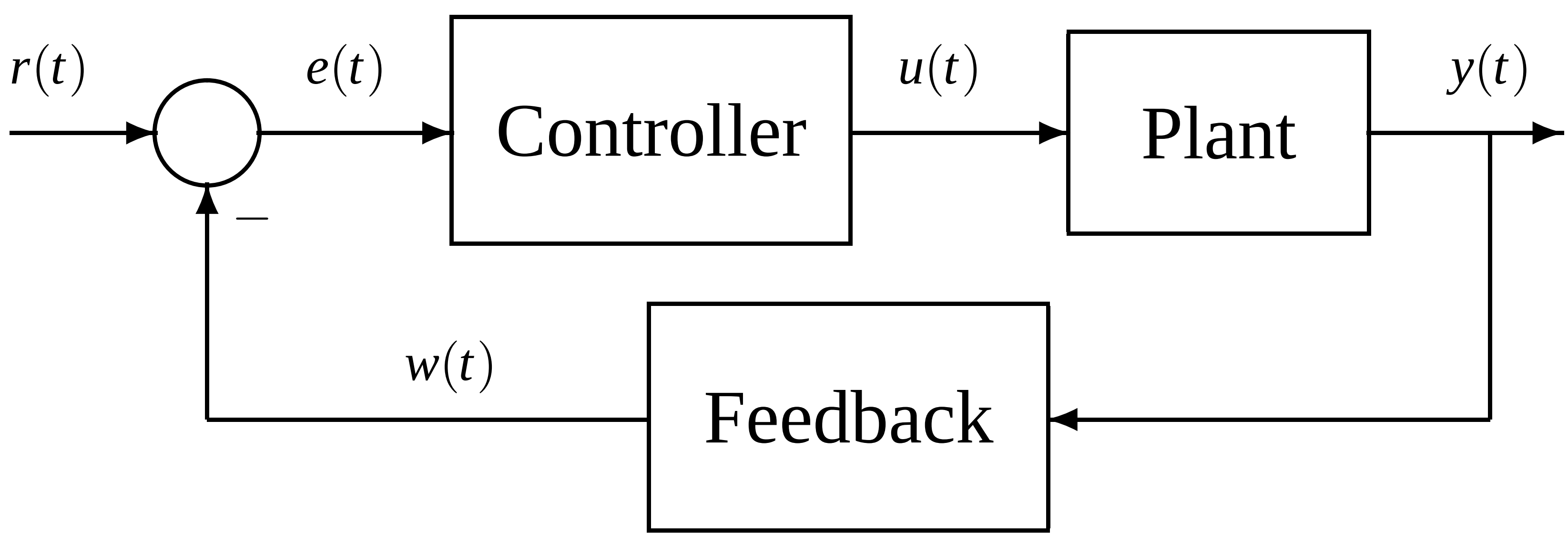
Adaptive Control
Basics and Applications

Dr. Dipankar Deb
Assistant Professor
IIT Guwahati

Feedback Control System



Issues of Automatic Feedback Control

- System modeling
- Control objectives

  stability, transient, tracking, optimality, robustness
- Parametric uncertainties

  payload variation, component aging, condition change
- Structural uncertainties

  component failure, unmodeled dynamics
- Environmental uncertainties

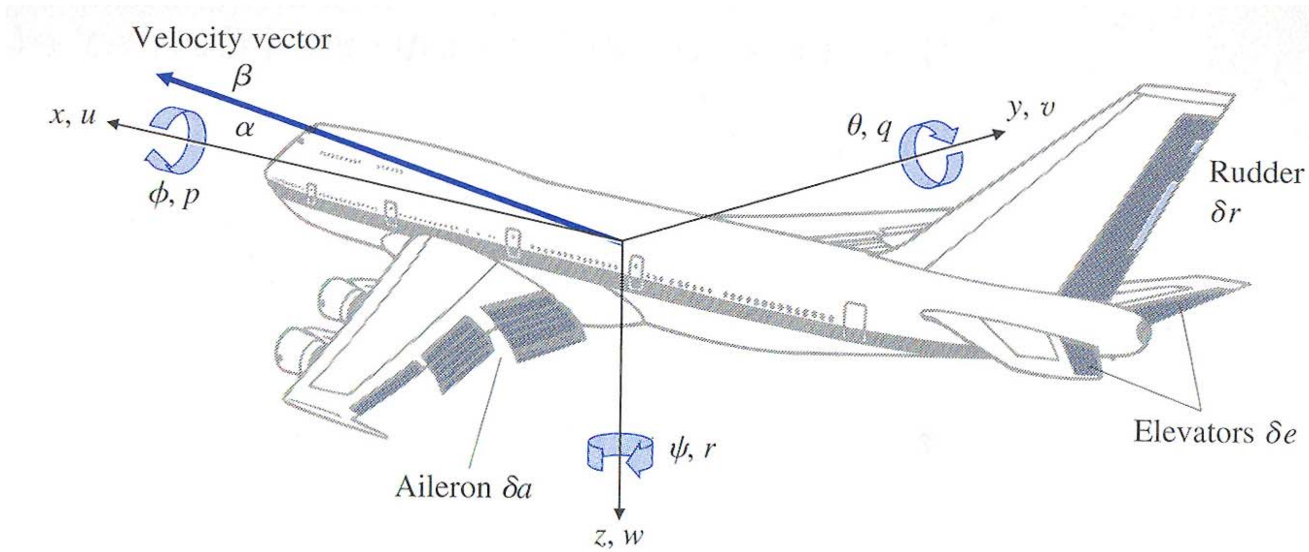
  external disturbances
- Nonlinearities

  smooth functions and nonsmooth (“hard”) characteristics

Adaptive Control Methodology

- Adapting to parametric uncertainties
- Robust to structural and environmental uncertainties
- Aimed at both stability (signal boundedness) and tracking
- Self-tuning of controller parameters
- Systematic design and analysis
- Real-time implementable
- Effective for failures and nonsmooth nonlinearities
- High potential for applications
- Attractive open and challenging issues

Aircraft Flight Control System Models



- State variables

x, y, z	$=$ position coordinates	ϕ	$=$ roll angle
u, v, w	$=$ velocity coordinates	θ	$=$ pitch angle
p	$=$ roll rate	ψ	$=$ yaw angle
q	$=$ pitch rate	β	$=$ side-slip angle
r	$=$ yaw rate	α	$=$ angle of attack

- Nonlinear equations of motion (in body axis)

  – Force equations:

$$
\begin{aligned}
m(\dot{u}+qw-rv) &= X - mg\sin\theta + T\cos\varepsilon \\
m(\dot{v}+ru-pw) &= Y + mg\cos\theta\sin\phi \\
m(\dot{w}+pv-qu) &= Z + mg\cos\theta\cos\phi - T\sin\varepsilon
\end{aligned}
$$

T: engine thrust; κ: thrust angle; X, Y, Z: aerodynamic forces

  – Moment equations:

$$
\begin{aligned}
I_x\dot{p} + I_{xz}\dot{r} + (I_z - I_y)qr + I_{xz}qp &= L \\
I_y\dot{q} + (I_x - I_z)pr + I_{xz}(r^2 - p^2) &= M \\
I_z\dot{r} + I_{xz}\dot{p} + (I_y - I_x)qp - I_{xz}qr &= N
\end{aligned}
$$

L, M, N: aerodynamic torques

- Linearized longitudinal equations

$$\begin{bmatrix} \dot{u} \\ \dot{w} \\ \dot{q} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} X_u & X_w & -W_0 & -g_0 \cos\theta_0 \\ Z_u & Z_w & U_0 & -g_0 \sin\theta_0 \\ M_u & M_w & M_q & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} u \\ w \\ q \\ \theta \end{bmatrix} + \begin{bmatrix} X_{\delta e} \\ Z_{\delta e} \\ M_{\delta e} \\ 0 \end{bmatrix} \delta e$$

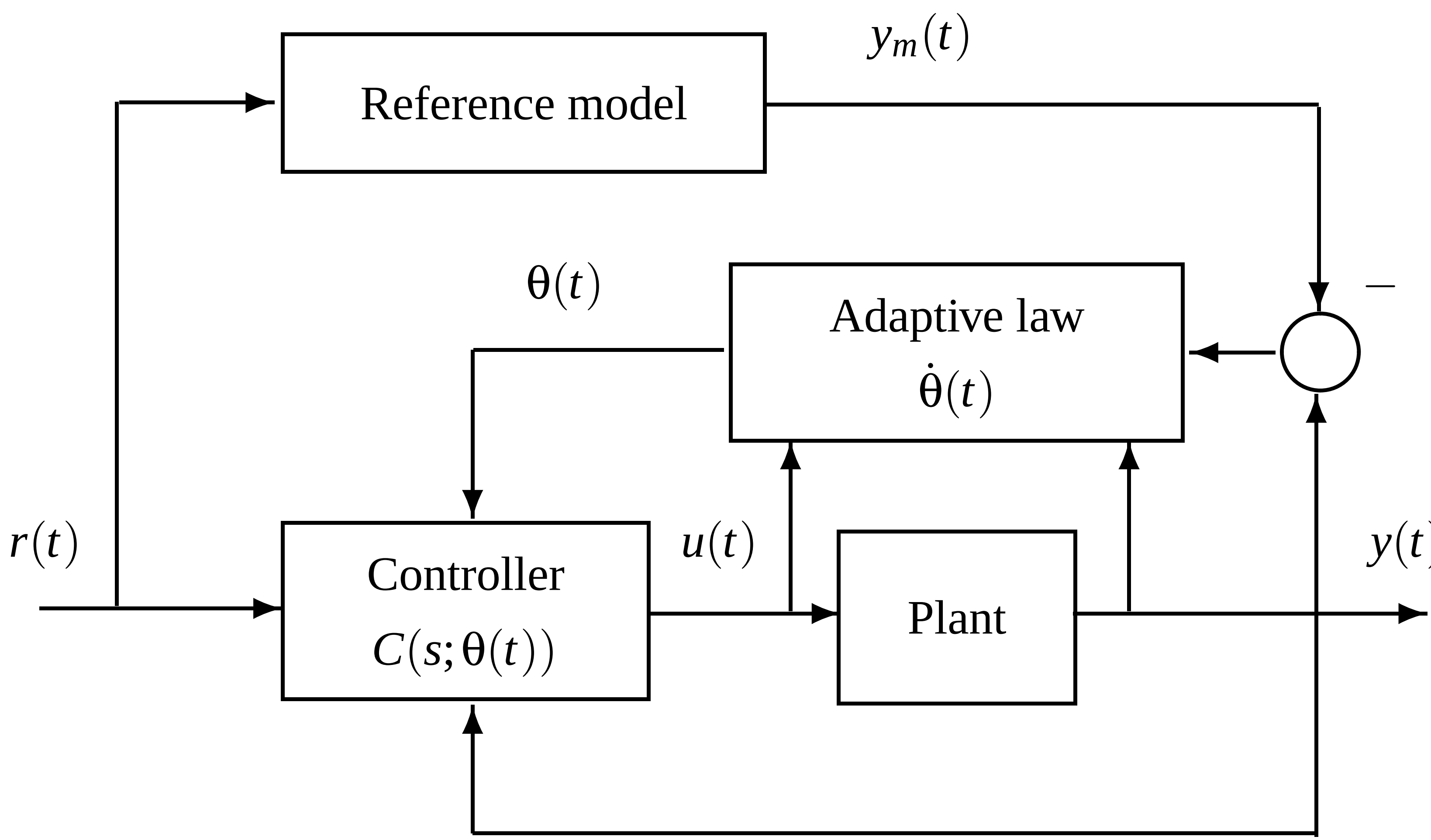
output = θ: pitch angle perturbation

- Linearized lateral equations

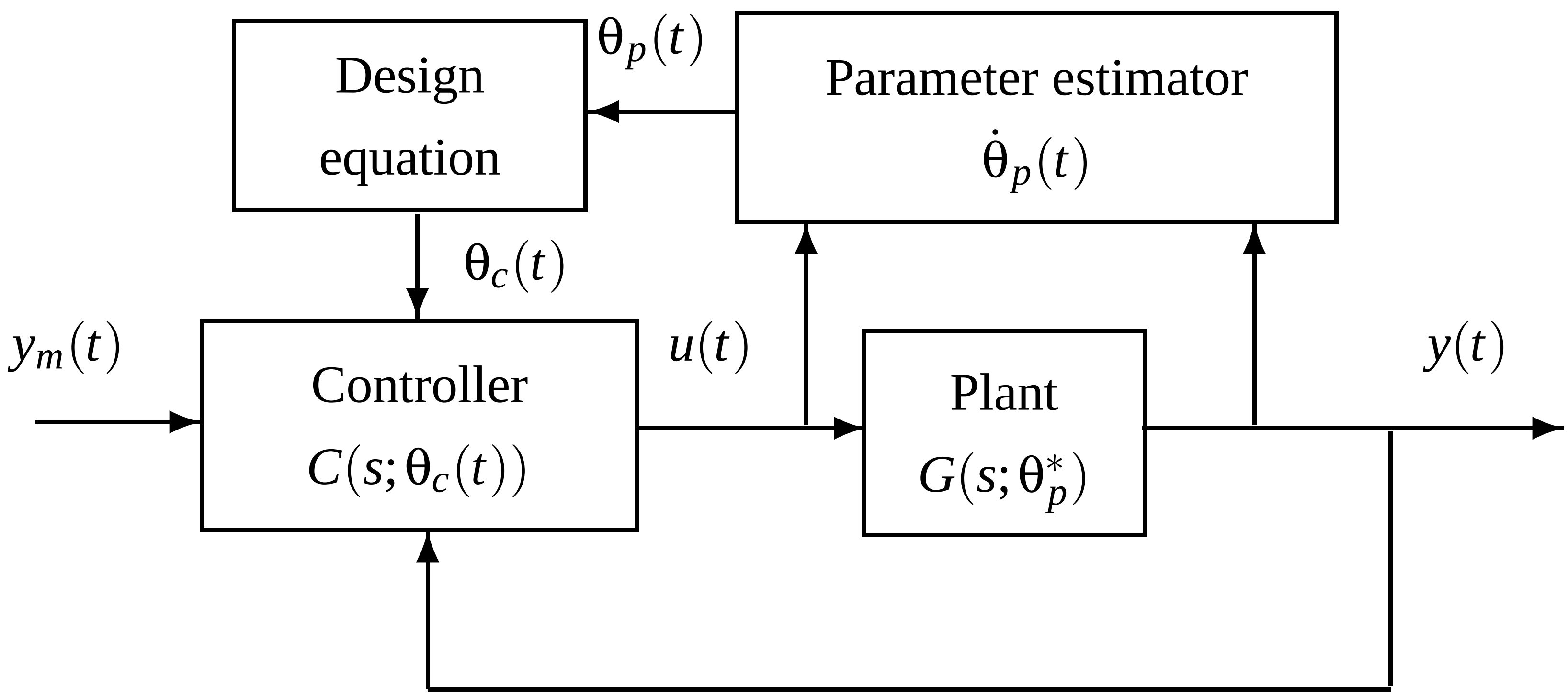
$$\begin{bmatrix} \dot{\beta} \\ \dot{r} \\ \dot{p} \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} Y_v & -U_0 & V_0 & g_0 \cos\theta_0 \\ N_v & N_r & N_p & 0 \\ L_v & L_r & L_p & 0 \\ 0 & \tan\theta_0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \beta \\ r \\ p \\ \phi \end{bmatrix} + \begin{bmatrix} Y_{\delta r} & Y_{\delta a} \\ N_{\delta r} & N_{\delta a} \\ L_{\delta r} & L_{\delta a} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta r \\ \delta a \end{bmatrix}$$

output = r: yaw rate perturbation

Direct Adaptive Control System



Indirect Adaptive Control System



Part I: Adaptive Control Theory

- Issues in Automatic Feedback Control
- Adaptive Control Methodology
- Direct Model Reference Adaptive Control
- Indirect Adaptive Pole Placement Control
- Multivariable Adaptive Control
- Nonlinear Adaptive Control
- Performance, Convergence and Robustness

Summary

- System uncertainties
  - common in control systems
  - challenges for system performance
- Adaptive control
  - handles system uncertainties effectively
  - ensures desired asymptotic performance
- Adaptive control theory
  - mature with systematic design procedures
  - developing with new challenges
- Adaptive control techniques
  - proved to be useful for many practical control problems
  - promising for new aerospace applications

