DISTURBANCE OBSERVER BASED CONTROL: *CONCEPTS, METHODS AND CHALLENGES*

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Outline of the Presentation

- Introduction
- Concept
- Design methods
- Applications
- Challenges

Disturbance Observer Based Control: Concepts

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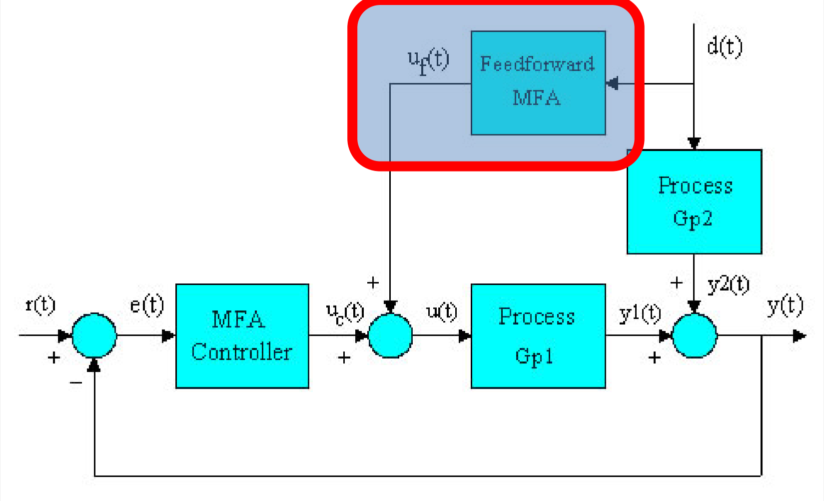
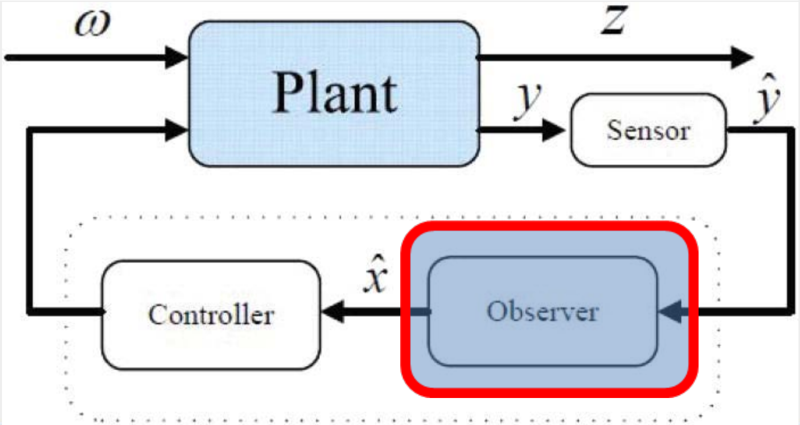
Key Motivation

- **<u>Feedforward</u>**
  - Classic control
  - transfer functions

- **<u>State observer based control</u>**
  - Morden Control;
  - State space approach





Disturbance Observer Based Control (DOBC)

- Main developments:
  1. **State space approach: Disturbance Accommodation Control (DAC), Unknown Input Observer (UIO), offset free, late 60s**

     C.D. Johnson. *Real-time disturbance-observers; origin and evolution of the idea part 1*: *The early years*. 40th Southeastern Symposium on System Theory, 2008.
  2. **Transfer function approach: Disturbance observer re-gained attention in the 80s (Ohnishi, 1982, 1983)**

     K. Ohishi, K. Ohnishi, and K. Miyachi. *The torque regulator using the observer of dc motor*. In Report of IEE of Japan, pages RN–82–33, 1982.
  3. **Nonlinear systems: Nonlinear disturbance observer based control. (Chen, 2000, 2001)**

     W.-H. Chen, D.J. Ballance, P.J. Gawthrop and J. O'Reilly. *A nonlinear disturbance observer for robotic manipulators.* IEEE Transactions on Industrial Electronics, 2000.
- Not only deal with disturbances but also **uncertainties**
- Independently developed

Other relevant methods

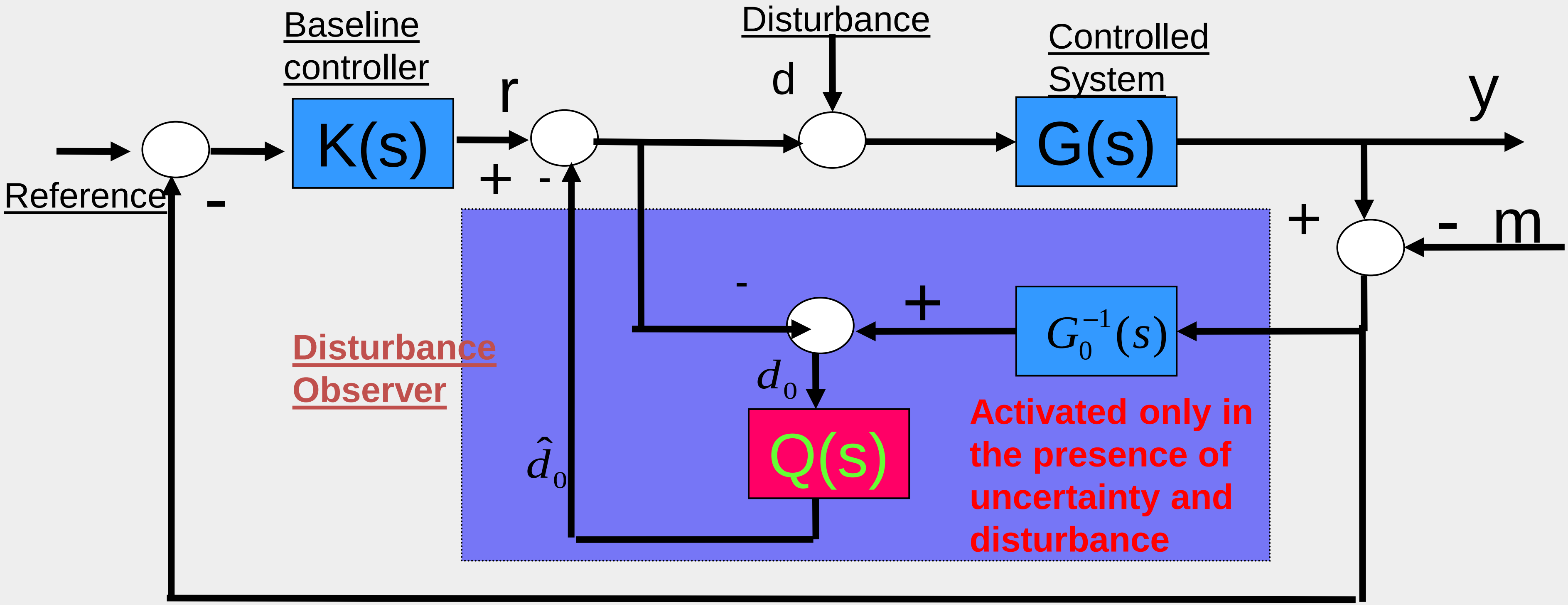
- **Linear disturbance observer**
  - Equivalent Input Disturbance (EID) based estimator (She)
  - Uncertainty and Disturbance Estimator (UDE) (Zhong)
  - Extended State Observer (ESO) (Han)
  - Generalized Proportional Integral Observer (GPIO)

