***, 2011, 58(2):647-659.

Y. Q. Xia, Z. Zhu, M. Y. Fu, "Back-stepping sliding mode control for missile systems based on extended state observer," ***IET Contr. Theory Appl.***, 2011, 5(1):93-102.

Y. Q. Xia, M. Y. Fu, et al., "Recent developments in sliding mode control and active disturbance rejection control," ***Contr. Theory Appl.***, 2013, 30(2):137-147.

K. F. Lu, **Y. Q. Xia**, M. Y. Fu, "Controller design for rigid spacecraft attitude tracking with actuator saturation," ***Inform. Science***, 2013, 220(20):343–366.

Z. Zhu, D. Xu, J. M. Liu, **Y. Q. Xia**, "Missile guidance law based on extended state observer," ***IEEE Trans. Industrial Electronics***, 2013, 60(12):5882-5891.

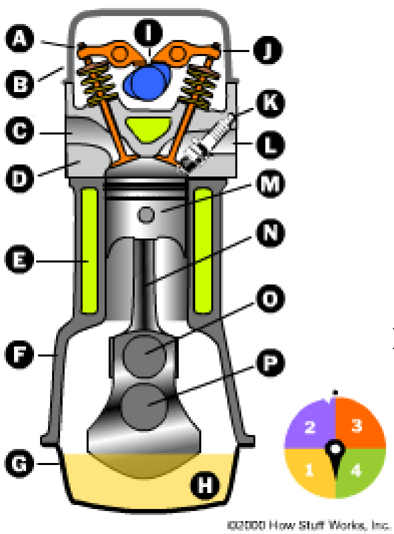
K. F. Lu, **Y. Q. Xia**, R. F. Chen, "Finite-time intercept angle guidance," ***International Journal of Control***, Accepted, 2014.

Internal combustion engine （内燃机）

Fuel

+

Air



Work

+

Emission

combustion

1. Electro-hydraulic SISO system control

----Low sampling rate with hysteresis

→LADRC+ feedforward control

2. Cross-coupled air system control

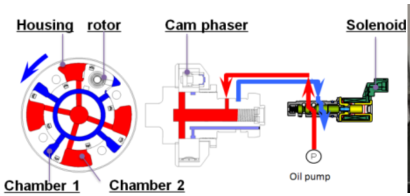
---with non-minimum phase behavior and sign-reversal

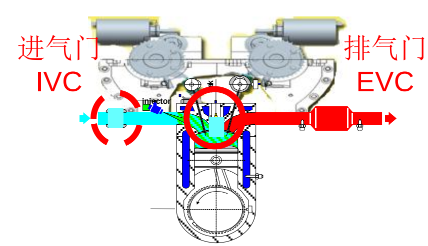
→2 LADRC+ static and dynamic feedforward

3. Cross-coupled combustion process control

---highly sensitive to operation condition variations

→3LADRC+ Decoupling + feedforward control





1. H. Xie, K. Song, and Y. He, "**A hybrid disturbance rejection control solution for variable valve timing system of gasoline engines**." *ISA Transactions*, Available online 12 November 2013, ISSN 0019-0578, http://dx.doi.org/10.1016/j.isatra.2013.10.006.
2. K. Song, H. Xie, L. Li, J. Lu, C. Li, and Z. Gao, "**Disturbance observation and rejection method for gasoline HCCI combustion control**," *SAE World Congr.*, Detroit, MI., 2013-01-1660, 2013.
3. H. Xie, K.Song, et.al., "**A Comprehensive Decoupling Control Method for Gasoline HCCI Combustion**", CCC 2013, Xi'an,China.
4. K.Song, H. Xie, et.al., "**Dynamic Feed-forward Control Aided with Active Disturbance Rejection for Boost Pressure and Mass Air Flow Control of Diesel Engines**", CCC 2014, Nanjing,China.

theoretical justification was lagging behind for quite some time

Ambition to deal with vast uncertainties

The uncertain systems: nonlinear, time-varying, MIMO

The disturbance signal: discontinuous

The feedback: in general nonlinear structure

Increasingly successful applied researches stimulated the theoretical research.

How to rigorously find the capacity of ADRC in dealing with vastly uncertain nonlinear systems?