Part II: Adaptive Control for Aerospace Systems

- Adaptive Control for Actuator and Sensor Nonlinearities
- Adaptive Inversion Control for Synthetic Jet Actuators
- Adaptive Actuator Failure Compensation
- Design for Linearized Longitudinal B737 Model
- Design for Linearized Lateral B737 Model
- Open Research Problems

Adaptive Control for Actuator and Sensor Nonlinearities

- Actuator and sensor nonlinearities
- Research motivation
- Adaptive inverse compensation
- Adaptive inverse control designs
- Adaptive control of sandwich nonlinear systems

Actuator and Sensor Nonlinearities

- Dead-zones

  hydraulic valves, servo motors

- Backlash

  gear-boxes, mechanical links

- Hysteresis

  piezoelectric materials

- Piecewise-linearity

  different operation conditions

- Non-linear characteristics

  non-uniform hardware properties

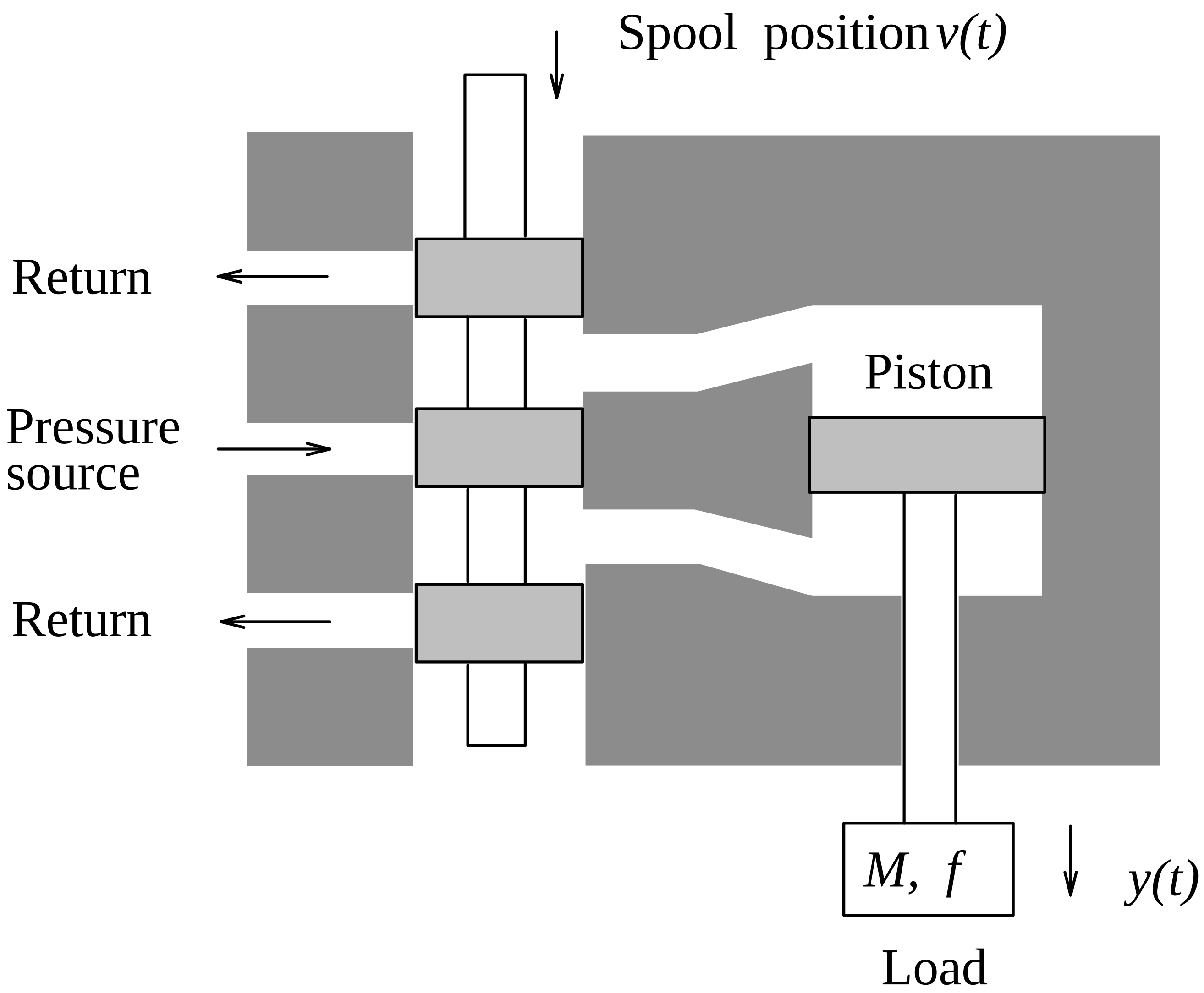


Figure 1: Dead-zone in a servo-valve.

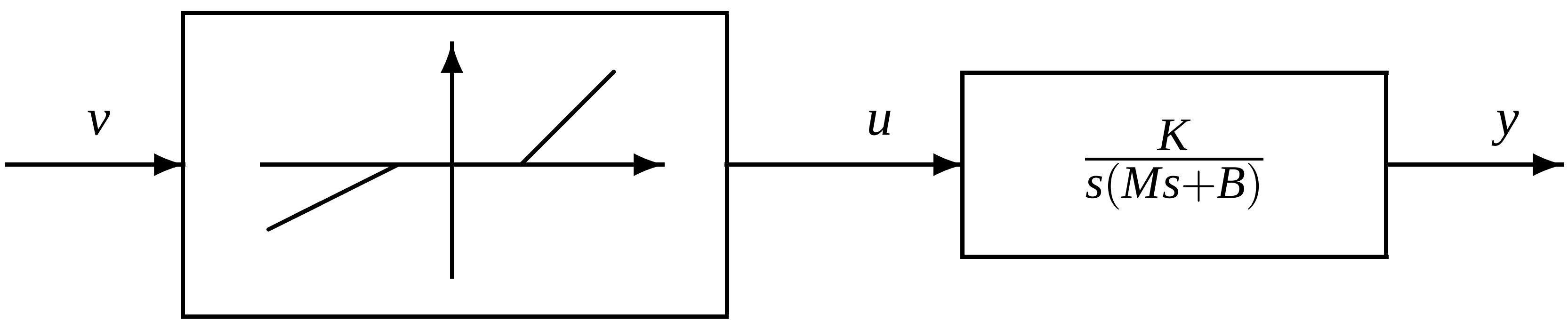


Figure 2: Block diagram of the servo-valve.

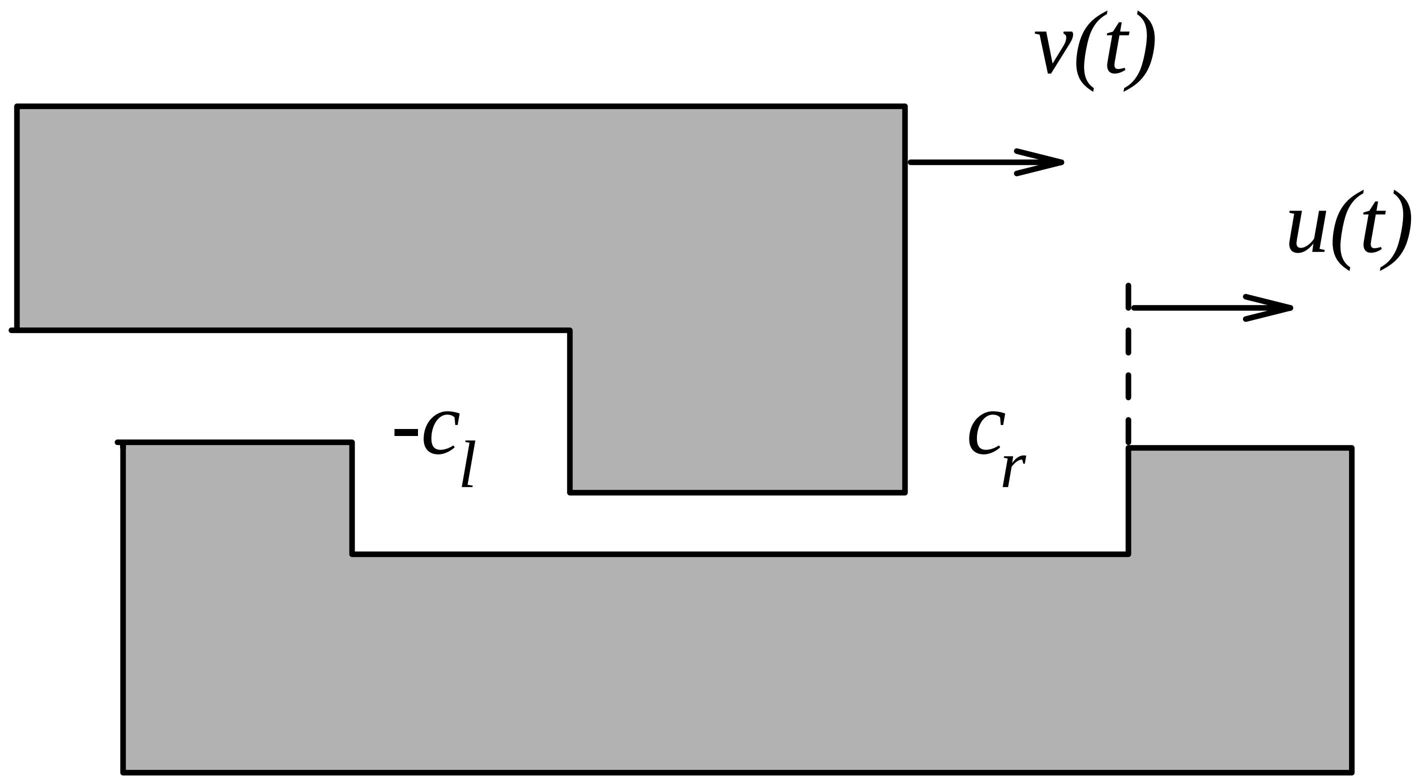


Figure 3: Backlash in mechanical links.

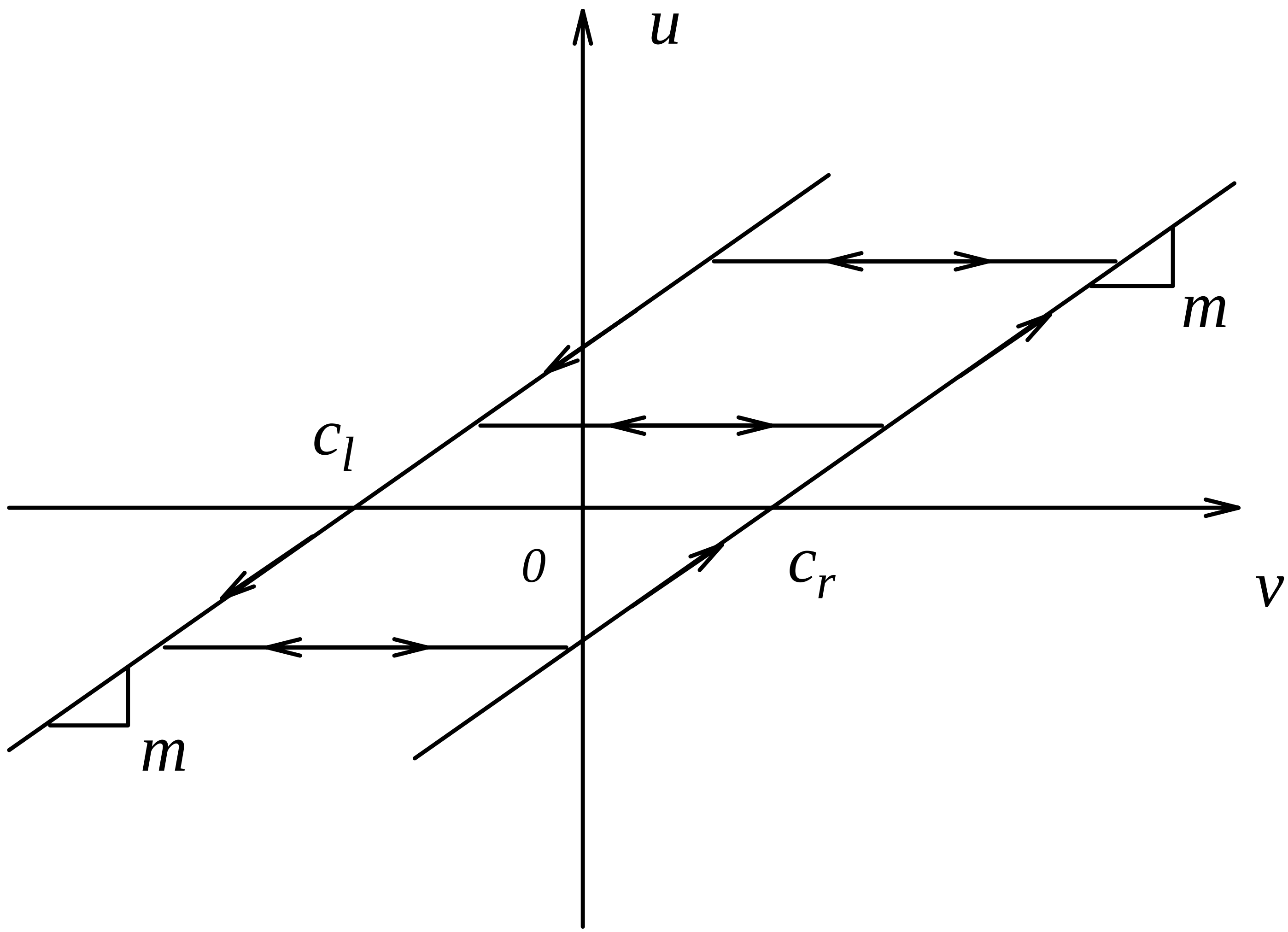


Figure 4: Backlash characteristic.

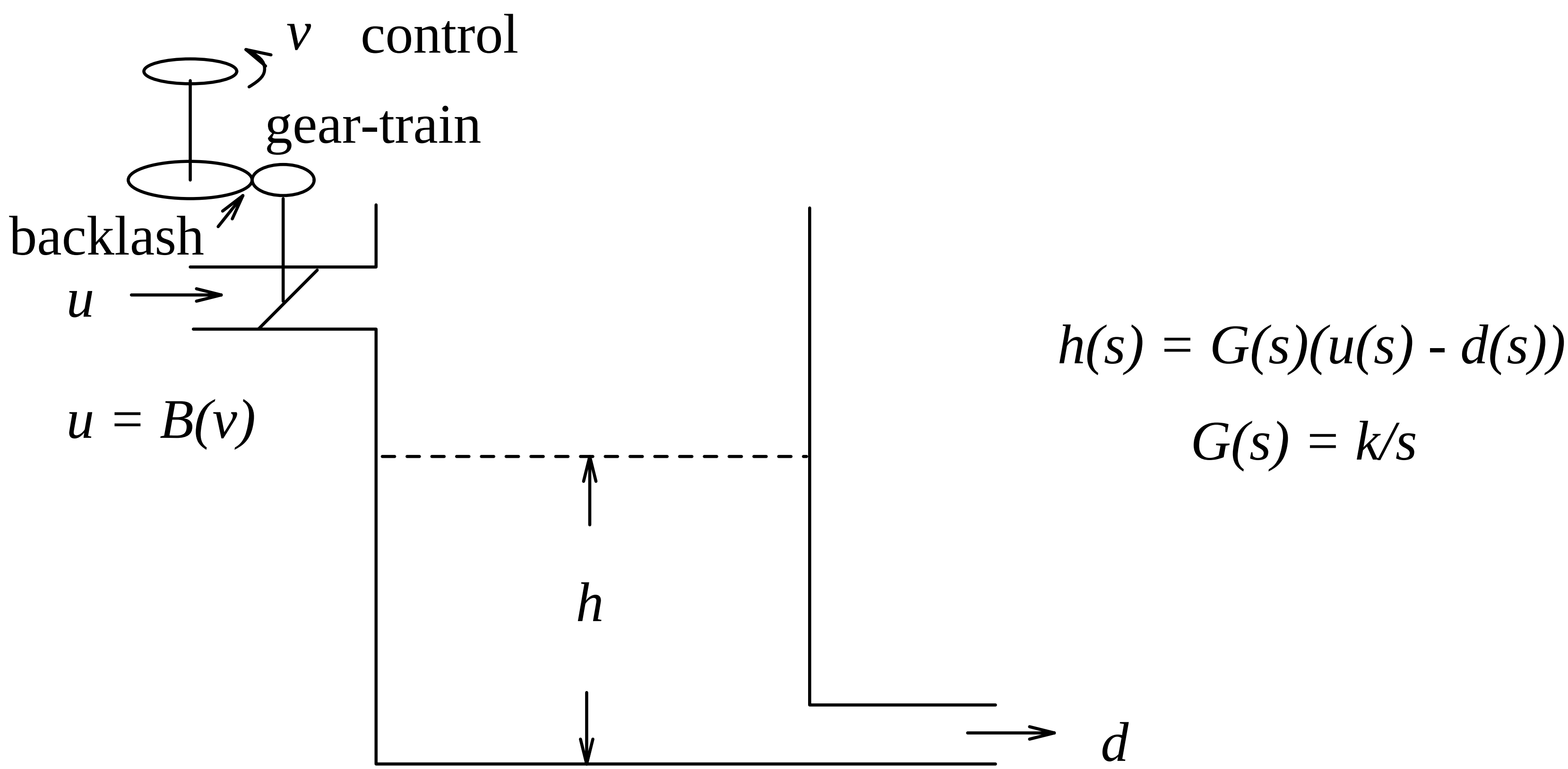


Figure 5: Backlash in the valve control mechanism of a liquid tank.