- **Adaptive Disturbance Rejection Control (ADRC).** Han, 1990s

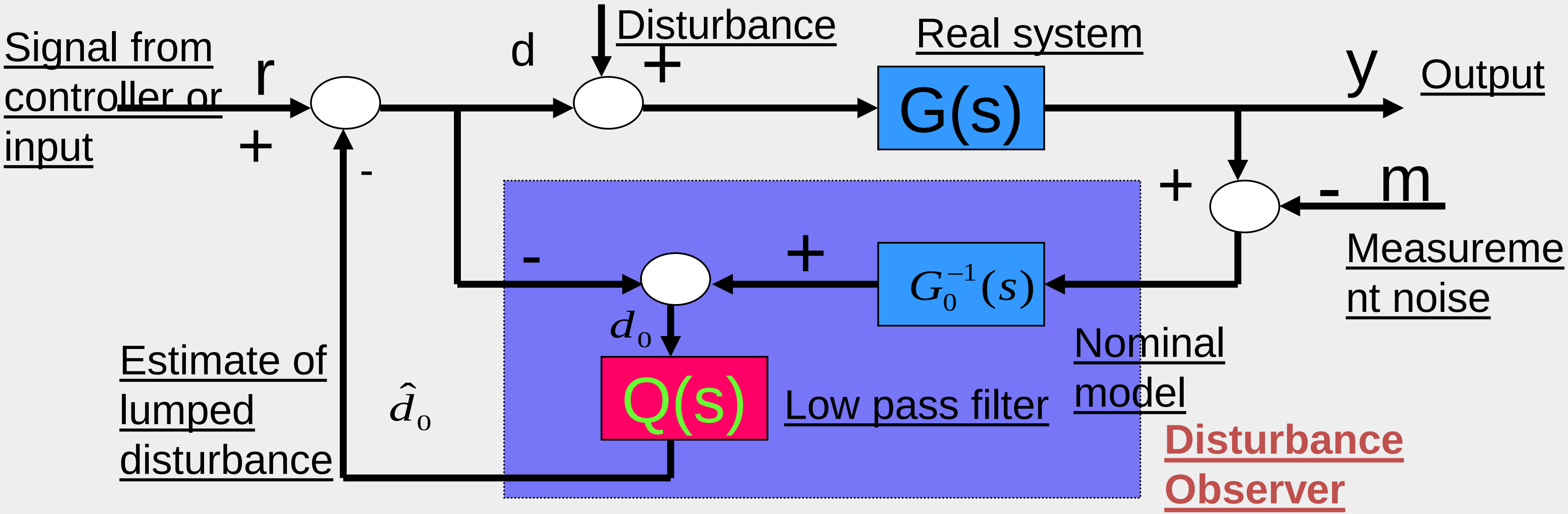
- **Various nonlinear disturbance observer design methods**
  - Fuzzy
  - Sliding mode observation
  - Intelligent/neural network

Not an exhaustive list!

Disturbance Observer Based Control (DOBC)



Basic Structure of Disturbance Observers



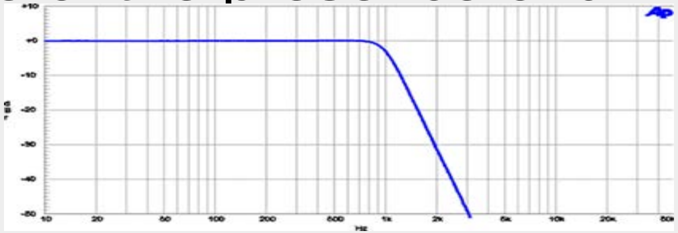
Equivalent noise $d_0 = [G_0^{-1}(s) - G^{-1}(s)]y + d - G_0(s)^{-1}m$

$$y(s) = \{Q(s)G_0^{-1}(s) + [1 - Q(s)]G^{-1}(s)\}^{-1}\{r + Q(s)G_0^{-1}(s)m + [1 - Q(s)]d\ \}$$

$$\approx G_o(s)r + m$$

LDOBC

- Not only estimate *d*, but also the model-plant mismatching and measurement noise.
- When *Q(s)*≅*1* within a specified frequency range, the real plant of G(s) behaves as $G_0(s)$ in spite of the presence of d.



$$y(s) \approx G_0(s)r(s) + m(s)$$

- In general, *Q(s)* is sensitive to the sensor noise. A proper cut-off frequency and *Q(s)* should be selected to attenuate the sensor noise.

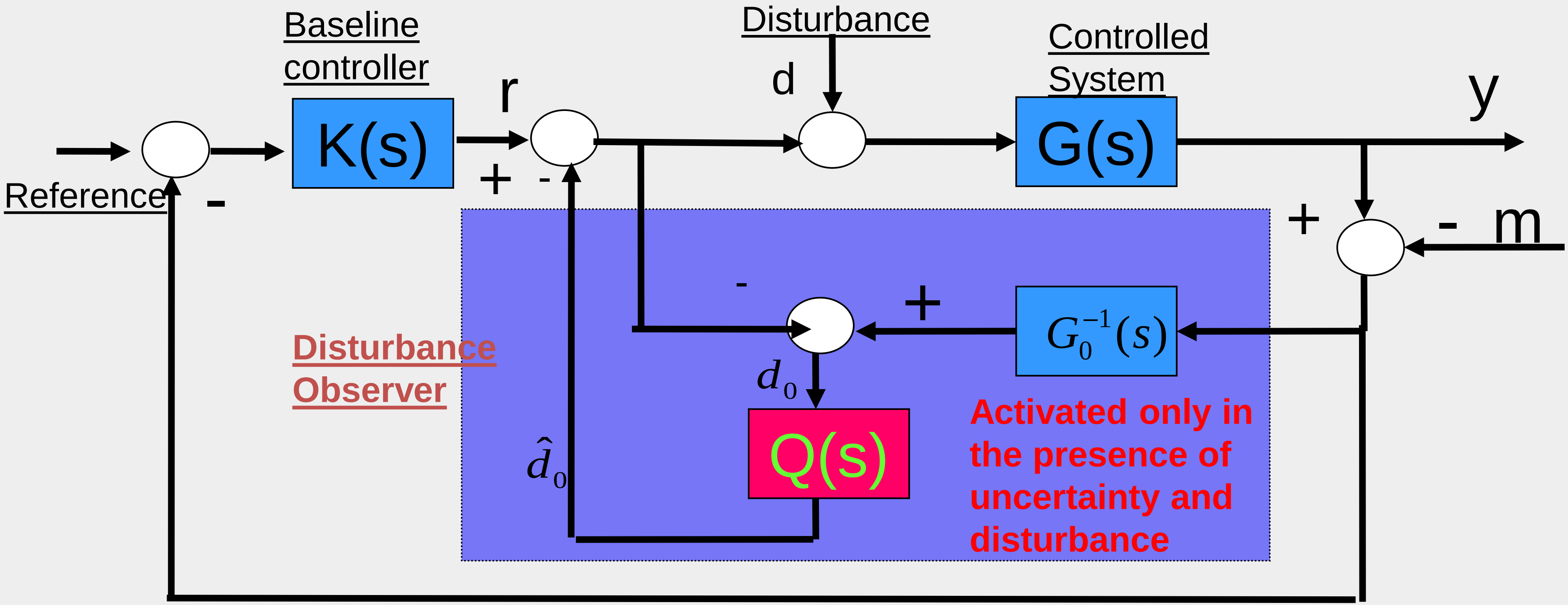
LDOBC (Cont.)