How to rationalize the outstanding performance in the presence of large uncertainties shown in numerous applied researches?

What are the limits on the scope of applications for ADRC?

Outline

- Principles and methods of ADRC
- Practice
- **Analysis**
- Conclusions

Analysis on ADRC

Linear ADRC (LADRC), Gao Z. (2003), leads to a break

linear control of nonlinear systems

- **LADRC for nonlinear uncertain systems**
  dynamic performance was analyzed
- **The capability of sampled-data LADRC**
  how to tuning the parameters of LADRC when the sampling rate is fixed
- **Frequency-domain analysis**
  high level of robustness was shown
  the influence of the input gain on the stability of ADRC was discussed
- **The stability of LADRC for plants with uncertain orders**
  one ADRC with fixed parameters for a group of plants with different orders

Nonlinear ADRC (NADRC)

Dan Wu(2012, IEEE TIE), Bao-Zhu Guo, Zhi-liang Zhao (2013 SIAM CO)
open the analysis for NADRC

Analysis on ADRC

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open the analysis for NADRC

Linear ADRC (LADRC)

A parameterized linear ADRC (LADRC) was proposed in Gao Z. (2003, CDC)

render the controller easy to tune

NADRC

ESO

$$\begin{cases} \dot{\hat{X}}_1 = \hat{X}_2 - G_1(\hat{X}_1 - Y) \\ \cdots \\ \dot{\hat{X}}_n = \hat{X}_{n+1} - G_n(\hat{X}_1 - Y) + \bar{B}(t)U(t) \\ \dot{\hat{X}}_{n+1} = -G_{n+1}(\hat{X}_1 - Y) \end{cases}$$

$$U(t) = -\bar{B}^{-1}(t)\hat{X}_{n+1} + U_0(Y, \hat{X}_2, \cdots \hat{X}_n)$$

LADRC

$$\begin{cases} \dot{\hat{X}}_1 = \hat{X}_2 - \beta_1(\hat{X}_1 - Y) \\ \cdots \\ \dot{\hat{X}}_n = \hat{X}_{n+1} - \beta_n(\hat{X}_1 - Y) + \bar{B}(t)U(t) \\ \dot{\hat{X}}_{n+1} = -\beta_{n+1}(\hat{X}_1 - Y) \end{cases}$$

$$U(t) = -\bar{B}^{-1}(t)\hat{X}_{n+1} - \bar{B}^{-1}(t)\sum_{i=1}^{n} k_i \hat{X}_i$$

for the canonical form system

$$s^{n+1} + \sum_{i=1}^{n+1} \beta_i s^{n-i+1} = (s + \omega_e)^{n+1}, \omega_e > 0$$

bandwidth of LESO

Linear ADRC (LADRC)

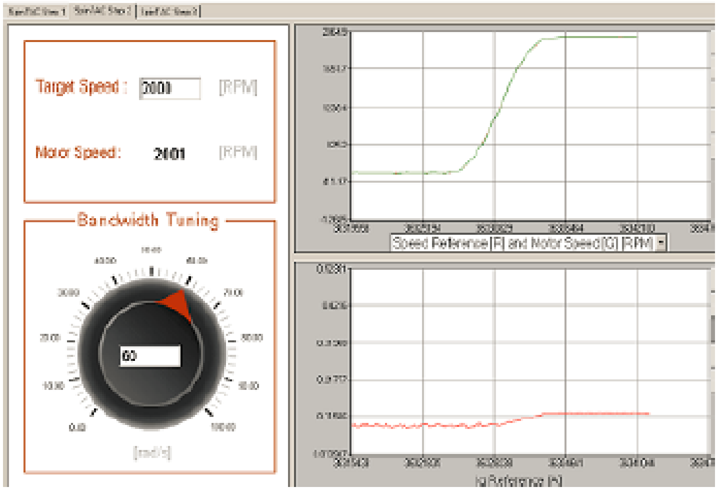


Figure 3. Simple Tuning Interface

SpinTAC

tuning 1 variable: bandwidth of ESO

LADRC has already shown great promise in many areas of control engineering

linear control of nonlinear systems

LADRC

$$\begin{cases} \dot{\hat{X}}_1 = \hat{X}_2 - \beta_1(\hat{X}_1 - Y) \\ \cdots \\ \dot{\hat{X}}_n = \hat{X}_{n+1} - \beta_n(\hat{X}_1 - Y) + \bar{B}(t)U(t) \\ \dot{\hat{X}}_{n+1} = -\beta_{n+1}(\hat{X}_1 - Y) \end{cases}$$