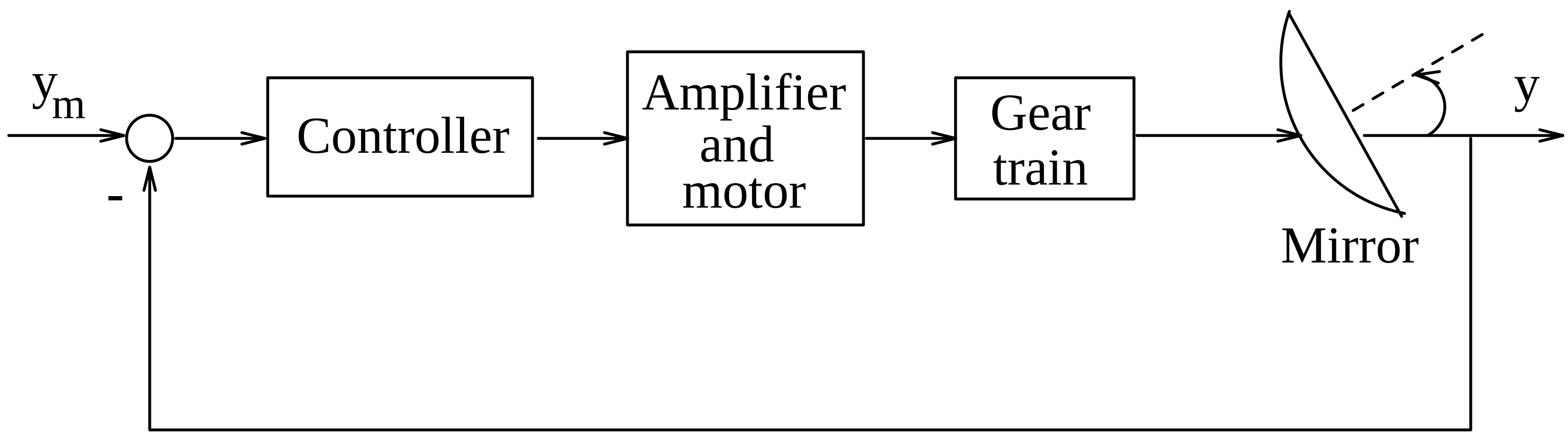


Figure 6: Output backlash in a positioning system.

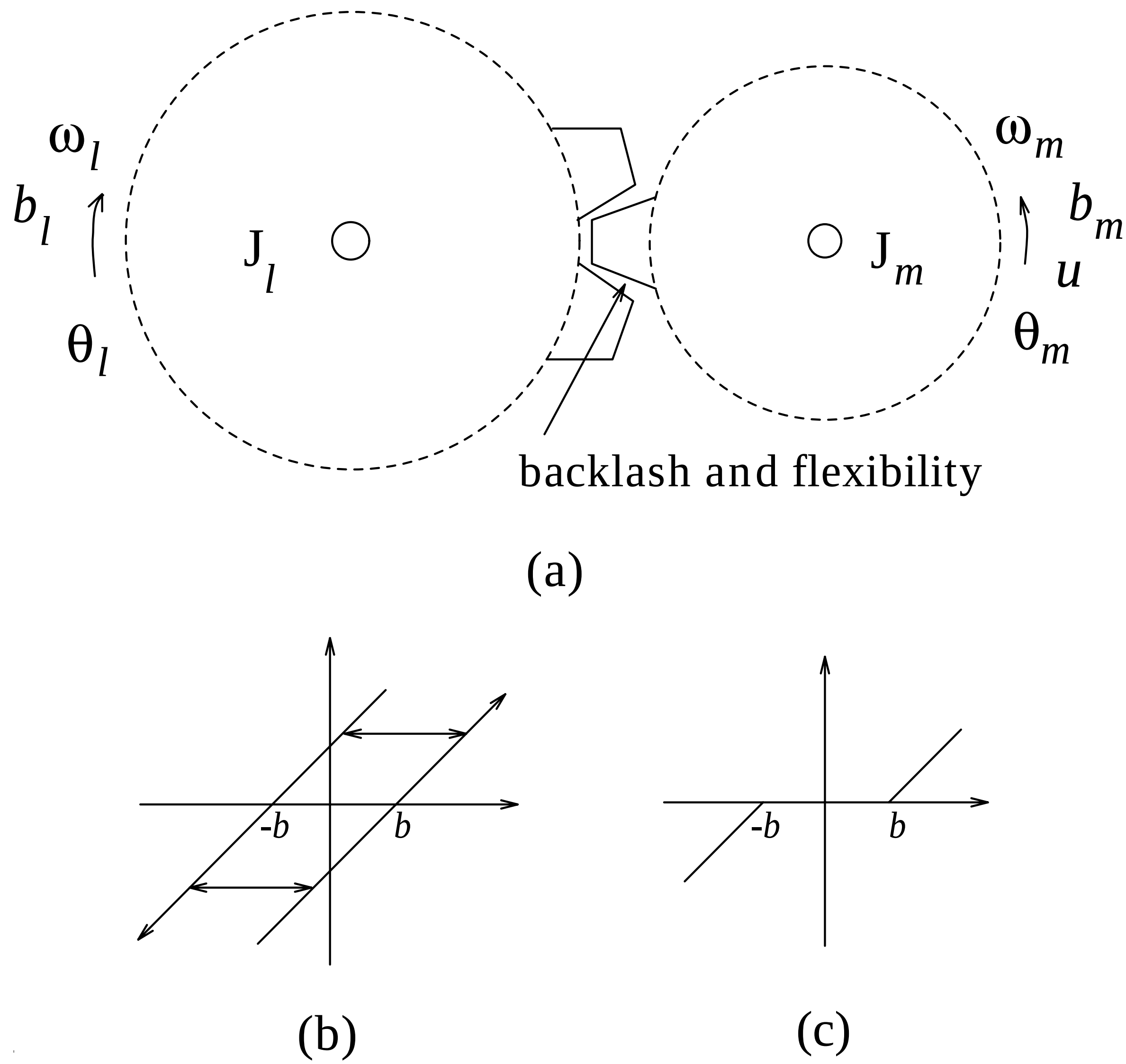


Figure 7: (a) Gear-train with backlash and flexibility; (b) Backlash for rigid gears: $\theta_l = B(\theta_m)$; (c) Dead-zone: $\delta = D(\theta_m - \theta_l)$.

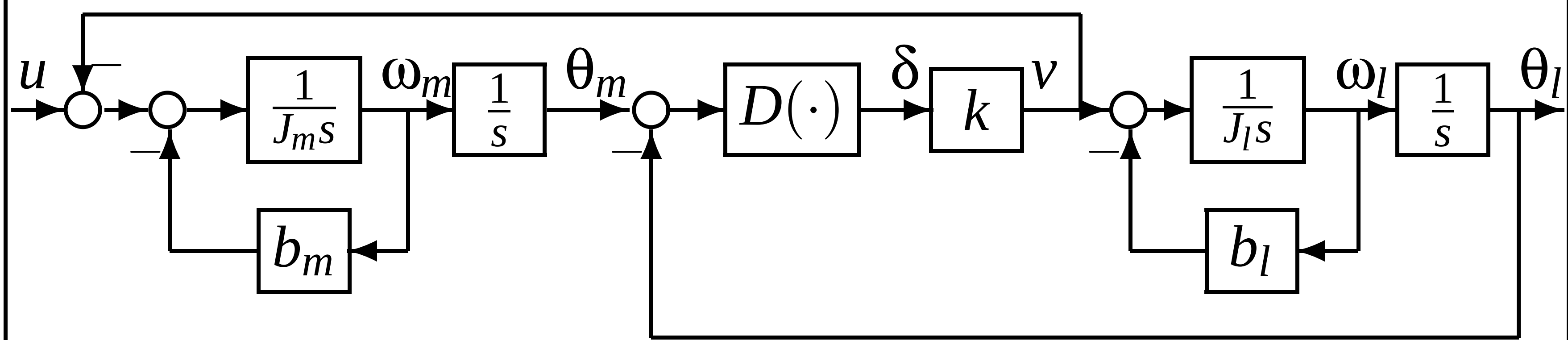


Figure 8: Sandwich nonlinear system with feedback blocks.

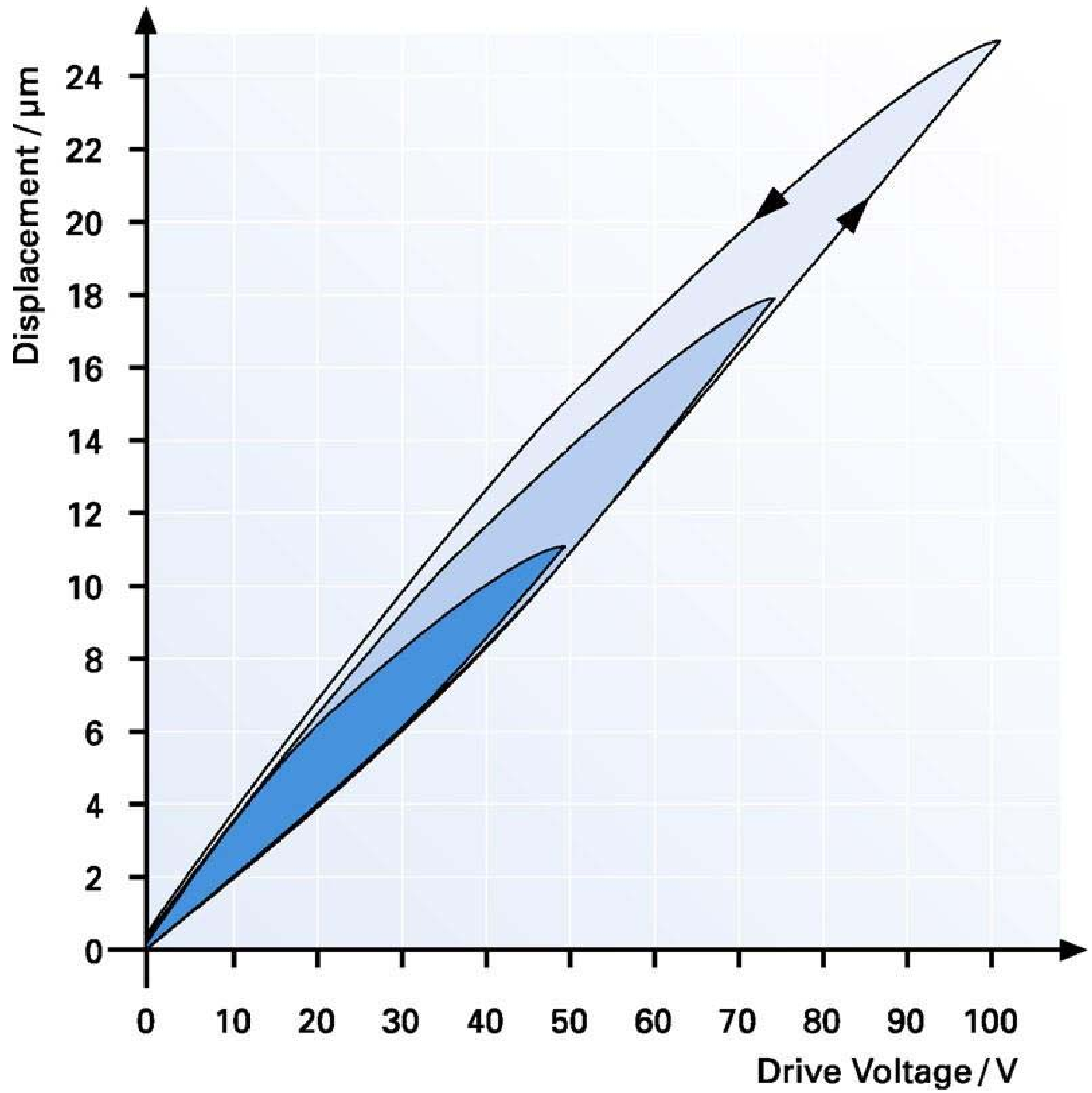


Figure 9: Hysteresis characteristic in precision control actuators.

Research Motivation

- Actuator and sensor nonlinearities limit performance
- Actuator and sensor nonlinearities are uncertain
- Adaptive compensation is a desirable choice
- Algorithm-based compensation is aimed at
  - reduction of system component cost
  - improvement of system performance.

Adaptive Inverse Compensation

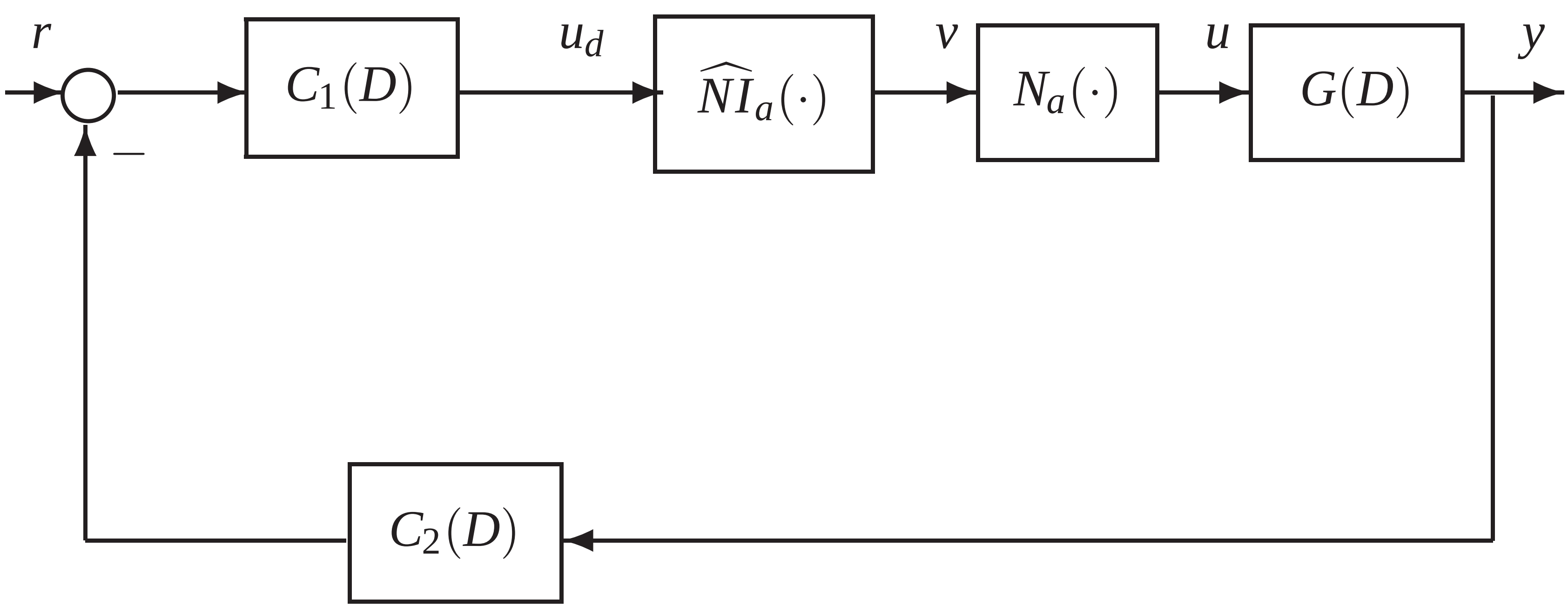


Figure 10: Adaptive inverse control for actuator nonlinearity.