- Classic frequency domain methods can be used to verify stability of DOBC;
- *Q(s)* is a low pass filter;
- The relative degree of *Q(s)* should be larger than *G(s);*

$$G(s)_n = \frac{1}{s^2 + s + 1}$$

- Only suitable for minimum phase systems
- Various modifications of the basic structure;
- *Q(s)* can be designed using loop shaping techniques;
- Robust stability can be guaranteed under certain conditions.

Disturbance Observer Based Control (DOBC)



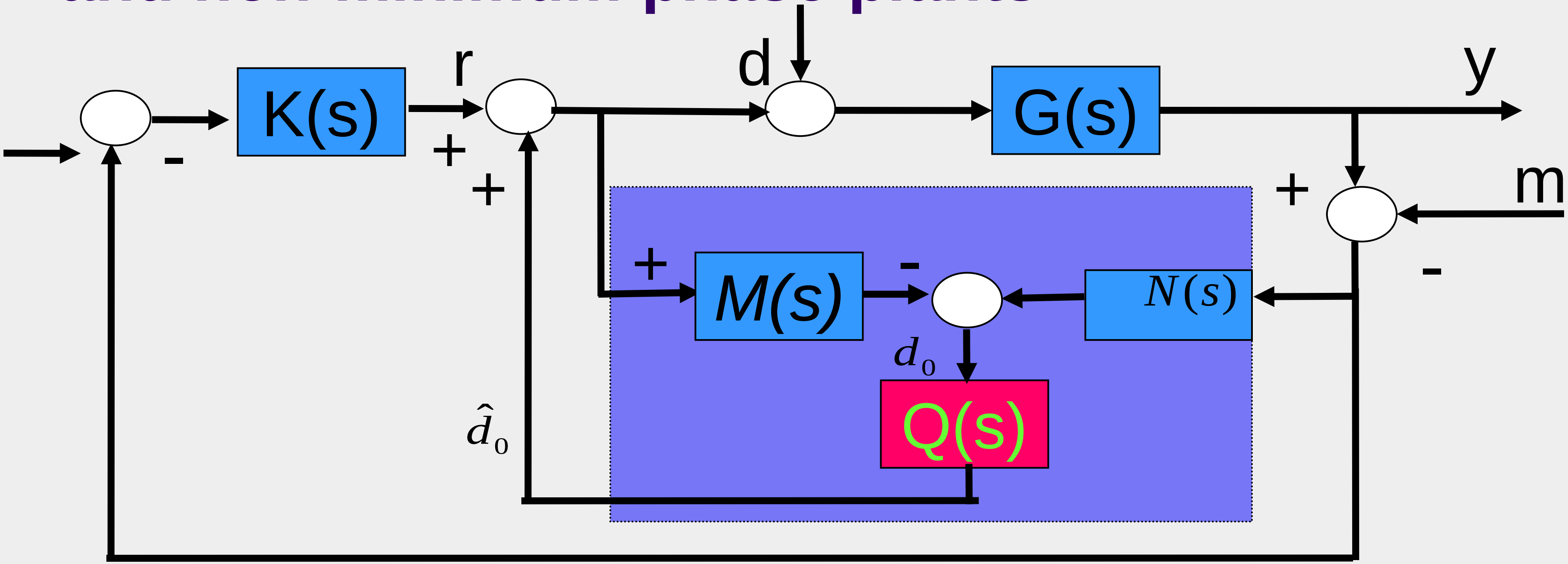
Two Stage Design Process

- **Feedback controller** designed based on nominal plants achieves stability and tracking performance ***without*** consideration of disturbance, uncertainties, and unmodelled dynamics/nonlinearity.
- **Disturbance observer** designed to compensate for these ignored factors and restore the performance: **disturbance attenuation and robustness**

Two designs are separated from each other with different objectives

Design Methods

More general structure of DOBC for unstable and non-minimum phase plants



$G_o = \frac{H(s)}{D(s)}$, $M(s) = \frac{H(s)}{L(s)}, N(s) = \frac{D(s)}{L(s)}$

Time Domain: DAC and Extended State Observer

$$\begin{cases} \dot{x} = Ax + B_u u + B_d d, \\ y = Cx. \end{cases}$$

$$\dot{\xi} = W\xi, \;\; d = V\xi,$$

$$\begin{cases} \dot{\hat{x}} = A\hat{x} + B_u u + L_x(y - \hat{y}) + B_d\hat{d}, \\ \hat{y} = C\hat{x}, \end{cases}$$

$$\begin{cases} \dot{\hat{\xi}} = W\hat{\xi} + L_d(y - \hat{y}), \\ \hat{d} = V\hat{\xi}, \end{cases}$$

C. D. Johnson, “Further study of the linear regulator with disturbances—The case of vector disturbances satisfying a linear differential equation,” *IEEE Trans. Autom. Control*, 15(2), pp. 222–228, 1970.

Reduced order or full order

J Su, W-H Chen and J Yang (2016). On Relationship between Time-Domain and Frequency-Domain Disturbance Observers and Its applications. *ASME J. of Dynamics, Measurement and Control. Vol. 138, No. 9.*

DOBC for Uncertain Systems

- Ignored non-linearity and un-modelled dynamics regarded as a part of disturbances

$$d_0 = [G_0^{-1}(s) - G^{-1}(s)]y + d - G_0(s)^{-1}m$$

$$\dot{x} = Ax + \Delta \boldsymbol{f}(\boldsymbol{x}) + Bu$$

- Disturbance observer estimates not only external disturbance but also the influence of uncertainties; **Functional observer**
- If the disturbance observer dynamics are **much faster than** the plant dynamics, the influence of the nonlinearities/uncertainties can be reasonably estimated; compensated in a large extent.
- Similar to the *state observer-controller* structure

Nonlinear DOBC

- Nonlinear DOBC could improve the performance against real external disturbances and un-modelled dynamics by sufficiently using information about nonlinear dynamics.
- More difficult – **nonlinear controller**, **nonlinear disturbance observer** and **nonlinear dynamics** of the system itself.
- Two cases
  - nonlinear systems with disturbances
  - **nonlinear systems with uncertainties or un-modelled dynamics**

Frequency domain design methods do not apply anymore!