$$U(t) = -\bar{B}^{-1}(t)\hat{X}_{n+1} - \bar{B}^{-1}(t)\sum_{i=1}^{n} k_i \hat{X}_i$$

for the canonical form system

$$s^{n+1} + \sum_{i=1}^{n+1} \beta_i s^{n-i+1} = (s + \omega_e)^{n+1}, \quad \omega_e > 0$$

bandwidth of LESO

Linear ADRC (LADRC)

$$\begin{cases} \dot{X}_1 = X_2 \\ \cdots \\ \dot{X}_{n-1} = X_n \\ \dot{X}_n = D(t) + F(X,t) + B(X,t)U(t) \\ Y = X_1 \end{cases}$$

$$\begin{cases} \dot{X}_1 = X_2 \\ \cdots \\ \dot{X}_{n-1} = X_n \\ \dot{X}_n = X_{n+1} + \bar{B}(t)U(t) \end{cases}$$

$$\begin{cases} \dot{\hat{X}}_1 = \hat{X}_2 - \beta_1(\hat{X}_1 - Y) \\ \cdots \\ \dot{\hat{X}}_n = \hat{X}_{n+1} - \beta_n(\hat{X}_1 - Y) + \bar{B}(t)U(t) \\ \dot{\hat{X}}_{n+1} = -\beta_{n+1}(\hat{X}_1 - Y) \end{cases}$$

$$s^{n+1} + \sum_{i=1}^{n+1} \beta_i s^{n-i+1} = \left(s + \omega_e\right)^{n+1}, \ \omega_e > 0$$

$$U(t) = -\bar{B}^{-1}(t)\hat{X}_{n+1} - \bar{B}^{-1}(t)\sum_{i=1}^{n} k_i \hat{X}_i$$

difficulty for analysis

$$X_{n+1} = D(t) + F(X,t) + \left[B(X,t) - \bar{B}(t) \right] U(t)$$

"total disturbance"

If the total disturbance is bounded, the errors of ESO are bounded. However, it is a function of states and control input.

Analysis-stability

•**L.Praly, Z.P.Jiang, Semiglobal stabilization in the presence of minimum-phase dynamic input uncertainties, IFAC Nonlinear Control Systems Design, 1998.**
•**L.Praly, Z.P.Jiang, Linear output feedback with dynamic high gain for nonlinear systems, Systems & Control Letters, 2004**

Consider the nonlinear uncertain system

$$\dot{z} = q(z, y)$$
$$\dot{x}_1 = x_2 + \delta_1(z, x_1)$$
$$\vdots$$
$$\dot{x}_i = x_{i+1} + \delta_i(z, x_1, \cdots, x_i)$$
$$\vdots$$
$$\dot{x}_n = u - u^* + \delta_n(z, x_1, \cdots, x_n)$$
$$y = x_1$$

Set $x_{n+1} = -u^*$ **Desing the following observer and control**

$$\dot{\hat{x}}_1 = \hat{x}_2 + k_1 r(x_1 - \hat{x}_1)$$
$$\vdots$$
$$\dot{\hat{x}}_n = \hat{x}_{n+1} + u + k_n r^n (x_1 - \hat{x}_1)$$
$$\dot{\hat{x}}_{n+1} = k_{n+1} r^{n+1} (x_1 - \hat{x}_1)$$

$$\bar{x}_{n+1} = \bar{\delta}_n(z, x_1, \cdots, x_n) - u^*$$

$$\bar{\delta}_i(z, x_1, \cdots, x_i) = \delta_i(z, x_1, \cdots, x_i) + \dot{\bar{\delta}}_{i-1}(z, x_1, \cdots, x_{i-1}),$$
$$\bar{\delta}_0(\cdot) = 0, i \in 3, 4, \ldots, n,$$

$$u = -\hat{x}_{n+1} - r^n Fcol\left(\frac{y}{r^a}, \quad \frac{\hat{x}_2}{r^{a+1}}, \quad \cdots, \quad \frac{\hat{x}_n}{r^{n+a-1}} \right)$$