Adaptive Inverse Control Designs

- Parametrization of nonlinearity $u(t) = N(v(t))$

$$u(t) = N(v(t)) = N(\theta^*; v(t)) = -\theta^{*T}\omega^*(t) + a_s^*(t)$$

- Parametrization of nonlinearity inverse $v(t) = \widehat{NI}(u_d(t))$

$$u_d(t) = -\theta^T(t)\omega(t) + a_s(t)$$

- Feedback control law for $u_d(t)$
  - based on model reference, pole placement, PID, lead/lag compensator, feedback linearization, or backstepping design
  - for $G(D)$ known or $G(D)$ unknown, SISO or MIMO
- Adaptive law for $\theta(t)$

$$\dot{\theta}(t) = -\frac{\Gamma\varepsilon(t)\zeta(t)}{m^2(t)} + f(t)$$

An Illustrative Example

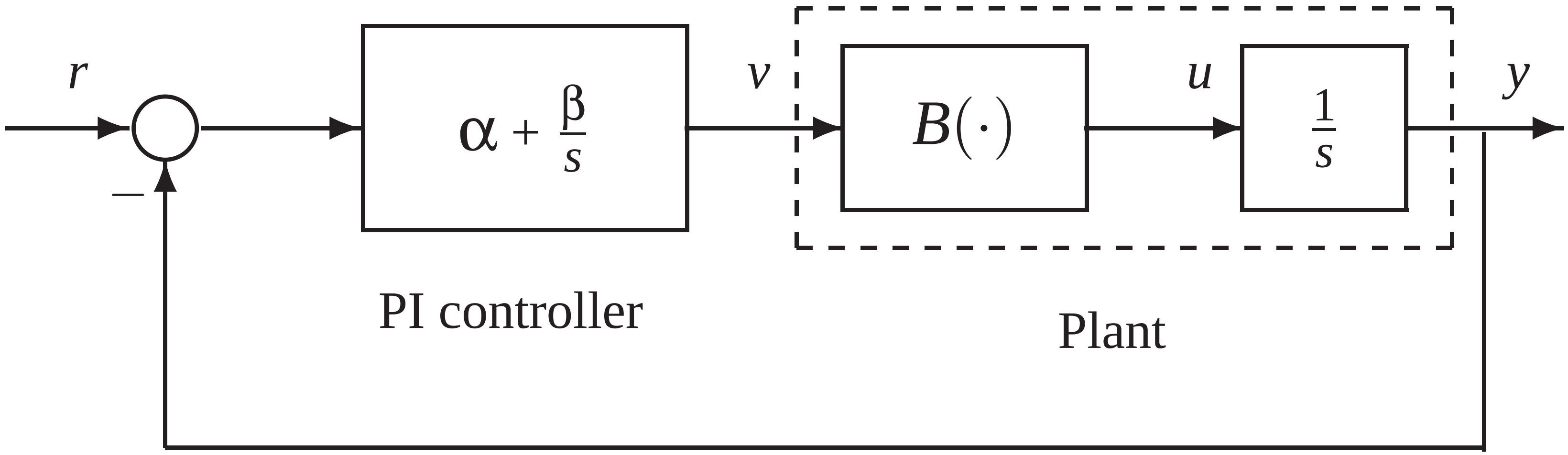
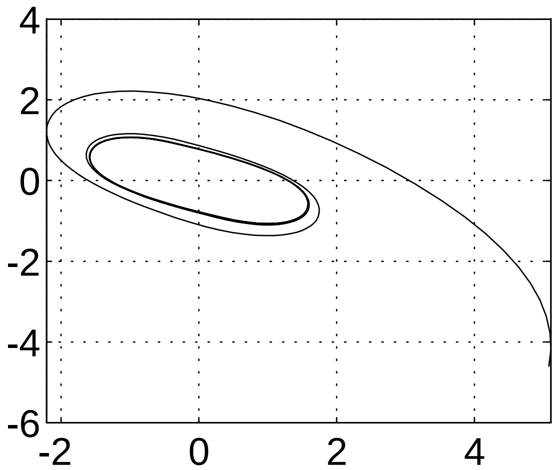
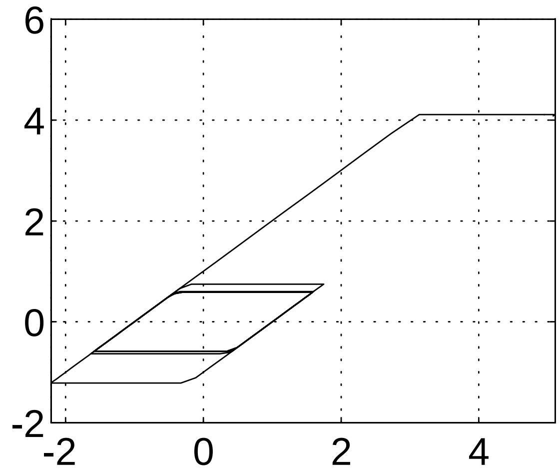


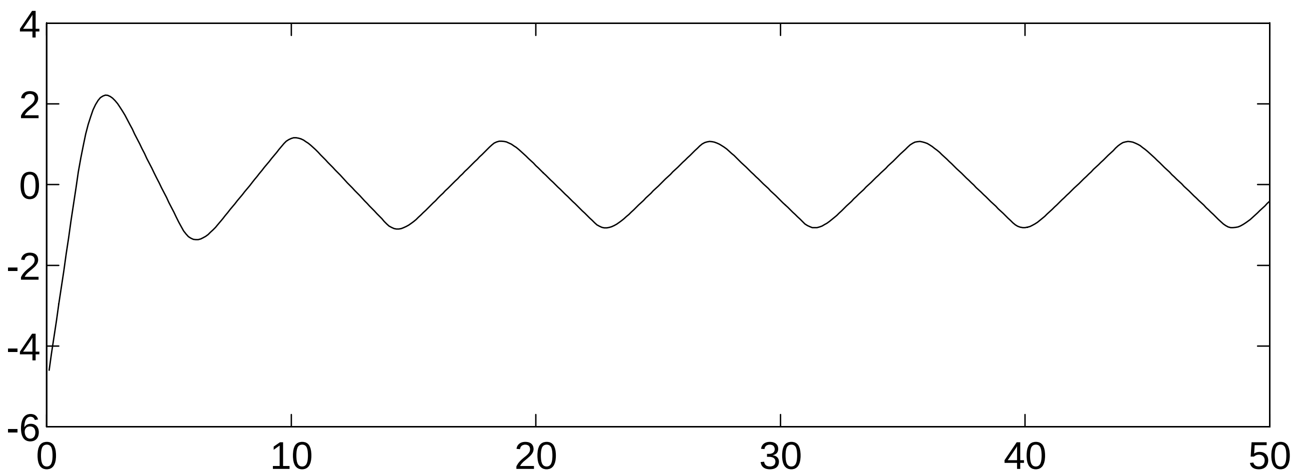
Figure 11: One-integrator plant with input backlash and PI controller.



(a) e(t) vs. v(t).



(b) u(t) vs. v(t).



(c) Tracking error e(t).

System response without backlash inverse

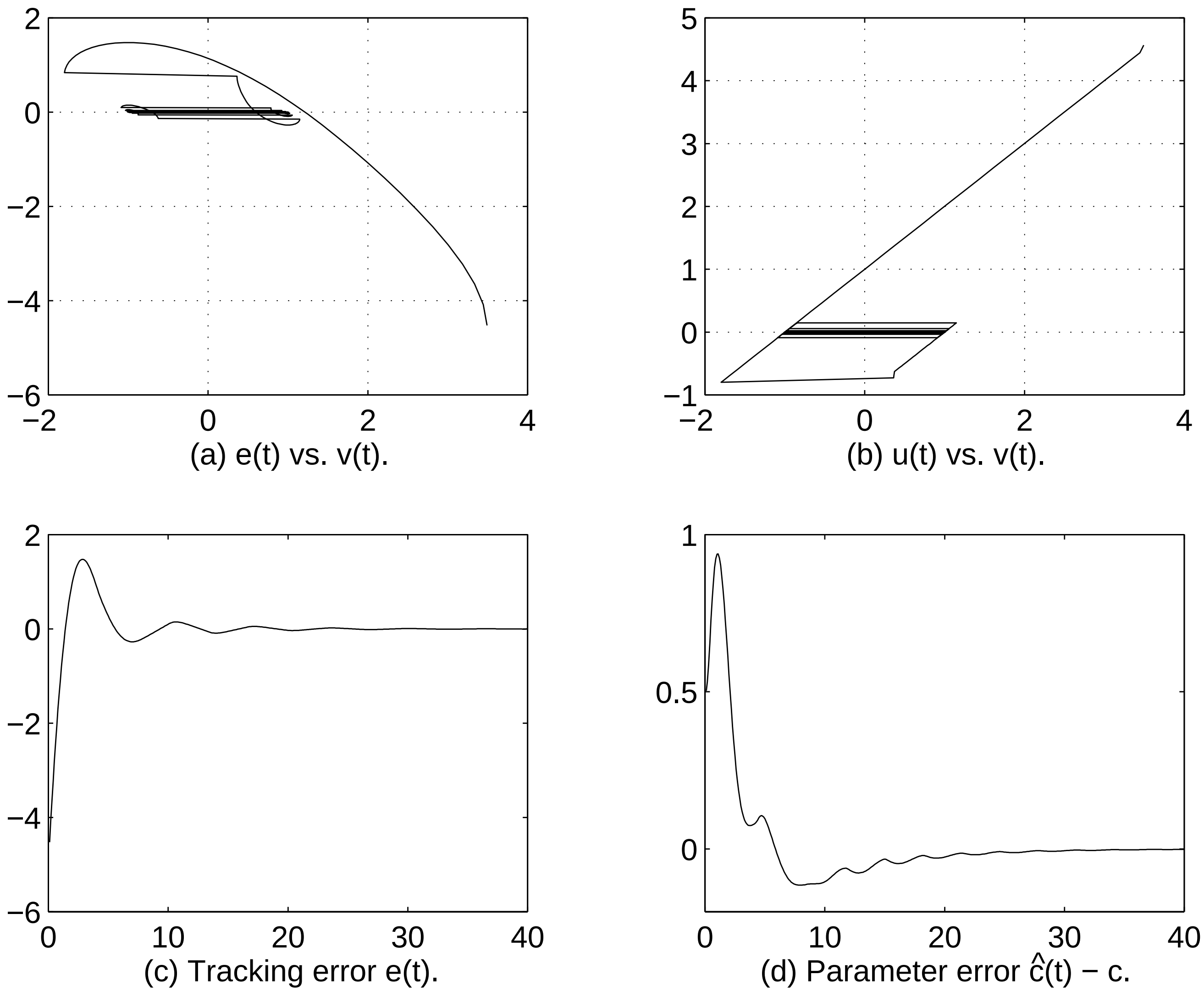


Figure 12: Adaptive backlash inverse control response.

Adaptive Inverse Control of Sandwich Systems

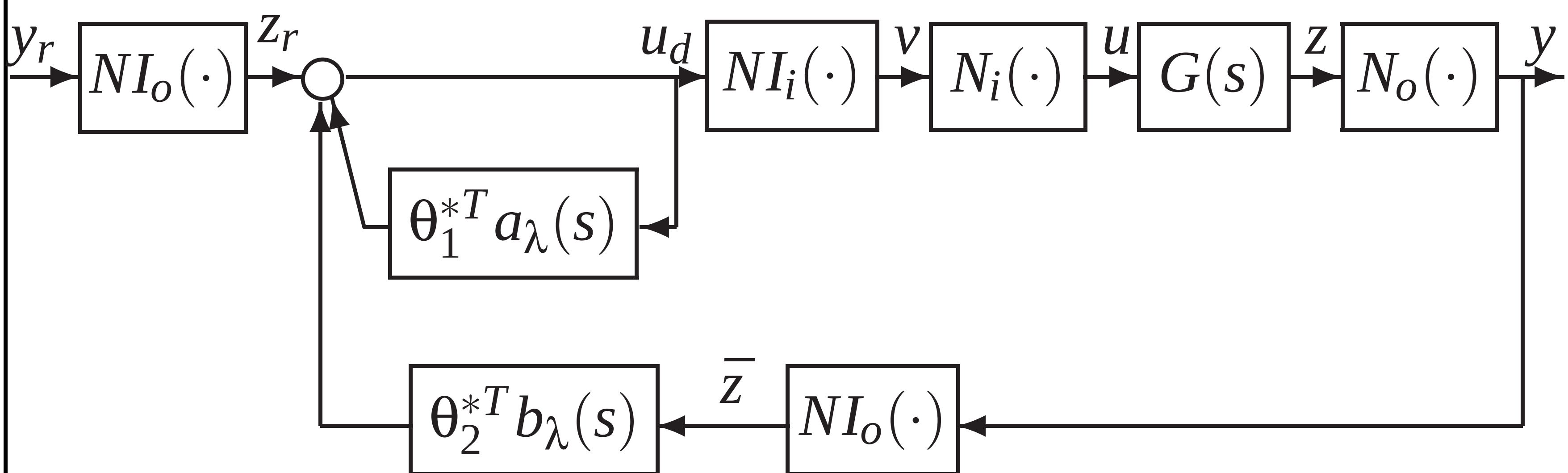


Figure 13: Adaptive compensation of actuator/sensor nonlinearities.