Basic Nonlinear Disturbance Observer Design

(Chen et al, IEEE Transactions in Industrial Electronics,2000)

- System

$$\dot{x} = f(x) + g_1(x)u + g_2(x)d$$

- Disturbance Observer

$$\dot{z} = -l(x)g_2(x)z - l(x)(g_2(x)p(x) + f(x) + g_1(x)u)$$

$$\hat{d} = z + p(x)$$

- The observer error dynamics

$$\dot{e}_1(t) + l(x)g_2(x)e_1(t) = 0$$

Nonlinear observer gain functions

- Requirements for choosing nonlinear gain functions

  (1) Observer error dynamics are stable;

  (2) $$l(x) = \frac{\partial p(x)}{\partial x}$$

- Two ways to choose the nonlinear gain functions
  - having chosen *l(x)*, *p(x)* is found by integration.
  - Start from *p(x)* and choose *p(x)* such that the estimation error approaches zero.
- They may work for an individual nonlinear plant but, in general, not trivial.
- A systematic way to choose the nonlinear gain functions is required

A special choice of the nonlinear observer gains

- Choose *p(x)* as

$$p(x) = p_0 L_f^{\rho-1} h(x)$$

- Gain functions

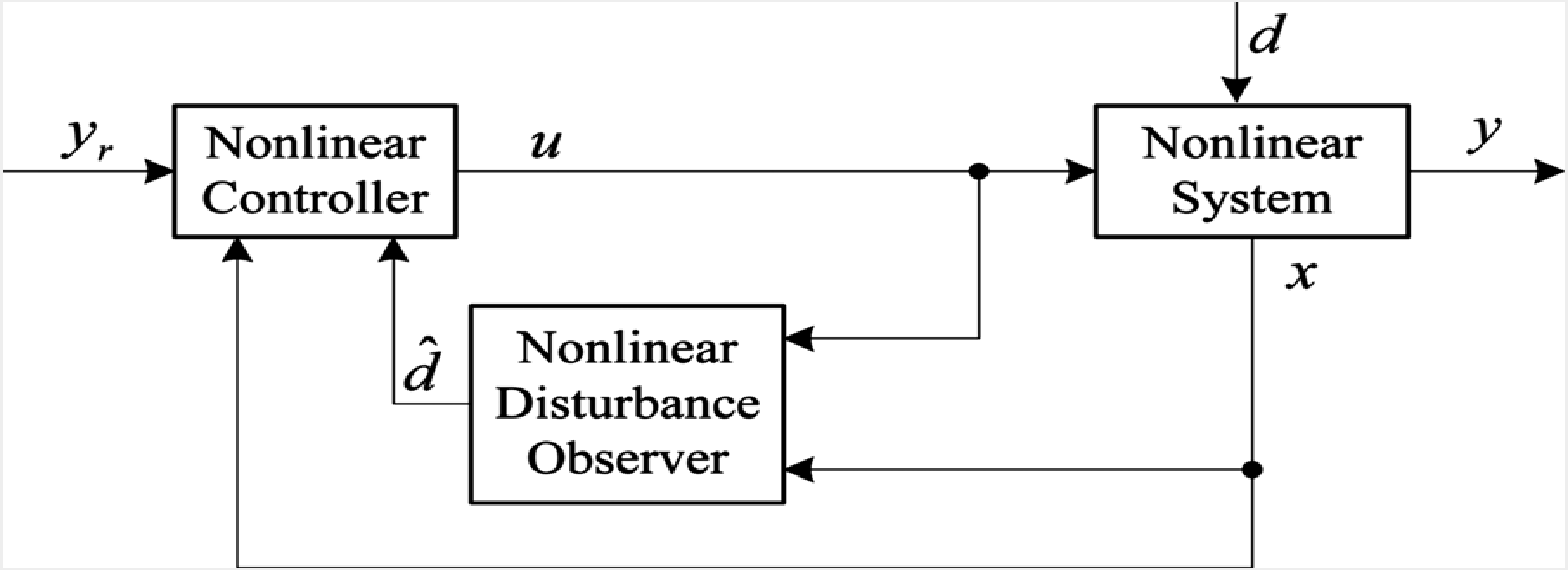
$$l(x) = p_0 \frac{\partial L_f^{\rho-1} h(x)}{\partial x}$$

where $p_0 \neq 0$ is a constant.

Stability Result: If the disturbance relative degree, ρ, is well-defined, then there exists a constant, p_0 , such that the estimation yielded by the observer with the design functions (5) and (6) approaches *d* exponentially.

Chen, IEEE/AMSE Transactions on Mechanics, 2003.

NDOBC: Structure



NDOBC: Design Procedure

- Nonlinear controllers without disturbances
  - feedback linearisation
  - dynamic inversion control
  - gain scheduling
  - nonlinear predictive control
  - sliding mode control
- Nonlinear disturbance observers
- Integration of ***any*** nonlinear controller with a nonlinear disturbance observer

A two step design procedure

Stability of NDOBC (Separation Principle)

Chen, IEEE/AMSE Transactions on Mechanics, 2003.

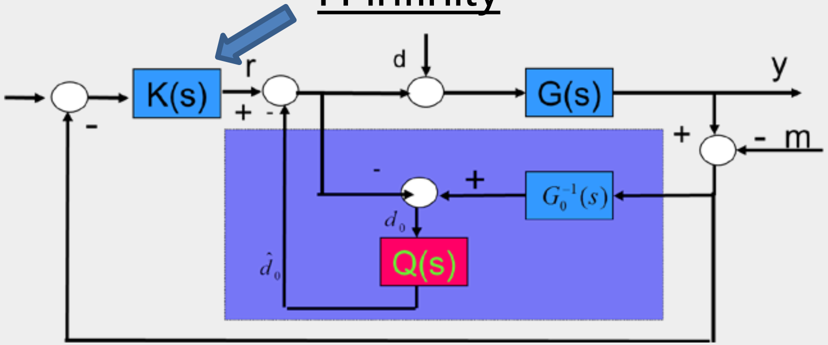
The closed-loop system under the nonlinear disturbance observer based control is globally exponentially stable if the following conditions are satisfied:

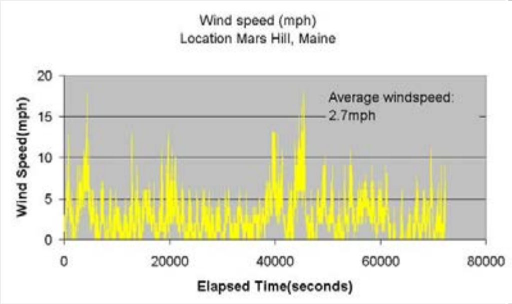
- the closed-loop system under the **nonlinear controller** is globally exponentially stable in the absence of disturbances;
- the **disturbance observer** is exponentially stable under an appropriately chosen design function $l(x)$ for any x varying within the state space;
- the solutions of the above composite system are defined and bounded for all t>0.