Bounded, converge to the origin

Analysis-stability

Simulation on the flight control system

$$\begin{cases} \dot{\alpha} = \omega_z - a_{11}(t)\alpha + a_{10}(t) \\ \dot{\omega}_z = u - u^* + a_{21}(t)\alpha + a_{22}(t)\omega_z \\ y = \alpha \end{cases}$$

Angle of attack: α,
Angular rate: ω_z.
Uncertain aero-dynamic parameters: $a_{10}, a_{11}, a_{21}, a_{22}$
Unknown disturbance: u^* **wind**

$$\begin{cases} \dot{\bar{x}}_1 = \bar{x}_2 \\ \dot{\bar{x}}_2 = \bar{x}_3 + u \end{cases} \qquad \bar{x}_1 = \alpha, \ \ \bar{x}_2 = \omega_z - a_{11}\alpha + a_{10},$$

$$\bar{x}_3 = -u^* + a_{21}\alpha + a_{22}\omega_z - a_{11}\bar{x}_2 - \dot{a}_{11}\alpha + \dot{a}_{10}$$ **total disturbance**

ADRC

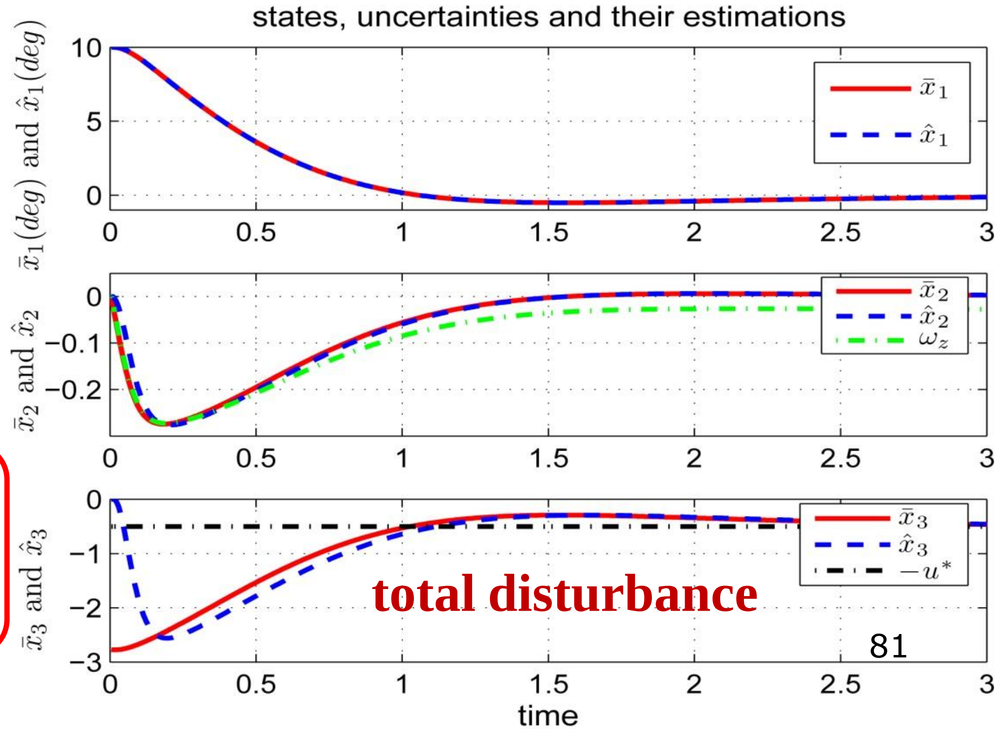
$$\dot{\hat{x}}_1 = \hat{x}_2 + \beta_1(y - \hat{x}_1)$$
$$\dot{\hat{x}}_2 = \hat{x}_3 + u + \beta_2(y - \hat{x}_1)$$
$$\dot{\hat{x}}_3 = \beta_3(y - \hat{x}_1)$$
$$u = -\hat{x}_3 - k_1 y - k_2 \hat{x}_2$$