Adaptive Inverse Control for Synthetic Jet Actuators

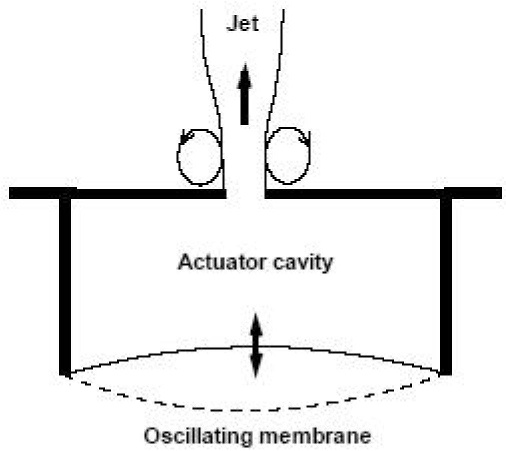
- Research motivation
- Synthetic jets for aircraft control
- Adaptive inverse approach
- Adaptive inverse control design and evaluation

Research Motivation

- Virtual shaping of airfoils using synthetic jets
- Synthetic jet actuators have unknown nonlinearities
- Adaptive inverse approach to cancel nonlinearities
- Adaptive feedback control for desired performance

Synthetic Jets for Aircraft Control

- **Physics of synthetic jet**



– piezo-electric sinusoidal voltage acts on diaphragm

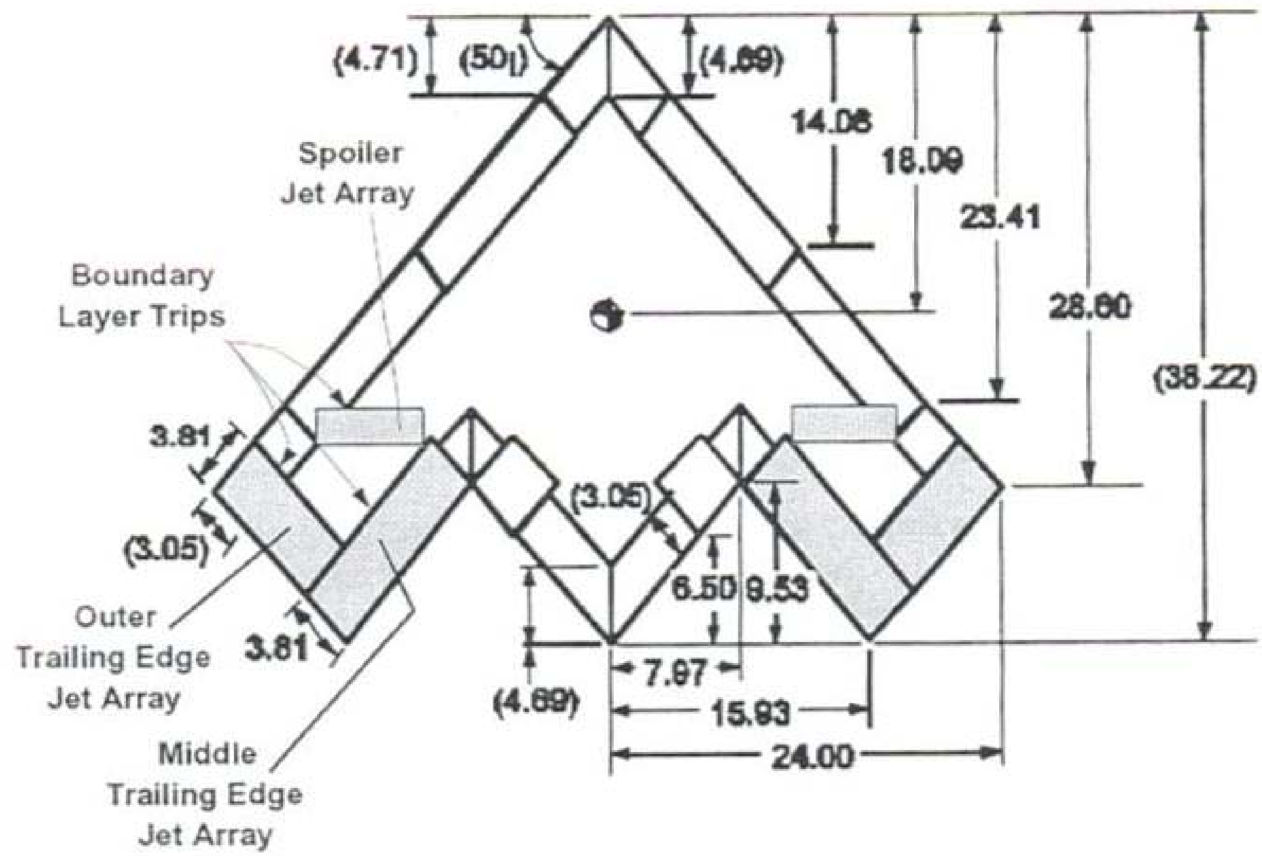
– diaphragm vibrations cause cavity pressure variations

– ejection and suction of air, creating vortices

– jet is synthesized by a train of vortices

– lift is produced on the airfoil—virtual shaping.

- Tailless aircraft with jets (top view)



- Mathematical model of synthetic jet actuators

$$u(t) = \theta_2^* - \frac{\theta_1^*}{v(t)} = N(v(t);\theta^*)$$

$u(t)$: equivalent virtual airfoil deflection (lift force)

$v = A_{pp}^2$: peak-to-peak voltage amplitude

$\theta^* = [\theta_1^*, \theta_2^*]^T$: unknown parameters dependent on many factors

- Control objective

adaptive compensation of $N(\cdot;\theta^*)$

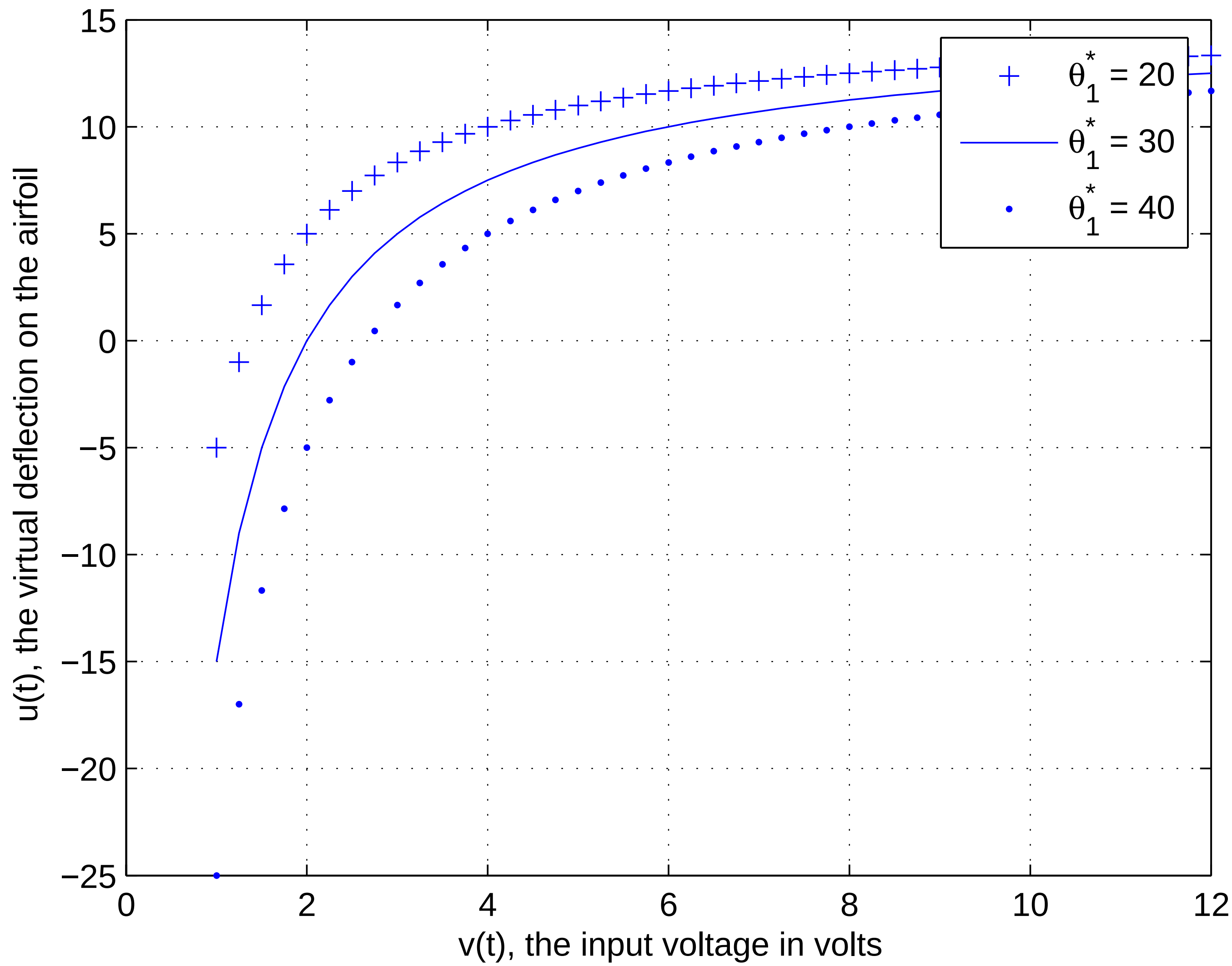
tracking control for aircraft flight trajectory

- Design strategy

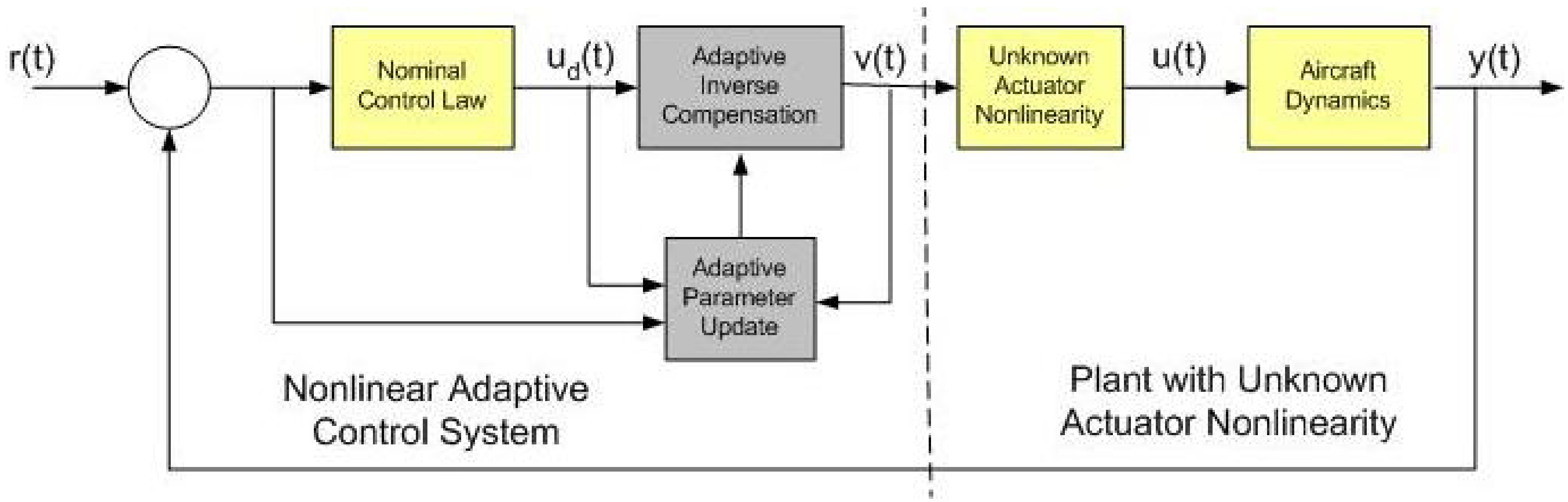
adaptive inversion of $N(\cdot;\theta^*)$

feedback control for aircraft dynamics

Variation of deflection with actuation voltage ($\theta_2^* = 15$)



Adaptive Inverse Approach



$u_d(t)$: Commanded Control Surface Deflection

$v(t)$: Synthetic Jet Array Input Signal

$u(t)$: Effective Virtual Surface Deflection

Adaptive Compensation Objective:

$u(t) \rightarrow u_d(t)$ which implies $y(t) \rightarrow r(t)$

- Nonlinearity parametrization

$$u(t) = N(\theta^*; v(t)) = -\theta^{*T}\omega(t),\ \omega(t) = [\frac{1}{v(t)}, -1]^T$$

- Nonlinearity inverse

$$v(t) = \widehat{NI}(u_d(t)) = \frac{\theta_1(t)}{\theta_2(t) - u_d(t)}$$

$$u_d(t) = -\theta^T(t)\omega(t),\ \theta = [\theta_1, \theta_2]^T$$

$u_d(t)$: a desired feedback control signal

- Control error

$$\begin{aligned} u(t) - u_d(t) &= \left(\frac{\theta_2(t) - u_d(t)}{\theta_1(t)}\right)(\theta_1(t) - \theta_1^*) - (\theta_2(t) - \theta_2^*) \\ &= (\theta(t) - \theta^*)^T \omega(t) \end{aligned}$$

Design Example: Linear Dynamics

- System model

$$\dot{x}(t) = Ax(t) + Bu(t)$$

- Feedback control signal

$$u_d(t) = -Kx(t) + r(t)$$

- Control error

$$u(t) - u_d(t) = (\theta(t) - \theta^*)^T \omega(t)$$

- Reference model

$$\dot{x}_r(t) = (A - BK)x_r(t) + Br(t)$$

- Error system

$$\dot{e}(t) = (A - BK)e(t) + B(\theta(t) - \theta^*)^T \omega(t), \; e(t) = x(t) - x_r(t)$$

- Adaptive laws

$$
\begin{aligned}
\dot{\theta}_i(t) &= g_i(t) + f_i(t) \\
g_1(t) &= -\gamma_1 e^T(t)PB\left(\frac{\theta_2(t) - u_d(t)}{\theta_1(t)}\right), \ \gamma_1 > 0 \\
g_2(t) &= \gamma_2 e^T(t)PB, \ \gamma_2 > 0 \\
f_i(t) &= \begin{cases} 0 & \text{if } \theta_i(t) > \theta_i^a, \text{ or} \\ & \text{if } \theta_i(t) = \theta_i^a \text{ and } g_i(t) \geq 0 \\ -g_i(t) & \text{otherwise} \end{cases}
\end{aligned}
$$

initial estimates $\theta_i(0)$ of θ_i^*: $\theta_i(0) \geq \theta_i^a > 0$

- Assumption (no saturation): $u_d(t) < \theta_2(t)$
- Closed-loop system properties
  - boundedness of $x(t)$ and $\theta(t)$, and $\theta_i(t) > \theta_i^a$
  - asymptotic tracking: $\lim_{t\to\infty}(x(t) - x_r(t)) = 0$.

Simulation Results

- System state variables

  lateral velocity: $x_1(t)$ roll rate: $x_2(t)$

  yaw rate: $x_3(t)$ roll angle: $x_4(t)$

- System model

$$A = \begin{bmatrix} -0.0134 & 48.5474 & -632.3724 & 32.0756 \\ -0.0199 & -0.1209 & 0.1628 & 0 \\ -0.0024 & -0.0526 & -0.0252 & 0 \\ 0 & 1 & 0.0768 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ -0.0431 \\ -0.0076 \\ 0 \end{bmatrix}$$

D. L. Raney, R. C. Montgomery, L. L. Green and M. A. Park, “Flight Control using Distributed Shape-Change Effector Arrays,” *AIAA* paper No. 2000-1560, April 3-6, 2000

- Control gain K
  - LQR design with $Q = I_4$, $R = 10$
  - $K = \begin{bmatrix} 1.0113 & -77.1793 & 115.8959 & -9.1691 \end{bmatrix}$

$$P = \begin{bmatrix} 0.751 & 14.980 & -159.812 & 8.2617 \\ 14.980 & 27181.878 & -138979.668 & 7843.345 \\ -159.813 & -138979.668 & 723352.800 & -40670.052 \\ 8.262 & 7843.345 & -40670.052 & 2301.187 \end{bmatrix}$$

- Reference signal:

$$r(t) = \begin{cases} 1.5\sin(t) & 0 \le t \le 60 \\ 1.5\sin(t) + 3\sin(2t) & t \ge 60 \end{cases}$$

- Adaptation gains: $\gamma_1 = 1$, $\gamma_2 = 2$

Simulation I: Adaptive inverse performance

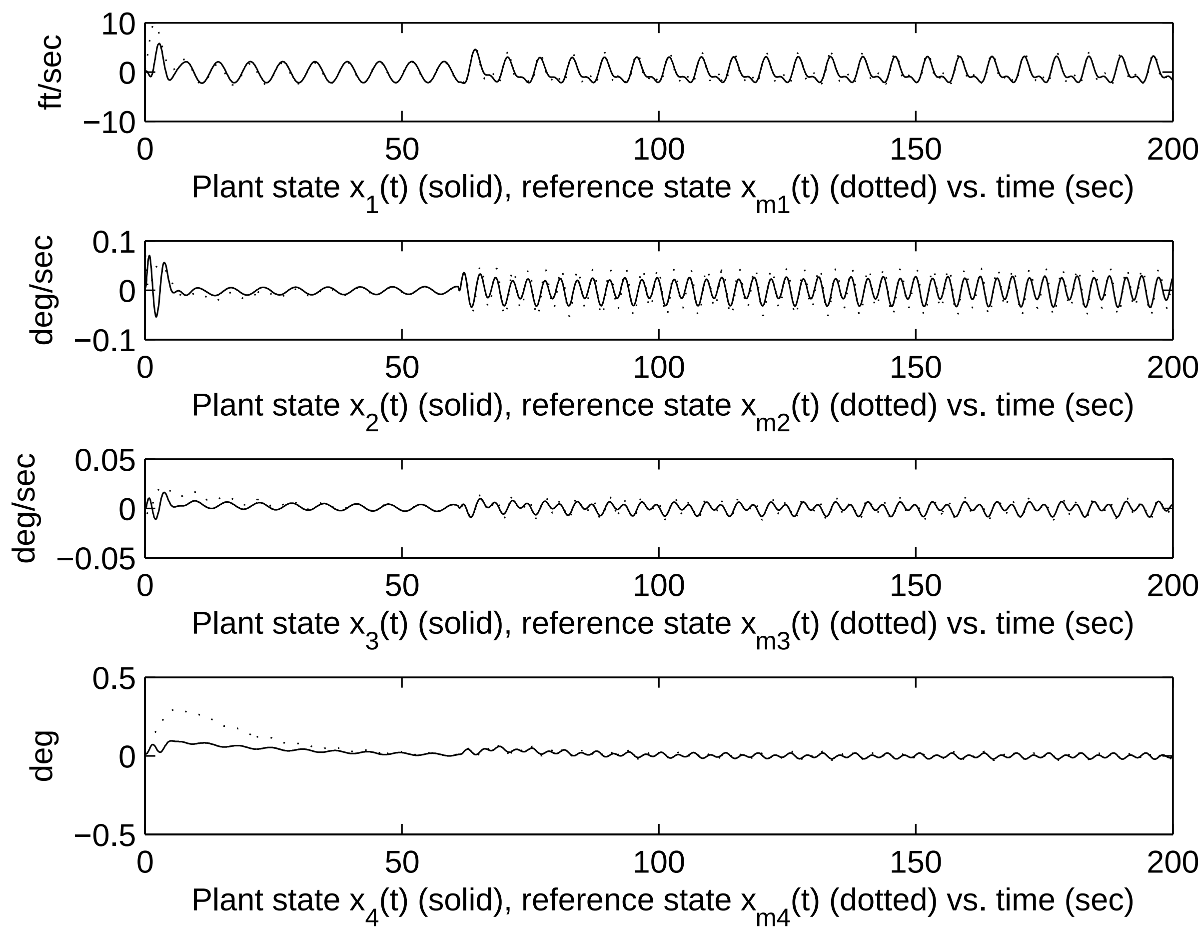


Figure 16: Plant and reference states.