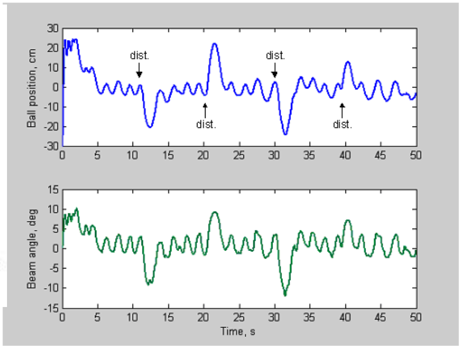
Disturbance cancellation and attenuation

- Complexity of disturbances: different types of disturbances.
- Integrating disturbance observers with H-infinity (Guo, 2005)

H infinity







L. Guo and W.-H. Chen (2005). Disturbance attenuation and rejection for a class of nonlinear systems via DOBC approach. Int. J. of Robust and Nonlinear Control. 15(3), pp.109-125

Composite Hierarchical Anti-Disturbance Control (CHADC) (Guo, 2004, …)

- Dividing and Conquering: Disturbance rejection and disturbance attenuation. Combining feedback with feedforward
- Tackling Different Types of Disturbances with Most Suitable Techniques
- Fully Exploiting Disturbance Information and Characteristics
- Disturbance modelling. Making a better use of data.

Mismatched disturbance

- Disturbance and control are not applied on the same channel
- It is, in general, true when considering the influence of uncertainties as disturbances

$$\begin{cases} \dot{x}_1 = x_2 + d \\ \dot{x}_2 = x_1 + 2x_2 + u \\ y = x_1 \end{cases}$$

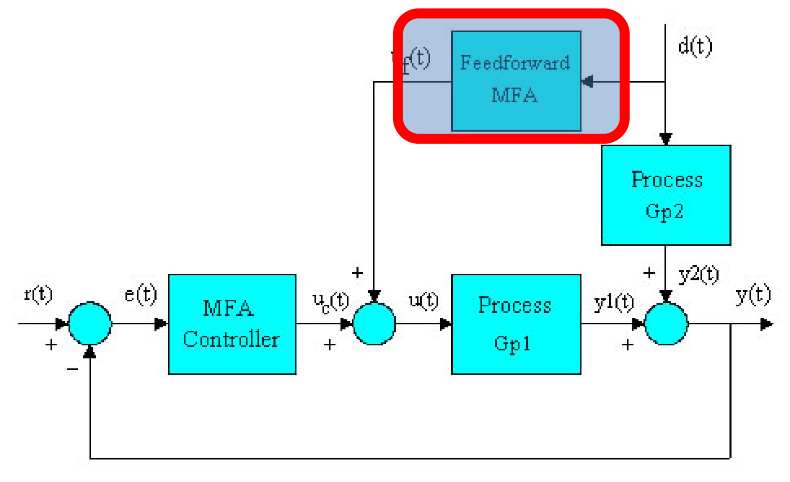
$$u = -2x_2 = 2d$$

$$\Rightarrow \quad y_s = x_{1s} = 0$$

$$x_{2s} = -d$$

- Not all states in steady state are zero;
- Not asymptotically stable; input to state stability
- States are affected by disturbance but we may decouple the influence of the disturbance from output at least at steady state

Mismatched Linear Systems



System Model

$$\begin{cases} \dot{x} = Ax + B_u u + B_d d \\ y = Cx \end{cases}$$

Composite Control Law

$$u = K_x x + K_d \hat{d},$$

$$K_d = -\left[C(A + B_u K_x)^{-1} B_u\right]^{-1} C(A + B_u K_x)^{-1} B_d$$

J. Yang, S. Li, W.-H. Chen and X. Chen (2012). Generalized Extended State Observer Based Control for Systems with Mismatched Uncertainties. IEEE Transactions on Industrial Electronics. 59 (12), pp.4792-4802.

Mismatched Nonlinear Systems

$$\begin{cases} \dot{x} = f(x) + g(x)u + p(x)w, \\ y = h(x), \end{cases}$$

J. Yang, W.-H. Chen and S. Li (2012). Static disturbance-to-output decoupling for nonlinear systems with arbitrary disturbance relative degree. *International Journal of Robust and Nonlinear Control.* 23(5), pp.562-577.

Composite Control Law Design:

$$u = \alpha(x) + \beta(x)v + \gamma(x)\hat{w},$$

$$v = -\sum_{i=0}^{\rho-1} c_i L_f^i h(x),$$

$$\gamma(x) = -\frac{\sum_{i=1}^{\rho-1} c_i L_p L_f^{i-1} h(x) + L_p L_f^{\rho-1} h(x)}{L_g L_f^{\rho-1} h(x)}$$

Other developments

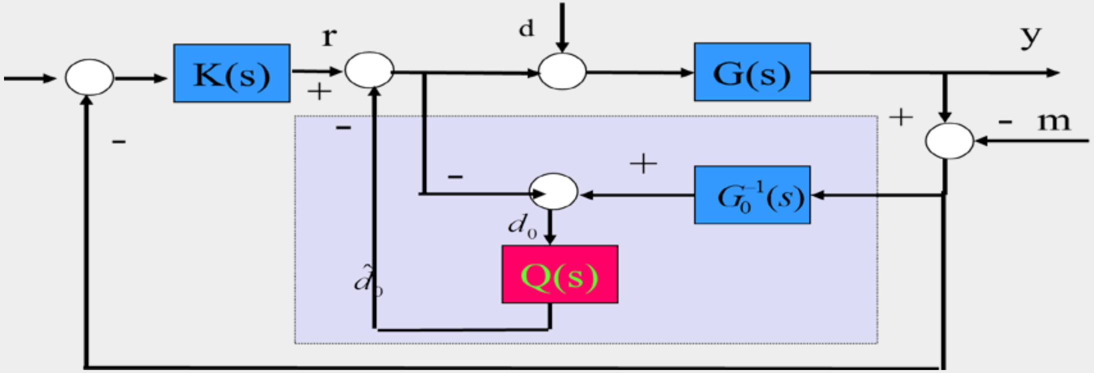
- Nonlinear Harmonic Observer (Chen 2003)
- Design of NDOBC using LMI’s (Guo and Chen, 2004)
- Nonlinear DOBC for slowly time-varying disturbances (Chen and Guo, 2003)
- Nonlinear DOBC for general disturbances, or high order observers