Desired performance

$$\begin{cases} \dot{\bar{x}}_1 = \bar{x}_2 \\ \dot{\bar{x}}_2 = -k_1\bar{x}_1 - k_2\bar{x}_2 \end{cases}$$

Outputs of ESO

$$(\hat{x}_1 \quad \hat{x}_2 \quad \hat{x}_3) \rightarrow (\bar{x}_1 \quad \bar{x}_2 \quad \bar{x}_3)$$



Xue W., Huang, Y., ISA Transaction 2014

Analysis

ADRC law

ESO

$$\begin{cases} \dot{\hat{X}}_1 = \hat{X}_2 - \beta_1(\hat{X}_1 - Y) \\ \cdots \\ \dot{\hat{X}}_n = \hat{X}_{n+1} - \beta_n(\hat{X}_1 - Y) + \bar{B}(t)U(t) \\ \dot{\hat{X}}_{n+1} = -\beta_{n+1}(\hat{X}_1 - Y) \end{cases}$$

$$s^{n+1} + \sum_{i=1}^{n+1} \beta_i s^{n-i+1} = (s + \omega_e)^{n+1}, \ \omega_e > 0$$

$$U(t) = -\bar{B}^{-1}(t)\hat{X}_{n+1} + U_0(Y, \hat{X}_2, \cdots \hat{X}_n)$$

Compensate for the total uncertainty
- **stability**

Desired Performance:
- **quick**
- **Smooth**
- **high precision**

Two-degrees-of-freedom controller design(双通道设计)

Performance:

- **transient:** **quick, smooth, high-precision**
- **stability:** **disturbance rejection**

Analysis - performance

➢ Freidovich, L.B., Khalil, H.K. (2008), Performance recovery of feedback-linearization based designs, IEEE Trans. Automat. Contr., Vol. 53, No. 10, 2324-2334.

Extended High-gain Observer(EHGO)

$$\dot{x} = Ax + B\left[b(x,z,\omega) + a(x,z,\omega)u\right]$$
$$\dot{z} = f_0(x,z,\omega)$$
$$y = Cx$$

$$A = \begin{bmatrix} 1 & 0 & \cdots & 0 & 0 \\ & 1 & 0 & & \\ & & \ddots & \ddots & \\ & & & 1 & 0 \\ & & & & 0 \end{bmatrix} \in R^{n\times n}, B = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix} \in R^n, C = \begin{bmatrix} 1 & 0 & \cdots & \cdots & 0 \end{bmatrix}$$

states: $x \in R^n, z \in R^m$

output: y

control input: $u(t) \in R$

disturbance: $\omega(t) \in R^l$

unknown nonlinear functions $a(\cdot), b(\cdot), f_0(\cdot), \ a(\cdot) > 0, z(t)$ **bounded**

$$\dot{\hat{x}} = A\hat{x} + B\left[\hat{\sigma} + \hat{b}(\hat{x}) + \hat{a}(\hat{x})u\right] + H(\varepsilon)(y - C\hat{x})$$

$$\dot{\hat{\sigma}} = \left(\frac{\alpha_{n+1}}{\varepsilon^{n+1}}\right)(y - C\hat{x})$$

LESO

$$u = \frac{-\hat{\sigma} - \hat{b}(\hat{x}) + \phi(\hat{x})}{\hat{a}(\hat{x})}$$

$$H(\varepsilon) = \left[\frac{\alpha_1}{\varepsilon}, \cdots, \frac{\alpha_n}{\varepsilon}\right]$$

➢ **all trajectories are bounded**

➢ **recovery the performance of the canonical cascade integrator systems:**

$$\dot{x}^* = Ax^* + B\phi(x^*)$$

$$x - x^* = O(\varepsilon) + O(T(\varepsilon)), \forall t \geq 0$$

Analysis

$$\begin{cases} x^{(n)}(t) = d(t) + f(X,t) + b(X,t)u(t) \\ y = x(t) \end{cases}, X = \left[x, \cdots x^{(n-1)}\right]^T$$