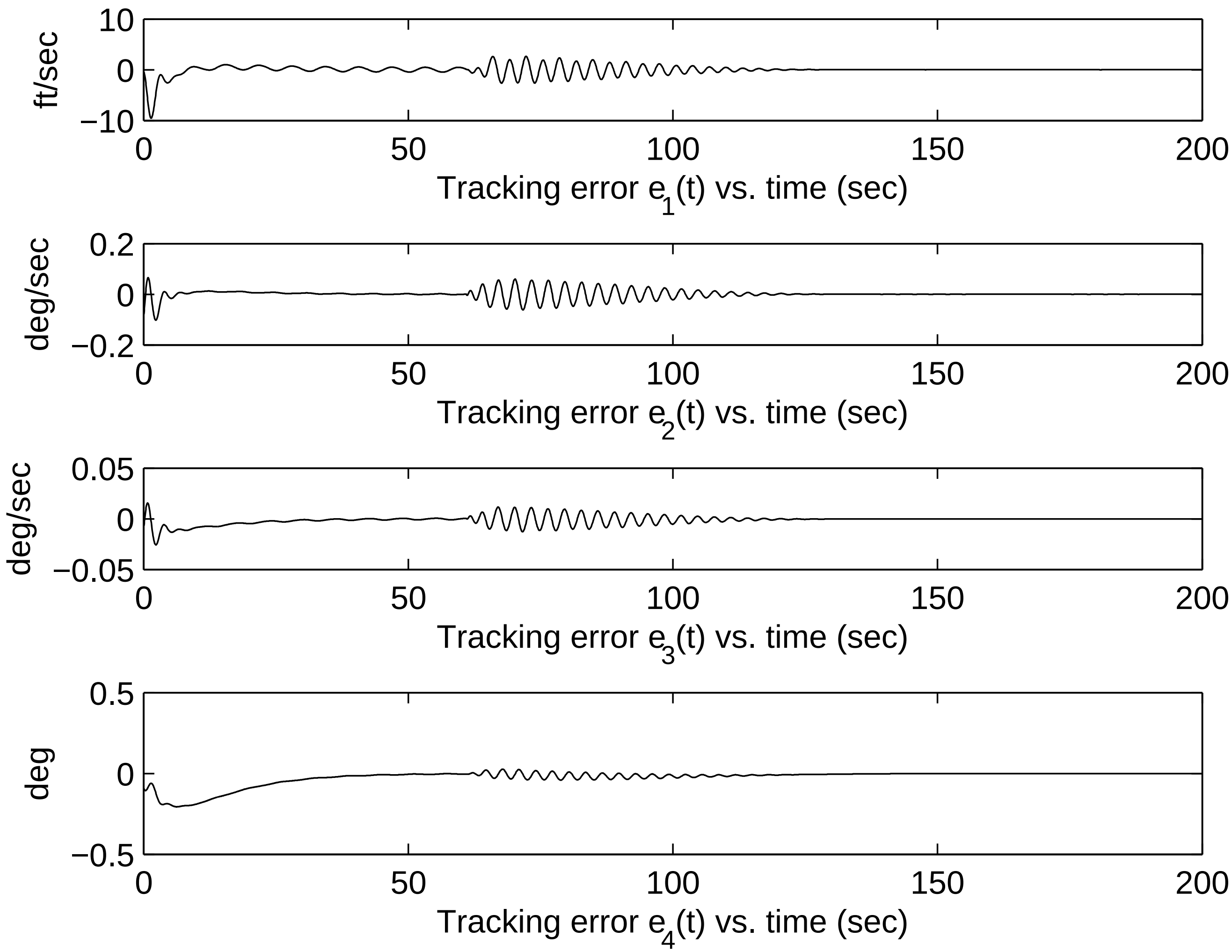


Figure 17: State tracking errors.

Simulation II: Comparison with a fixed inverse

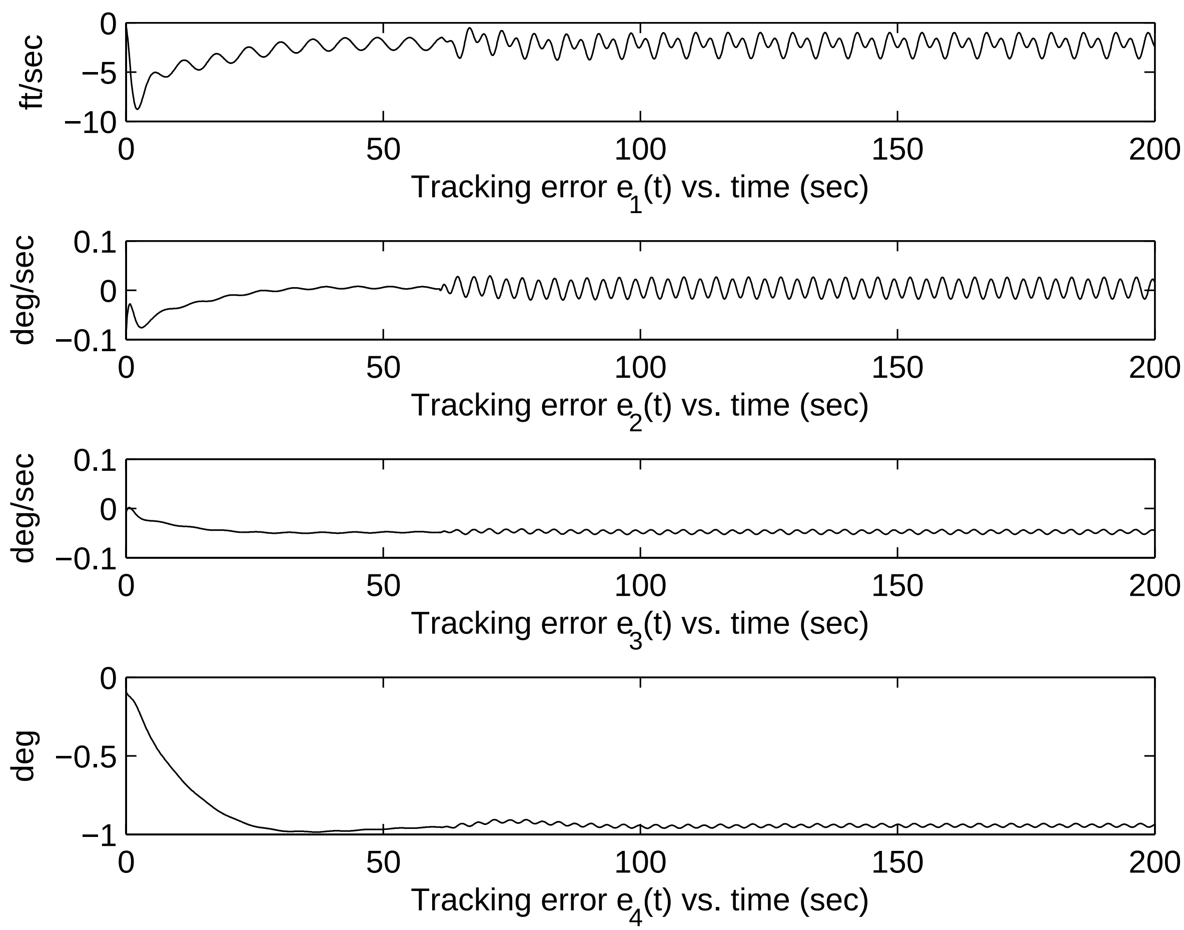


Figure 18: State tracking errors with a fixed inverse.

Simulation III: Effect of saturation

- A possible modification for control signal

$$\bar{u}_d(t) = -Kx(t) + r(t)$$

$$u_d(t) = \begin{cases} \theta_2 - \delta & \text{if } \bar{u}_d(t) \geq \theta_2 - \delta \\ \bar{u}_d(t) & \text{otherwise} \end{cases}$$

$\delta > 0$ is a small constant

- Simulation signals

  (i) $r_1(t) = 5r(t)$ (convergent)

  (ii) $r_2(t) = 6r(t)$ (non-covergent)

  both leading to saturation of $u_d(t)$.

(i) convergent results

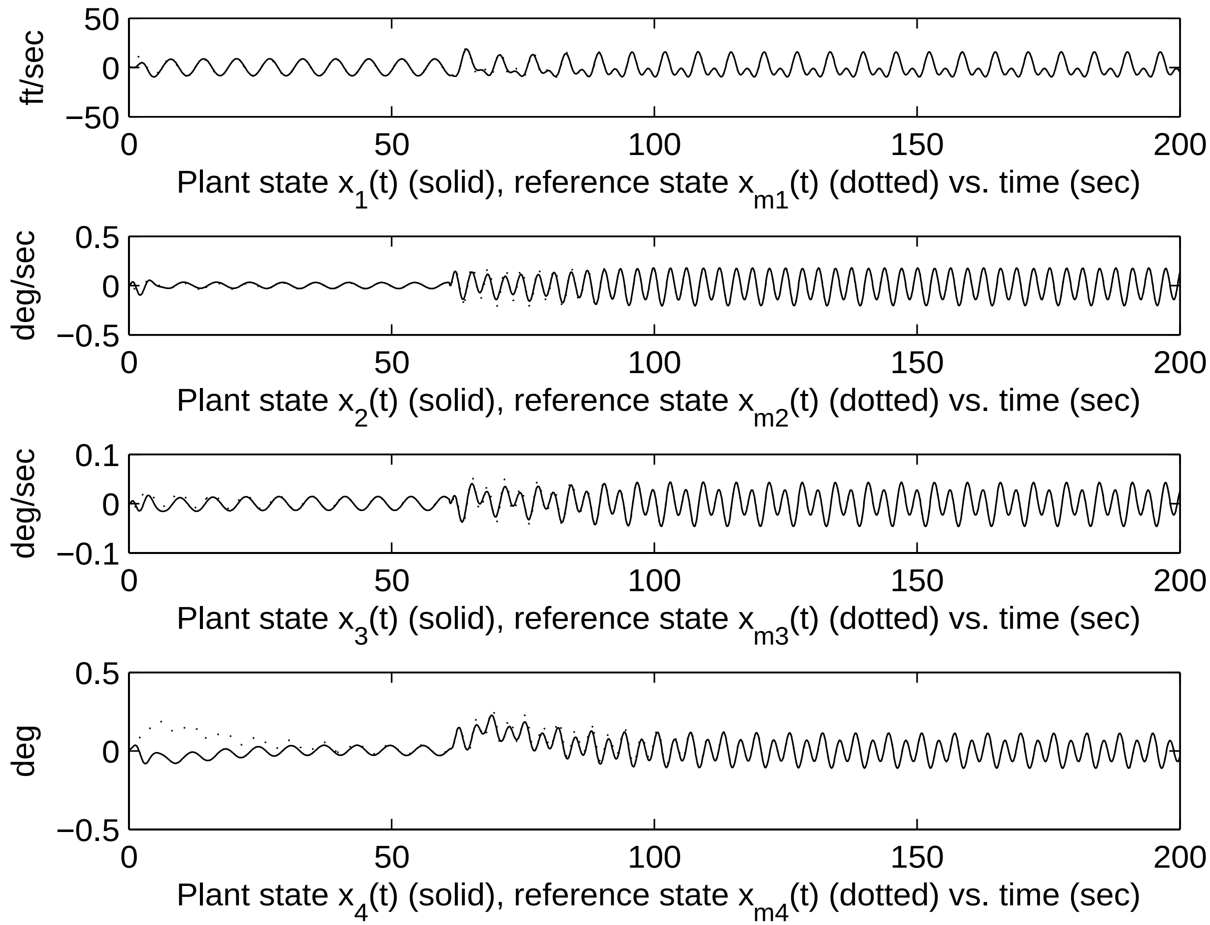


Figure 19: Plant and reference states (with saturation).

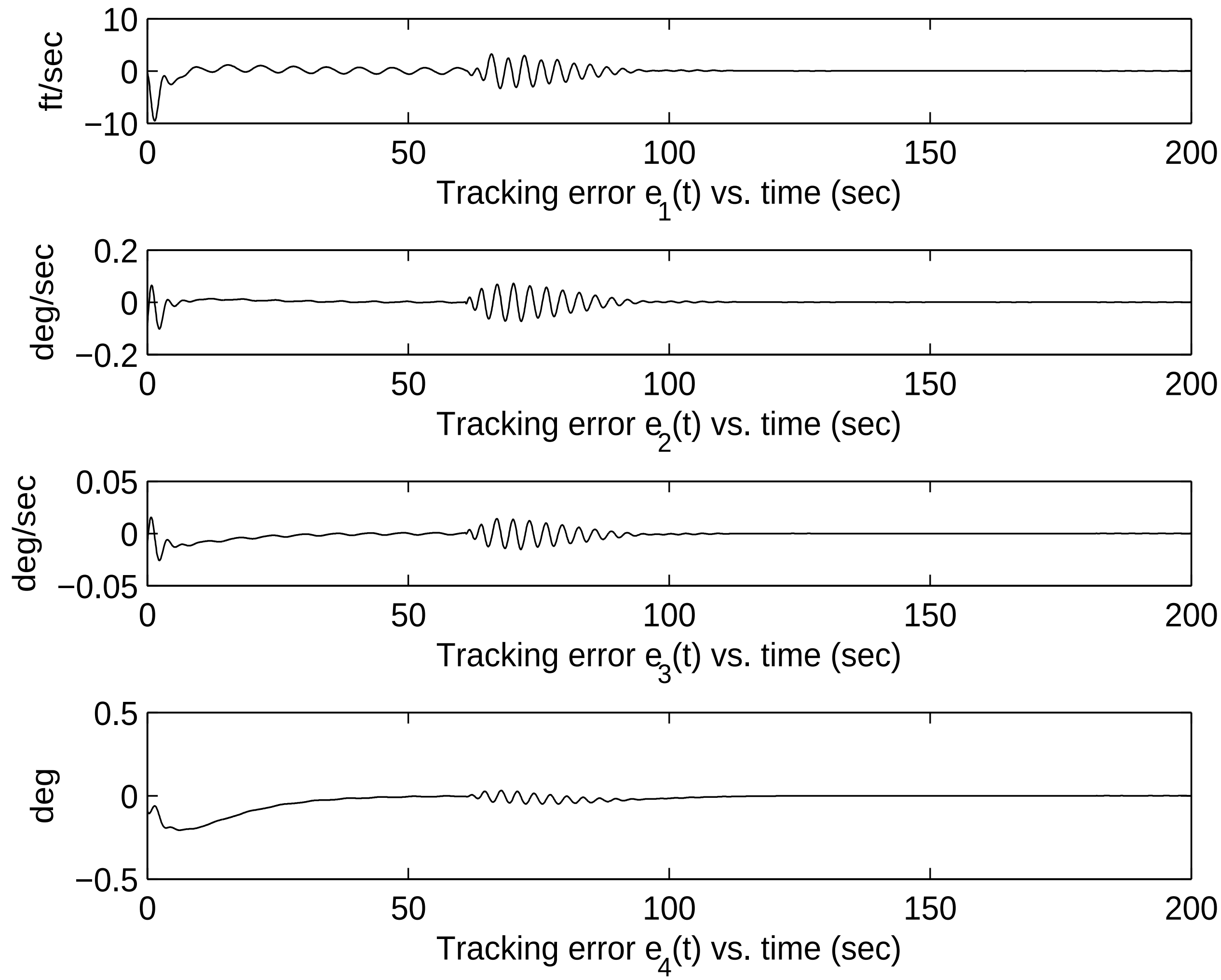


Figure 20: State tracking errors (convergent).