Relationships with Other Control Methods

Robust Control and DOBC

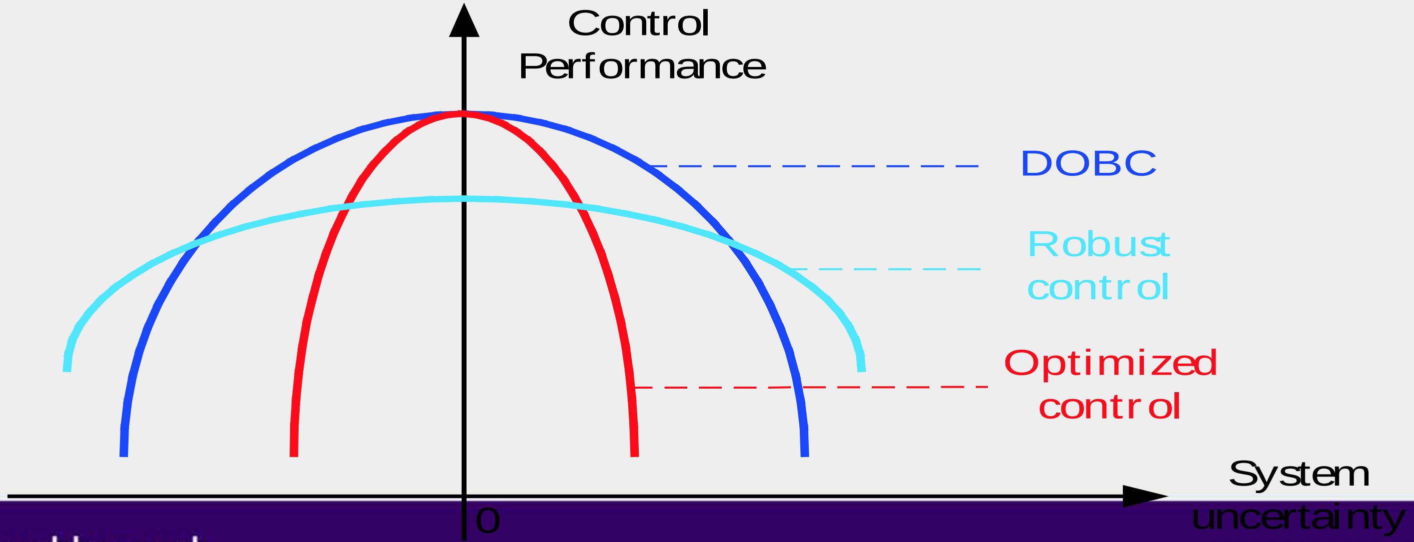
- **Worst case based design; Find a solution for a minimax problem.**
- **Over conservative; nominal performance is sacrificed for robustness.**
- **Most time near the operating condition; rarely operating at extreme situations.**

A promise approach for trading off between the nominal performance and robustness



Robust Control and DOBC

A promise approach for trading off between the nominal performance and robustness



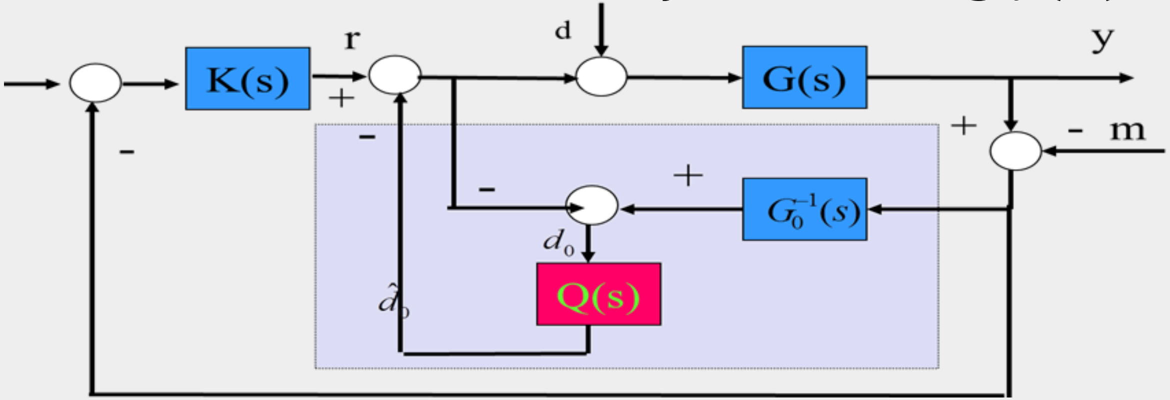
Adaptive Control and DOBC

Adaptive Control

Structured, parametrised uncertainty

$$\dot{x} = f(x) + \sum g_i(x)\,\theta_i + g(x)u$$

DOBC



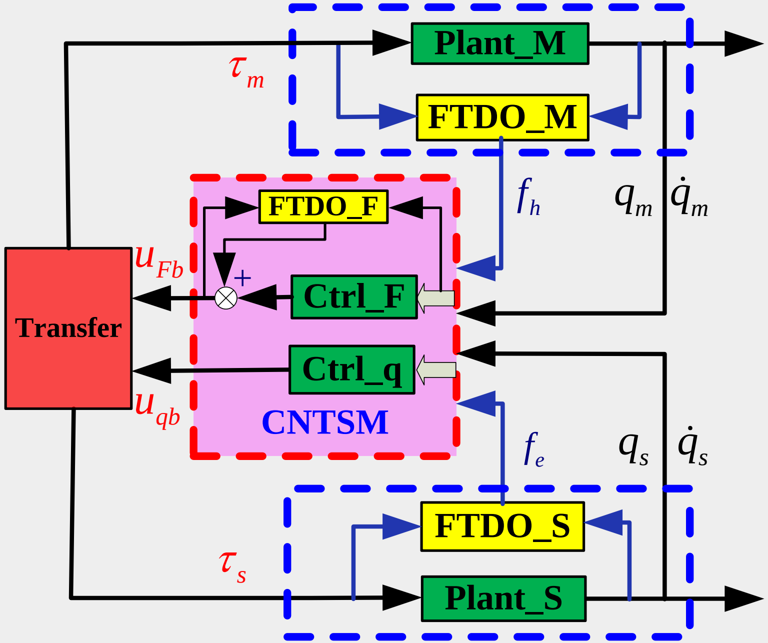
- C. D. Johnson, “A new approach to adaptive control,” in Control and Dynamic Systems V27: Advances in Theory and Applications, vol. 27. USA: Academic, 1988, pp. 1–69.
- C.D Johnson, Adaptive controller design using disturbance-accommodation techniques. Int. J. Control. 42(1),pp.193-210, 1985

DOBC and Adaptive control

- Inner disturbance observer loop acts as an adaption mechanism under uncertainty.
- Estimate the total difference between the nominal model and the physical system, including both structured or unstructured uncertainty.
- Degraded performance for structured uncertainty
- More **robust** than most of adaptive control algorithms.
- A “crude” adaptive control mechanism.
- ???