Discontinuous disturbance: contains the first class discontinuous points

$A1)\ \sup_{t\in[t_0,\infty)} |d(t)| \le w_1,\ \sup_{t\in[t_0,\infty), t\notin\{t_i\}_{i=1}^{\infty}} |\dot{d}(t)| \le w_1,\ \inf_i \{t_{i+1} - t_i\} \ge w_3$

square wave disturbance
load change

Unknown dynamics

$A2)\ f(x,t), b(x,t), \bar{b}(t)$: continuously differentiable and there exist locally Lipschita functions s.t. $\forall t \ge t_0$

$$|f(x,t)| \le \psi_1(\|X\|),\ \left\|\frac{\partial f(x,t)}{\partial x}\right\| \le \psi_2(\|X\|),\ \left\|\frac{\partial f(x,t)}{\partial t}\right\| \le \psi_3(\|X\|)$$

$$0 < c \le |b(x,t)| \le \psi_4(\|X\|),\ \left\|\frac{\partial b(x,t)}{\partial x}\right\| \le \psi_5(\|X\|),\ \left\|\frac{\partial b(x,t)}{\partial t}\right\| \le \psi_6(\|X\|)$$

X bounded $\Rightarrow$ $f(x,t), b(x,t)$ and partial derivatives bounded

$A3)\ \frac{b(X,t)}{\bar{b}(t)} \in [w_4, w_5] \subset \left(0, \frac{2n}{n-1}\right), \left|\dot{\bar{b}}(t)\right| \le w_6, \forall t \ge t_0$ **the weakest condition on $\bar{b}(t)$ by now**

n=1: same sign; n=2: (0,4) **previous: (0,2)**

Xue W. Phd thesis, 2012; Huang Y, Xue W. ISA Transactions, 2014

Analysis

$$\begin{cases} x^{(n)}(t) = d(t) + f(X,t) + b(X,t)u(t) \\ y = x(t) \end{cases}, X = \left[x, \cdots x^{(n-1)} \right]^T$$

Theorem 1. Assume $|x_i(t_0)| \le \rho_0 (i \in \underline{n})$. **There exist positives** $\omega^*, \rho, \eta_i^* (i \in \underline{3})$, **such that** $\forall \omega_e \ge \omega^*$

1. $\sup_{t\in[t_0,\infty)} \|X(t)\| \le \rho$ **stability**

2. $\sup_{t\in[t_0,\infty)} \|X(t) - X^*(t)\| \le \eta_1^* \max\left\{\frac{\ln \omega_e}{\omega_e}, \frac{1}{\omega_e}\right\};$

performance recovery ⇒

$$\begin{cases} x^{*(n)}(t) = -K^T X^* \\ X^*(t_0) = X(t_0) \end{cases}$$

$$X^* = \left[x^*, \cdots x^{*(n-1)} \right]^T$$

3. $\|\hat{x}_i - x_i\| \le \frac{\eta_2^*}{\omega_e}, t \in \left[t_j + \eta_3^* \max\left\{\frac{\ln \omega_e}{\omega_e}, 0\right\}, t_{j+1} \right), \quad i = 2, \ldots, n+1, j \ge 1;$

estimation for states (including total disturbance)

Xue W. Phd thesis, 2012; Huang Y, Xue W. ISA Transactions, 2014

Analysis

$$\begin{cases} x^{(n)}(t) = d(t) + f(X,t) + b(X,t)u(t) \\ y = x(t) \end{cases}, X = \left[x, \cdots x^{(n-1)}\right]^T$$

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$$\begin{cases} x^{*(n)}(t) = -K^T X^* \\ X^*(t_0) = X(t_0) \end{cases}$$

$$X^* = \left[x^*, \cdots x^{*(n-1)}\right]^T$$

3. $\|\hat{x}_i - x_i\| \le \frac{\eta_2^*}{\omega_e}, t \in \left[t_j + \eta_3^* \max\left\{\frac{\ln \omega_e}{\omega_e}, 0\right\}, t_{j+1}\right), \quad i = 2, \ldots, n+1, j \ge 1;$

estimation for states (including total disturbance)

Similar results have been extended to (Xue, et.al ,ISA transactions, 2014)

$$\begin{cases} \dot{X}_1 = F_1(X_1, \theta(t)) + B_1(X_1) X_2 \\ \dot{X}_2 = F_2(X_1, X_2, \theta(t)) + B_2(X_1, X_2, \theta(t)) U \end{cases}$$