(ii) non-convergent results

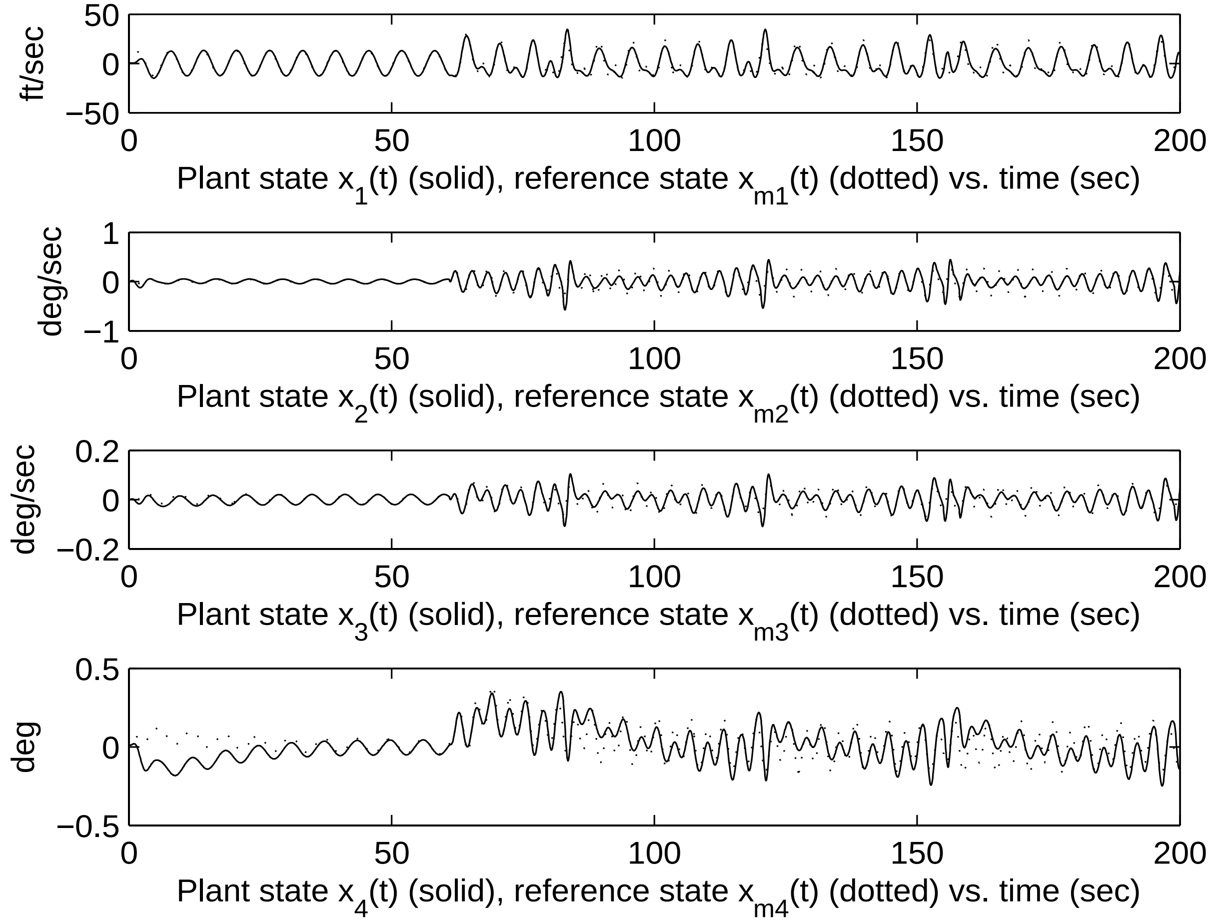


Figure 21: Plant and reference states (with saturation).

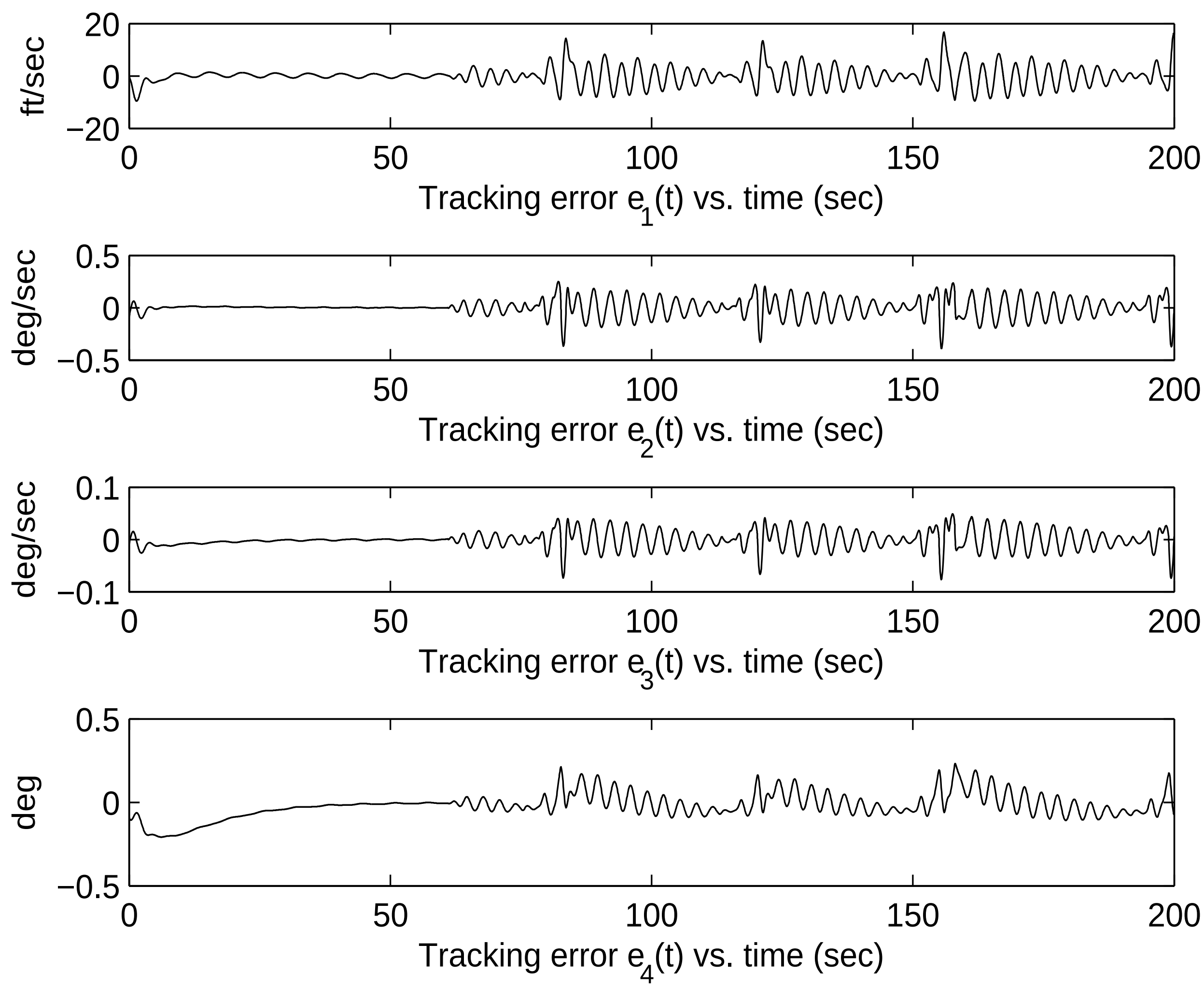


Figure 22: State tracking errors (non-convergent).

Discussion

- Synthetic jet actuators are for novel aircraft
- Compensation of actuator nonlinearity is crucial
- Actuator parameters are highly uncertain
- Algorithm-based adaptive inverse is promising
- It is applicable to jet arrays and nonlinear dynamics
- Actuator saturation is an important issue
- Actuator failure is another important issue
  - adaptive failure compensation
  - adaptive nonlinearity compensation.

Adaptive Actuator Failure Compensation

- Research motivation
- Systems with actuator failures
- Research goals and technical issues
- Adaptive failure compensation techniques
- Study of aircraft flight control applications

Research Motivations

- Actuator failures
  - common in control systems
  - uncertain in failure time, pattern, parameters
  - undesirable for system performance
- Adaptive control
  - deals with system uncertainties
  - ensures desired asymptotic performance
  - is promising for actuator failure compensation
  - has potential for critical applications

- Effective methods for handling system failures
  - multiple-model, switching and tuning
  - indirect adaptive control
  - fault detection and diagnosis
  - robust or neural control
- Direct adaptive failure compensation approach
  - use of a single controller structure
  - direct adaptation of controller parameters
  - no explicit failure (fault) detection
  - stability and asymptotic tracking
- Potential applications include
  - aircraft flight control
  - smart structure vibration control
  - space robot control

Systems with Actuator Failures

System Models

$$\dot{x} = f(x) + \sum_{j=1}^{m} g_j(x)u_j, \; y = h(x)$$

$$\dot{x} = Ax + \sum_{j=1}^{m} b_j u_j, \; y = Cx$$

– state variable vector: $x(t) \in R^n$

– output: $y(t)$

– input vector: $u = [u_1, \ldots, u_m]^T \in R^m$ whose components may fail during system operation

– $f(x)$, $g_j(x)$, $h(x)$, A, b_j, C with unknown parameters.

Actuator Failures

- Loss of effectiveness

$$u_j(t) = k_j(t)v_j(t),\ k_j(t) \in (0,1),\ t \geq t_j$$

- Lock-in-place

$$u_j(t) = \bar{u}_j,\ t \geq t_j,\ j \in \{1,2,\ldots,m\}$$

- Lost control

$$u_j(t) = \bar{u}_j + \sum_k \bar{d}_{jk}\omega_{jk}(t) + \delta_j(t), t \geq t_j, j \in \{1,\ldots,m\}$$

- Failure uncertainties

  the failure values k_j, $\bar{u}_j$ and $\bar{d}_{jk}$, failure time t_j, pattern j, and components $\delta_j(t)$ are all unknown.

  How much, how many, which and when the failures happen??

- Examples
  - aircraft aileron, stabilizer, rudder or elevator failures
    - ◇ their segments stuck in unknown positions
    - ◇ their unknown broken pieces (including wings)
  - satellite motion control actuator failures
  - MEM actuator/sensor failures on fairing surface
  - heating device failures in material growth
  - generator failures in power systems
  - transmission line failures in power system
  - power distribution network failures
  - cooperating manipulator failures
  - bioagent distribution system failures
  - etc.

System Input (for "lost control" failures $\bar{u}_j(t)$)

System input in the presence of actuator failures is

$$u(t) = v(t) + \sigma(\bar{u}(t) - v(t))$$

$v = [v_1, v_2, \ldots, v_m]^T$: a designed control input, and

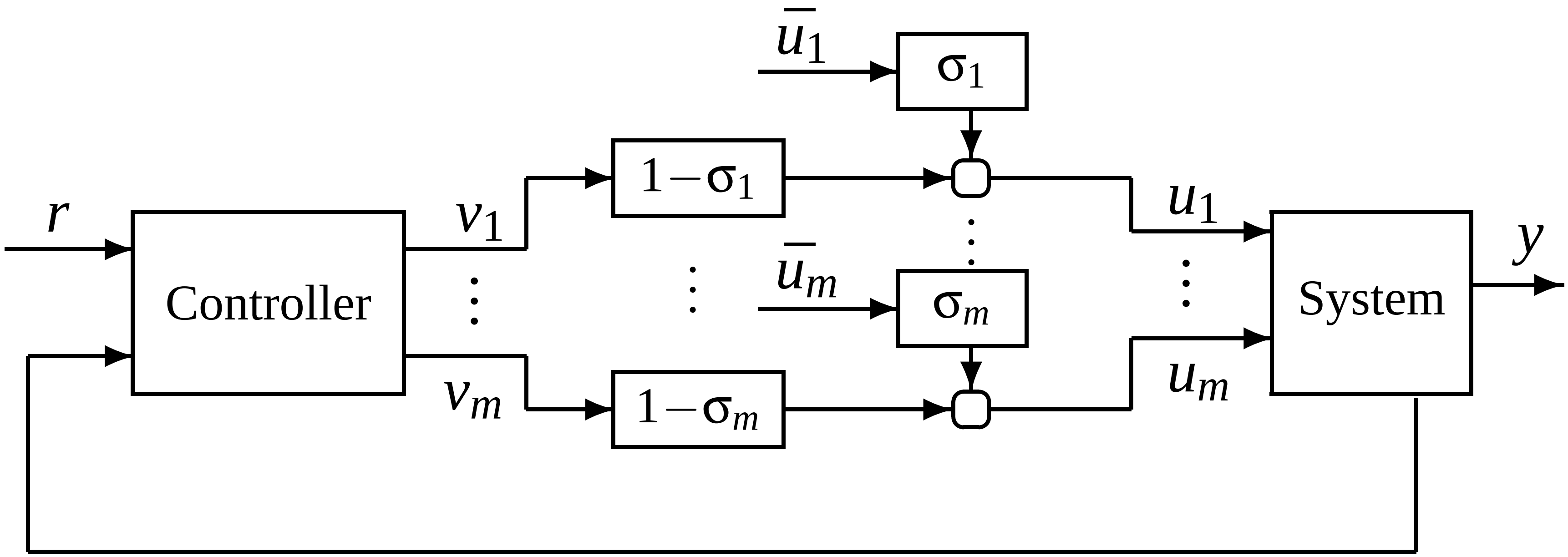
$$\bar{u}(t) = [\bar{u}_1(t), \bar{u}_2(t), \ldots, \bar{u}_m(t)]^T$$

$$\sigma = \mathrm{diag}\{\sigma_1, \sigma_2, \ldots, \sigma_m\}$$

$$\sigma_j = \begin{cases} 1 & \text{if the } j\text{th actuator failed, i.e., } u_j(t) = \bar{u}_j(t) \\ 0 & \text{otherwise} \end{cases}$$

Actuation error $u(t) - v(t) = \sigma(\bar{u}(t) - v(t))$ is uncertain.

Block Diagram



Research Goals

- Theoretical framework for adaptive control of systems with uncertain actuator (sensor, or component) failures
- Guidelines for designing control systems with guaranteed stability and tracking performance despite parameter and failure uncertainties
- Solutions to key issues in adaptive failure compensation: controller structures, design conditions, adaptive laws, stability, robustness
- New adaptive control techniques for critical systems (e.g., aircraft) to improve reliability and survivability.

Technical Challenges

- Redundancy
  - necessary for failure compensation
  - problematic for control: up to $m - q$ failures
- Failure uncertainties

  parametric, structural, and environmental
- Robustness and transient performance
- Application issues
  - system modeling and control implementation
  - aircraft, robot, smart structure, power system, satellite

Adaptive Failure Compensation

Control Objective

Stability and *asymptotic tracking* for up to $m-q$ failures.

Basic Assumption

The system is so constructed that for any up to $m-q$ $(0 < q \leq m)$ failed actuators, the alive actuators can still achieve some desired performance.

Key Task

Adaptively adjust the remaining actuators (controls) to achieve desired performance when system and failure parameters are unknown.