Applications

Robotic Manipulator and Remote Operation

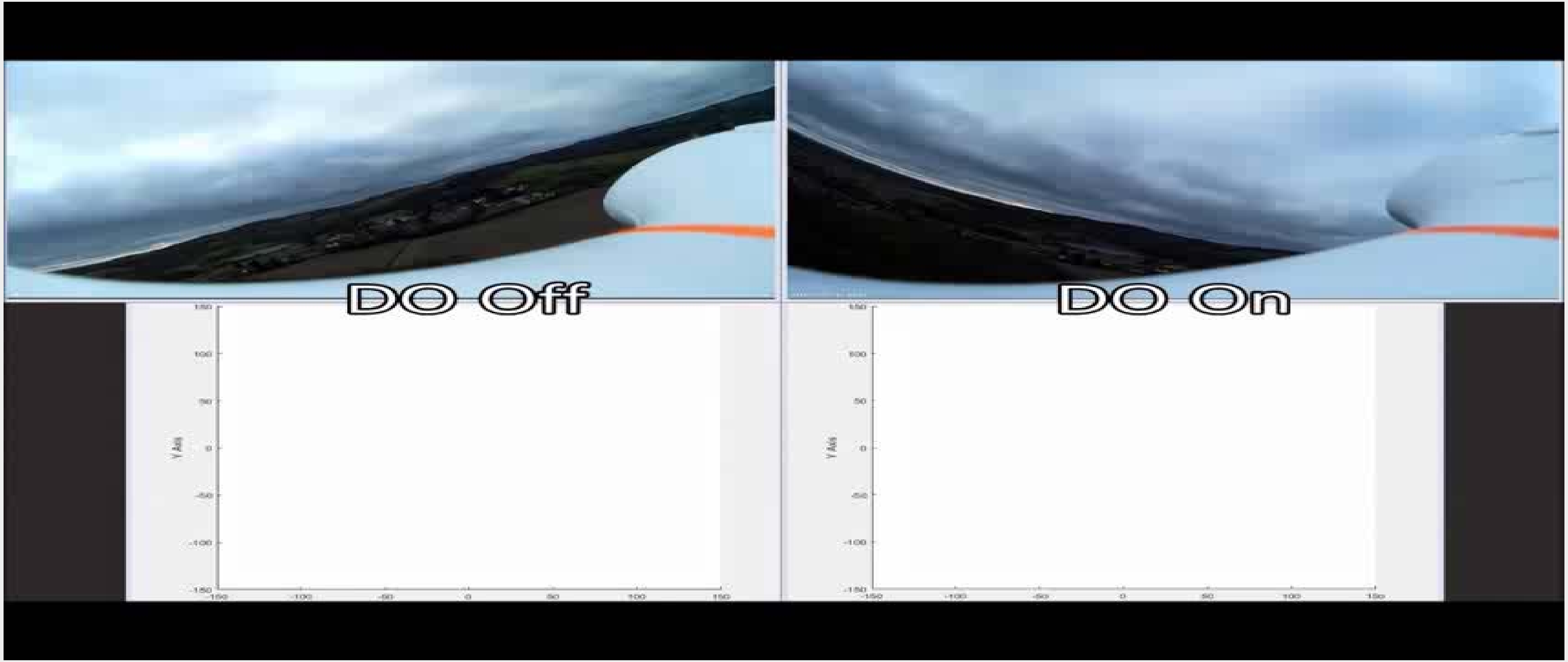


W.-H. Chen, D.J. Ballance, P.J. Gawthrop and J. O'Reilly. A nonlinear disturbance observer for robotic manipulators. IEEE Transactions on Industrial Electronics, 2000.

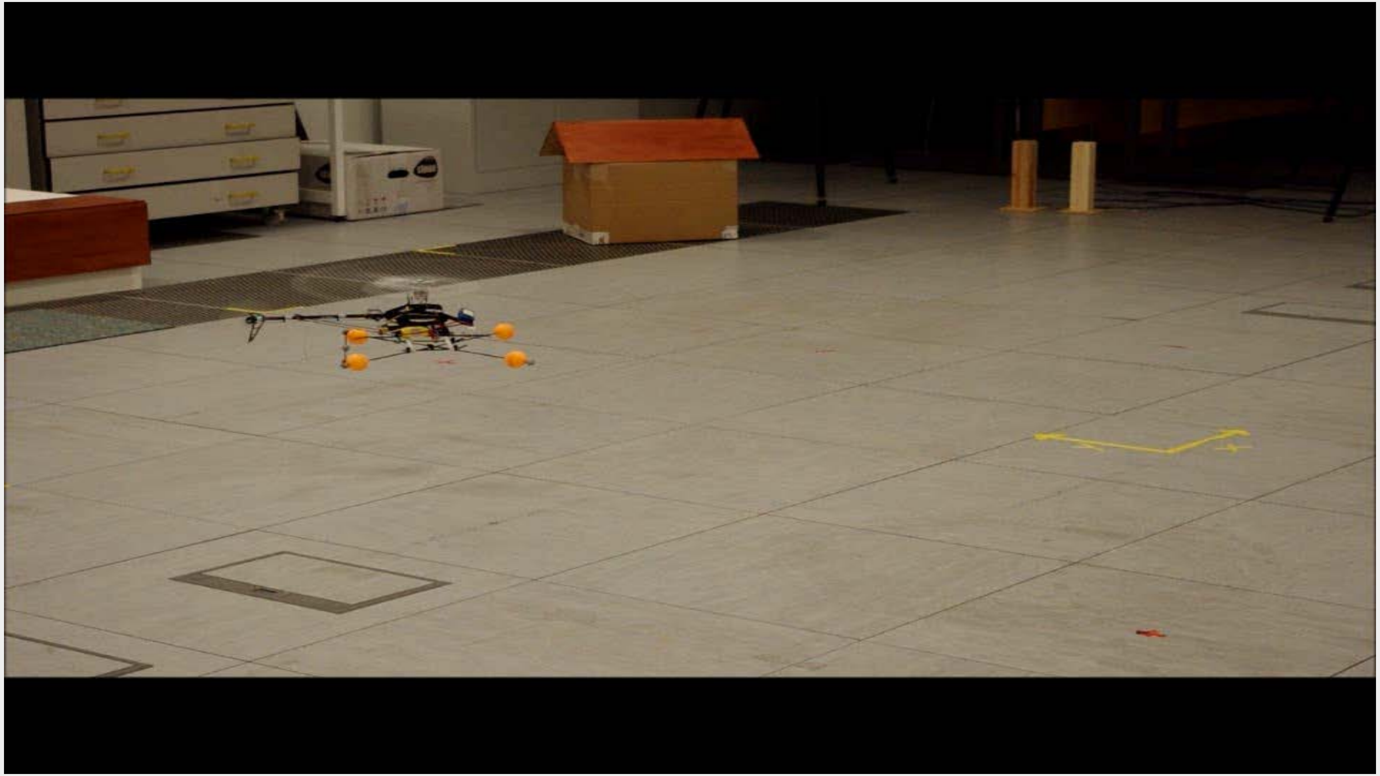
Bilateral force control; touching/haptic

Flight test of DOBC algorithm (2006)

Flight test results (27th Nov, 2017)



Flight test of DOBC algorithm (2008)