Analysis

Group of Guo Baozhu at Chinese Academy of Science

Extended the analysis on ADRC to the infinite-dimension systems

- **◆Guo B., Jin F. Sliding Mode and Active Disturbance Rejection Control to Stabilization of One-Dimensional Anti-Stable Wave Equations Subject to Disturbance in Boundary Input. *IEEE Transactions On Automatic Control*, 58(5), 1269–1274(2013).**
- **◆Guo B., Jin F. The active disturbance rejection and sliding mode control approach to the stabilization of the Euler-Bernoulli beam equation with boundary input disturbance. *Automatica*, 49, 2911–2918(2013)**

Opened the theoretical analysis of nonlinear ESO and nonlinear ADRC for nonlinear time-varying uncertain systems

- **◆Guo B., Zhao Z. On the convergence of an extended state observer for nonlinear systems with uncertainty. *Systems & Control Letters*, 60, 420–430(2011).**
- **◆Guo B., Zhao Z. On Convergence of the Nonlinear Active Disturbance Rejection Control for MIMO Systems. *SIAM J. Control and Optimization*, 51(2), 1727–1757(2013).**

Analysis

- Capability of (n+1)th order LESO for nth nonlinear uncertain systems.

- IF A1-A3 not satisfied:

1) A simple example $d(t)=t^m (m\geq 2)$, $f(x,t)=0$, a (n+m)th order LESO

2) $f(x,t)\, or\, b(x,t): discontinuous$, to be studied

Theorem 1. Assume $|x_i(t_0)|\leq \rho_0 (i\in \underline{n})$. **There exist positives** $\omega^*, \rho, \eta_i^* (i\in \underline{3})$, **such that** $\forall \omega_e \geq \omega^*$

1. $\sup_{t\in[t_0,\infty)} \|X(t)\| \leq \rho$ **stability**

2. $\sup_{t\in[t_0,\infty)} \|X(t)-X^*(t)\| \leq \eta_1^* \max\left\{\frac{\ln \omega_e}{\omega_e}, \frac{1}{\omega_e}\right\};$ **performance recovery** ⟹

$$\begin{cases} x^{*(n)}(t) = -K^T X^* \\ X^*(t_0) = X(t_0) \end{cases}$$

$$X^* = \left[x^*, \cdots x^{*(n-1)}\right]^T$$

3. $\|\hat{x}_i - x_i\| \leq \frac{\eta_2^*}{\omega_e}, t\in\left[t_j + \eta_3^* \max\left\{\frac{\ln \omega_e}{\omega_e}, 0\right\}, t_{j+1}\right), \quad i=2,\ldots,n+1,\ j\geq 1;$

estimation for states (including total disturbance)

Analysis

- The larger ω_e , the smaller $\sup_{t\in[t_0,\infty)}\left\|X(t)-X^*(t)\right\|$ and $\left\|\hat{x}_i - x_i\right\|$.

  In practice, ω_e is restricted by physical limitations:

  sampling rate, delay, measurement noise, etc.

Further research

- ◆sampled-data: capability of ADRC (Xue W. et al, 2013)
- ◆measurement noise: tuning ω_e (Bai W. et al, 2014CCC)

Theorem 1. Assume $|x_i(t_0)| \le \rho_0 (i \in \underline{n})$. There exist positives $\omega^*, \rho, \eta_i^* (i \in \underline{3})$, such that $\forall \omega_e \ge \omega^*$

1. $\sup_{t\in[t_0,\infty)}\left\|X(t)\right\| \le \rho$ stability
2. $\sup_{t\in[t_0,\infty)}\left\|X(t)-X^*(t)\right\| \le \eta_1^* \max\left\{\frac{\ln\omega_e}{\omega_e}, \frac{1}{\omega_e}\right\}$; performance recovery ⟹ $\begin{cases} x^{*(n)}(t) = -K^T X^* \\ X^*(t_0) = X(t_0) \end{cases}$ $X^* = \left[x^*, \cdots x^{*(n-1)}\right]^T$
3. $\left\|\hat{x}_i - x_i\right\| \le \frac{\eta_2^*}{\omega_e}, t \in \left[t_j + \eta_3^* \max\left\{\frac{\ln\omega_e}{\omega_e}, 0\right\}, t_{j+1}\right), \quad i = 2, \ldots, n+1, j \ge 1;$

estimation for states (including total disturbance)