Design Tools

- State feedback for state tracking

$$u = K^T x + k_r r + k_c, \quad \lim_{t \to \infty} (x(t) - x_r(t)) = 0$$

- State feedback for output tracking

$$u = K^T x + k_r r + k_c, \quad \lim_{t \to \infty} (y(t) - y_r(t)) = 0$$

- Output feedback for output tracking

$$u = \theta_1^T \omega_1 + \theta_2^T \omega_2 + \theta_3 r + k_c, \ \omega_1 = F_1(s)u, \ \omega_2 = F_2(s)y$$

$$\lim_{t \to \infty} (y(t) - y_r(t)) = 0.$$

- Designs for linear systems
  - model reference for minimum phase systems
  - pole placement for nonminimum phase systems
  - decoupling for MIMO systems
- Designs for nonlinear systems
  - feedback linearizable systems
  - parametric-strict-feedback systems
  - output-feedback systems
  - output feedback for state-dependent systems.
- Aircraft flight control applications

  lateral: Boeing 737, Boeing 747, DC-8

  longitudinal: Boeing 737, Twin Otter, hypersonic.

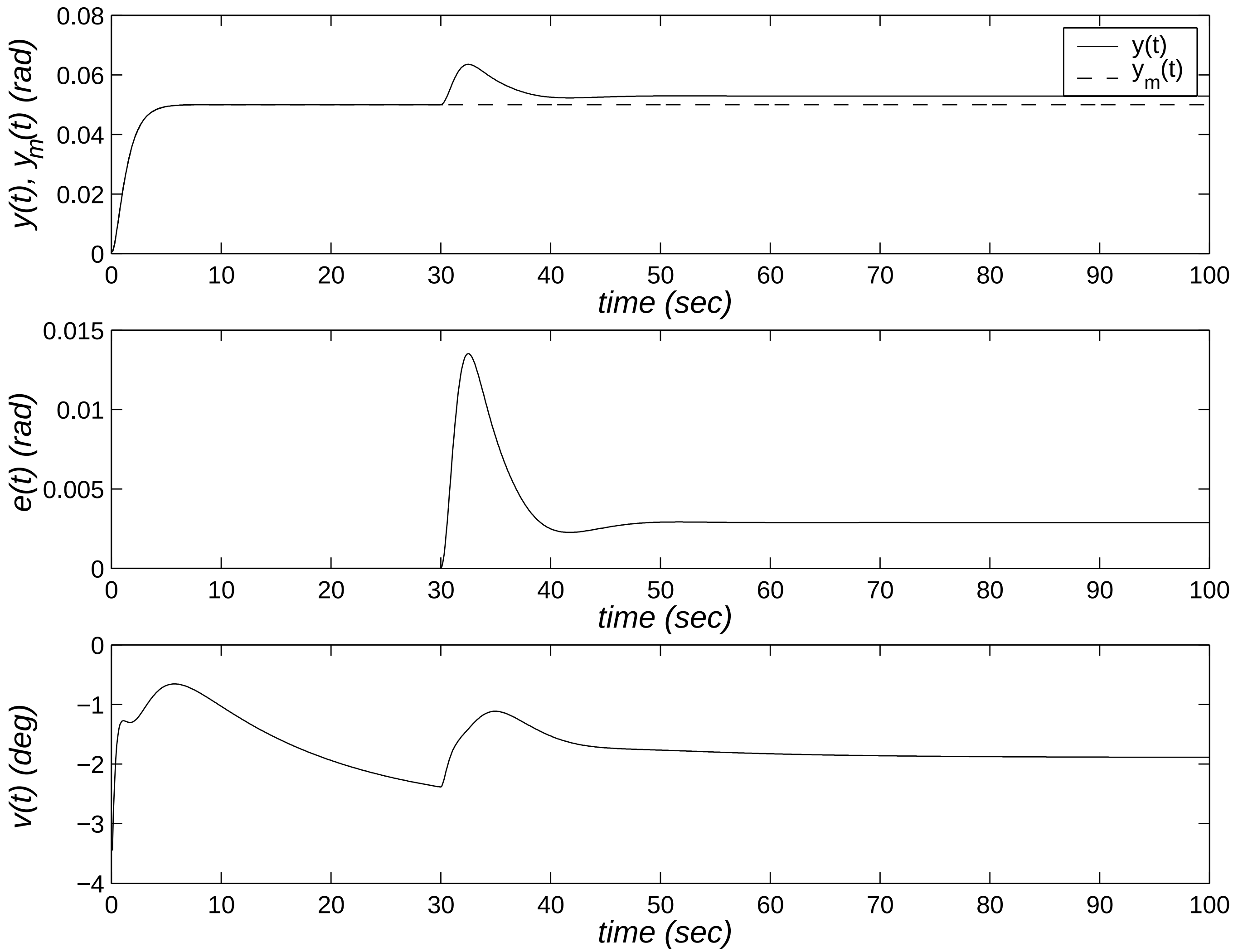
Example: Boeing 737 Landing

- System model

$$\dot{x}(t) = Ax(t) + Bu(t),\ y(t) = \theta,\ B = [b_1, b_2]^T$$

  $x = [U_b, W_b, Q_b, \theta]^T$: forward speed U_b, vertical speed W_b, pitch angle θ, pitch rate Q_b; $u = [dele_1, dele_2]^T$: elevator segment angles

- Study of an aircraft with two elevator segments
- Output feedback output tracking design
- One elevator segment fails during landing at $t = 30$ sec.
- Simulation results
  - response with no compensation (fixed feedback)
  - response with adaptive compensation.


0.08
0.06
0.04
0.02
0
y(t), y_m(t) (rad)
y(t)
y_m(t)
0 10 20 30 40 50 60 70 80 90 100
time (sec)
0.015
0.01
0.005
0
e(t) (rad)
0 10 20 30 40 50 60 70 80 90 100
time (sec)
0
−1
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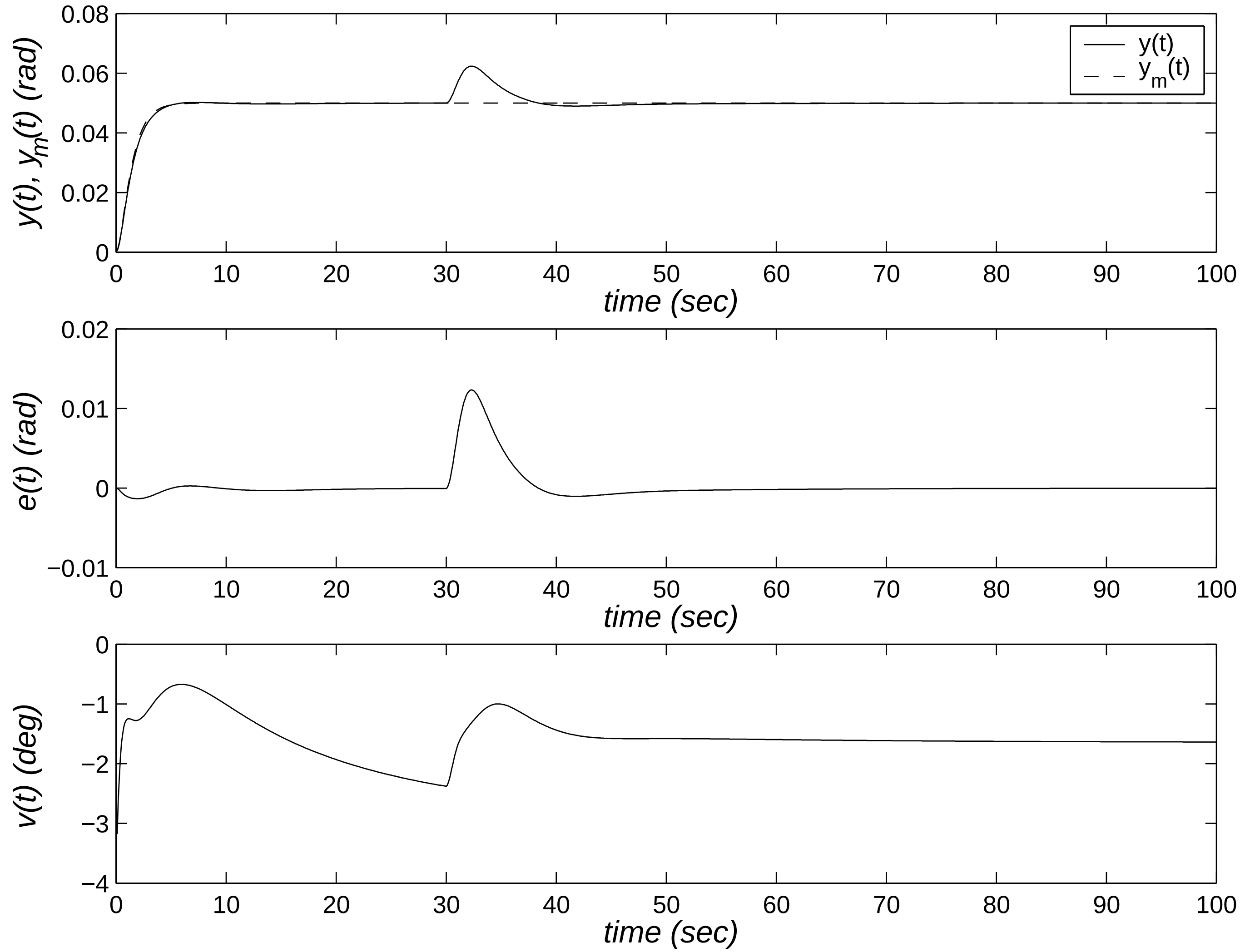
−3
−4
v(t) (deg)
0 10 20 30 40 50 60 70 80 90 100
time (sec)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y(t), y_m(t) (rad)
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time (sec)
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e(t) (rad)
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time (sec)
0
−1
−2
−3
−4
v(t) (deg)
0 10 20 30 40 50 60 70 80 90 100
time (sec)

Example: Boeing 737 Lateral Motion

- MIMO system model

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

$x = [v_b, p_b, r_b, \phi, \psi]^T$: lateral velocity v_b, roll rate p_b, yaw rate r_b, roll angle ϕ, yaw angle ψ

$y = [\phi, \psi]^T$: roll angle ϕ, yaw angle ψ

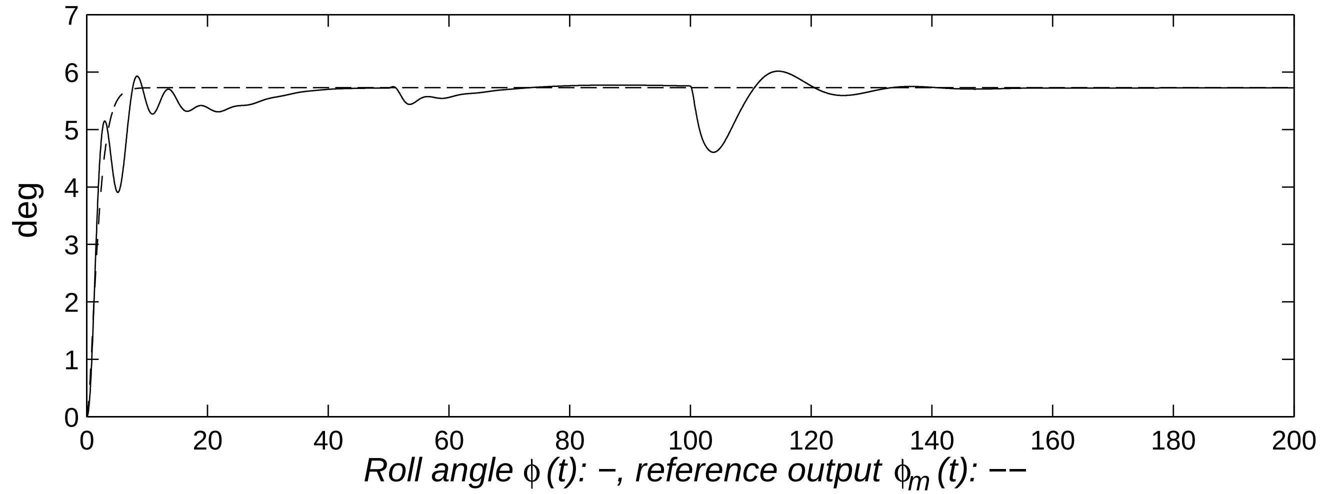
$u = [d_r, d_a]^T$: rudder position d_r, aileron position d_a,

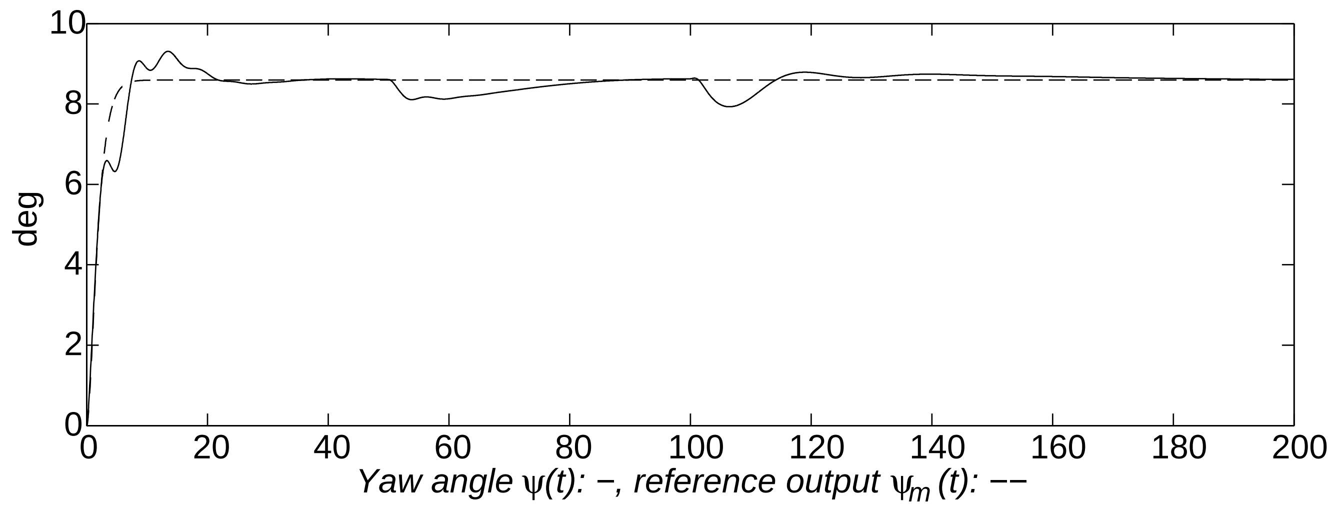
segmented into: d_{r1}, d_{r2}, d_{a1}, d_{a2}

- Actuator failures

d_{r2} fails at $t = 50$, d_{a2} fails at $t = 100$ seconds

- Simulation results


deg
7
6
5
4
3
2
1
0
0
20
40
60
80
100
120
140
160
180
200
Roll angle ϕ (t): −, reference output ϕm (t): −−


deg
10
8
6
4
2
0
0
20
40
60
80
100
120
140
160
180
200
Yaw angle ψ(t): −, reference output ψm (t): −−

Discussion

- Effective failure compensation has major interest
- Direct adaptive compensation is aimed at
  - automatic tuning of controller parameters
  - handling of large class of failures
  - guaranteed system tracking performance
- A solution framework has been developed for
  - parametrization of actuator failures
  - failure compensation conditions
  - adaptive compensation designs
- Desired performance was verified on numerous aircraft models
- There is high potential for other applications.

Conclusions

- Adaptive control is a mature control methodology
- Adaptive controllers adjust themselves to system uncertainties
- Effective uncertainty compensation is a key for aerospace systems
- Adaptive control technologies have high potential.

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- Adaptive compensation techniques are developed for
  - practical actuator and sensor nonlinearities
  - actuator failures (and sensor failures, in progress)
- Applications to aerospace systems have been formulated
- Various designs were verified on aircraft system models
- Further research and more advances are critical.

Research Interests

- Adaptive control theory
  - actuator/sensor/component failure compensation
  - multivariable and nonlinear systems
  - actuator and sensor nonlinearity compensation
- Adaptive control applications
  - aircraft flight control
  - fairing structure vibration reduction
  - space robot cooperative and compensation control
  - synthetic jet actuator compensation control
  - satellite motion control
  - high precision pointing systems
  - dynamic sensor/actuator networks

Some On-Going Research

- Rudder failure compensation by engine differentials
  - aircraft model with engine differentials
  - adaptive failure compensation control
- Adaptive compensation control for aircraft damages
  - dynamic modeling of aircraft damages
  - direct adaptive damage compensation control
- Applications to aircraft and UAVs
- Adaptive compensation control for synthetic jet actuators
- Adaptive failure compensation for space robots
- Adaptive compensation of sensor failures
- Adaptive control of power systems with failures