DOBC: Challenges

Stability Analysis of DOBC for *<u>Uncertain</u>* Nonlinear Systems

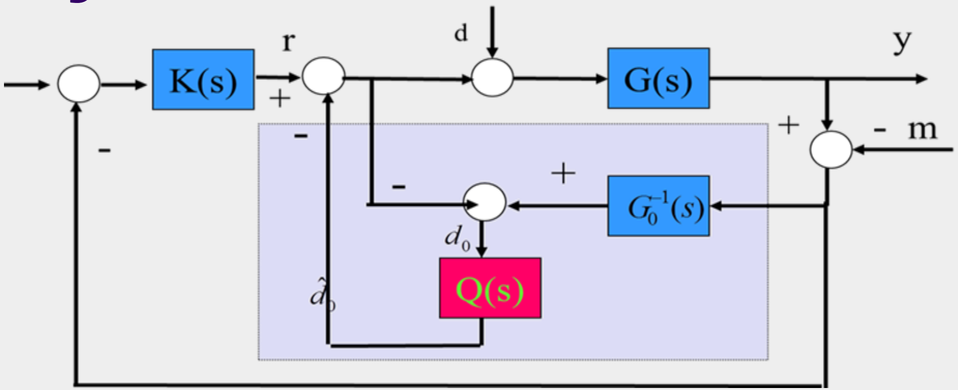
- Stability analysis of DOBC for nonlinear systems with external disturbance has been well established
- Equivalent disturbance due to uncertainty is a function of state– coupling effect.

$$\dot{x} = f(x) + \Delta f(x) + [g(x) + \Delta g(x)]u + g_1(x)w$$

- Two related questions:
  - For a given level of uncertainty, under what condition the closed loop system under DOBC is stable?
  - For a given DOBC, under what level of uncertainty the closed-loop system remains stable?

W.-H. Chen, J. Yang and Z Zhao (2016). Robust Control of Uncertain Nonlinear Systems: A Nonlinear DOBC approach. ASME J. of Dynamics, Measurement and Control. Vol.138, No.7, DS-14-1436

Performance recovery



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- G. Park, H. Shim, and Y Joo. Recovering Nominal Tracking Performance in an Asymptotic Sense for Uncertain Linear Systems. SIAM J. Control Optim., 56(2), 700–722, 2018
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Nonlinear systems with states not being measurable

H Lu, C Liu, L Guo, and W-H Chen (2015). Flight Control Design for Small-Scale Helicopter Using Disturbance-Observer-Based Backstepping, Journal of Guidance, Control, and Dynamics, 38(11), pp.2235-2240

Key Features of DOBC

- **Flexible structure:** Separate conflict design tasks
  - Tracking performance vs disturbance attenuation
  - Nominal performance vs robustness
- **Less conservativeness**. Not a worst case-based design. Nominal performance recovered.
- **Two step** design process: “separation principle”
  - **“Patch” feature**. Add to an **existing** feedback controller to improve disturbance rejection and robustness.
- Complimentary to robust control and nonlinear control

References

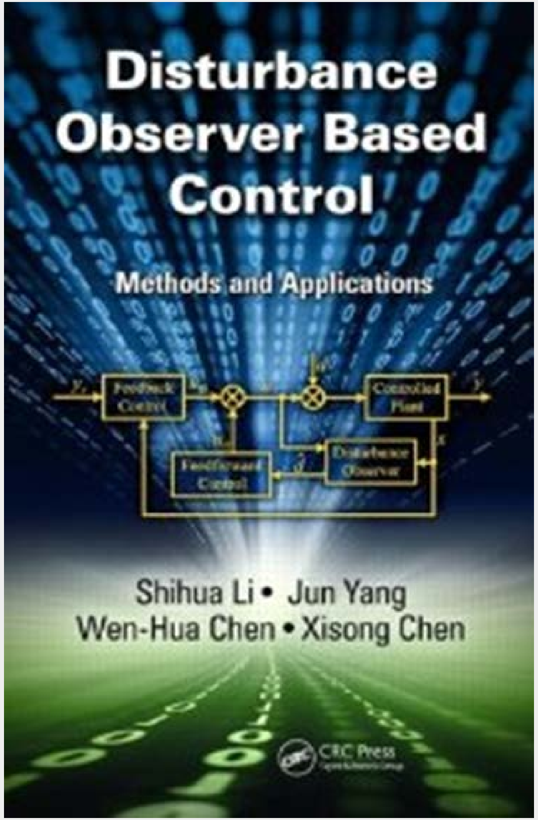
- W.-H Chen, J. Yang, L Guo and S. Li. *Disturbance observer based control and related methods: an overview*. IEEE Transactions on Industrial Electronics. Vol. 63, No. 2, pp.1083-1095, 2016.

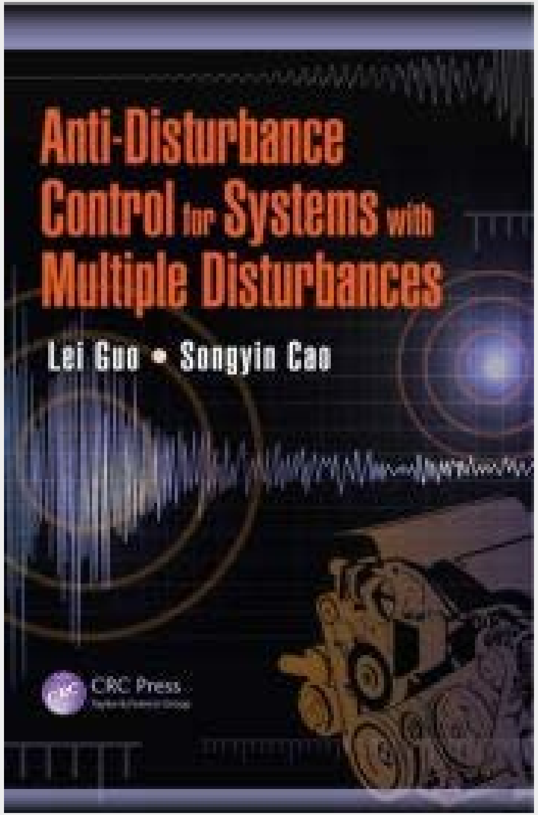
- J Yang, W-H Chen, S Li, L Guo and Y Yan. *Disturbance/ Uncertainty Estimation and Attenuation Techniques in PMSM Drives–A Survey*. IEEE Transactions on Industrial Electronics. Vol. 64(4), pp.3273-3285, 2017.

- **Special Section on Advances in Disturbance/uncertainty estimation and attenuation. *IEEE Transactions on Industrial Electronics*. Vol.62, No.9, pp.5658-5980. Edited by W-H Chen, K Ohnishi and L Guo. 2015.**

- **Special issue on Disturbance Observer and Its Applications. *Transactions on the Institution of Measurement and Control*, Vol.38, No.6, pp.621-792. Edited by J Yang, W-H Chen and Z Ding. 2016.**

Books


Disturbance Observer Based Control
Methods and Applications
Shihua Li • Jun Yang
Wen-Hua Chen • Xisong Chen
CRC Press


Anti-Disturbance Control for Systems with Multiple Disturbances
Lei Guo • Songyin Cao
CRC Press