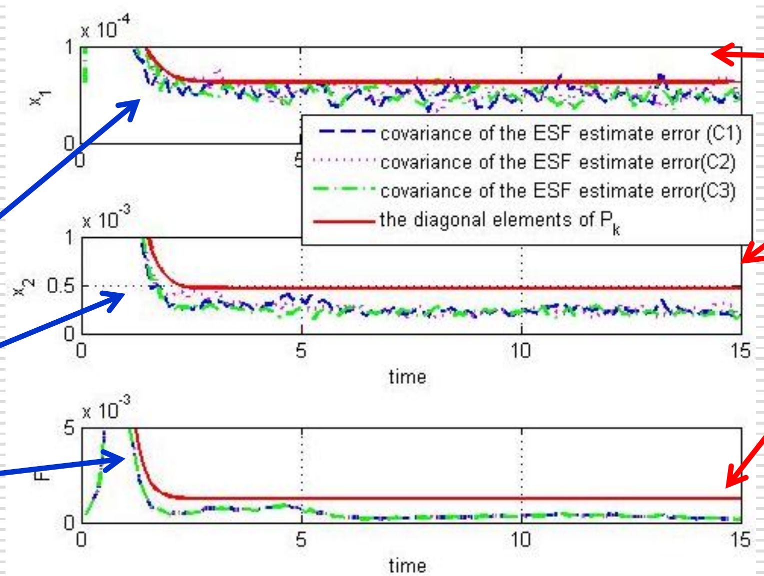
Analysis

□Bai W, Xue W, Huang Y, Fang H. The extended state filter (ESF) for a class of multi-input multi-output nonlinear uncertain hybrid systems, CCC2014, this afternoon (WeB22)

- ✓ stability conditions of ESF for nonlinear filtering problem are given.
- ✓ filtering error can be evaluated online.
- ✓ optimize the parameters of ESO to improve the estimation performance.
  - No longer high-gain
  - gain: changed automatically according to the uncertain dynamics and noise

contributions to the research of nonlinear filter, fresh idea for ADRC

Bounds of Filtering errors



Filtering Errors

Analysis on ADRC

Linear ADRC (LADRC), Gao Z. (2003), leads to a break

- Frequency-domain analysis
  - high level of robustness was shown
  - the influence of the input gain on the stability of ADRC was discussed
- The stability of LADRC for plants with uncertain orders
  - one ADRC with fixed parameters for a group of plants with different orders
- The stability of LADRC for nonlinear uncertain systems
  - dynamic performance was analyzed
- The capability of sampled-data LADRC
  - how to tuning the parameters of LADRC when the sampling rate is fixed

Nonlinear ADRC (NADRC) for nonlinear uncertain systems

The theoretical research of ADRC has been developed from different angles.

The research is still in its early stage.

Further study on challenging theoretical problems is still to come.

Conclusions

■ Principles and methods of ADRC

a new paradigm for control of nonlinear uncertain systems / disturbance rejection

Complex physical process ≠ **Complex Controller**

⇧

Simple Controller

■ Practice

The applied researches in some ADRC groups around the world are shown.

■ Analysis

The theoretical research of ADRC has been developed from different angles.
The research is still in its early stage.
Further study on challenging theoretical problems is still to come.

Conclusions

ADRC

•represents a new set of principles, methods and engineering tools

•a great challenge in building a sound theoretical basis

Challenges will lead to ever more exhilarating research in the future!

Acknowledgments

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CCC2014

WeA22 - Invited Session: ADRC in Power Generation and Regulation

WeB22 - Invited Session: Precision Control of Mechanical Systems on ADRC

ADRC group in the net: QQ128464029 (477 members by now)

Welcome to join!

Active Disturbance Rejection Control: (自抗扰控制)

Methodology, Practice and Analysis

Thanks!

Active Disturbance Rejection Control:

Methodology, Practice and Analysis

-- In Memory of Prof. Jingqing Han