Adaptive and Autonomous Aerospace Systems

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Part 2: Adaptive Control

Lect 1: Introduction to adaptive control and main architectures

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Outline

- Introduction to adaptive control systems: historical background and new perspectives
- Robust vs adaptive control
- Architectures: direct vs indirect approach
- Model Reference Adaptive Control
- Augmentation approach
- L1 adaptive control

Historical background

The motivation for the study and implementation of adaptive control systems came from applications in aerospace to reduce wind-tunnel tests and overcome limitations of gain-scheduling.

The history of adaptive control systems is almost as long as the entire field of control systems, as the concept of adaptation is close to the notion of feedback.

- Research in adaptive control started in the early 1950’s:
  - fixed-gains controller not sufficient for large flight envelope;
  - development of several adaptive schemes for self-adjustments of controller parameters (MIT rule, sensitivity methods);
  - 1958, R. Kalman, Self-Tuning Controller: Optimal LQR with explicit identification of parameters.

1950-1960: flight tests X-15 (NASA, USAF, US Navy)

- Program to bridge the gap between manned flight in the atmosphere and space flight (Mach 4 - 6, at altitudes above 30,500 meters).
- 199 flights beginning June 8,1959 and ending October 24, 1968.
- Fatal crash on Nov. 15, 1967, X-15A-3.

➢ Crash due to <u>stable</u> albeit <u>non-robust</u> adaptive controller - *“Brave era”, Astrom 1985*

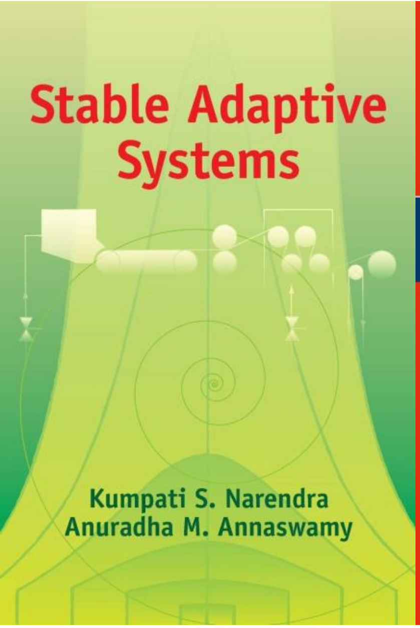
Motivation

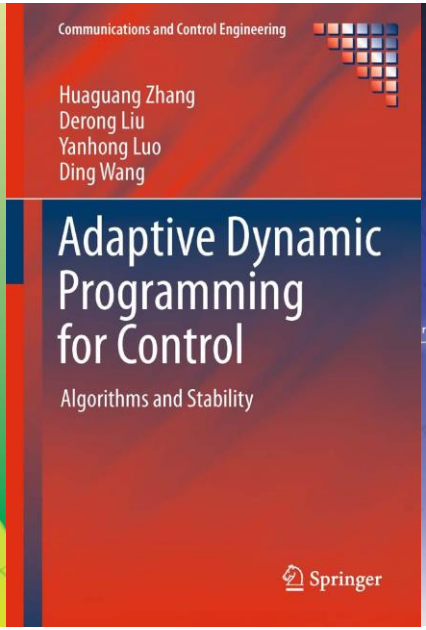
1970-1990

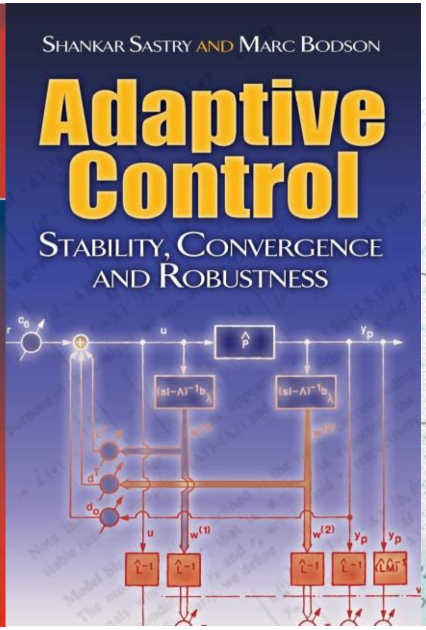
- Early results found to be suffering from **robustness issues** (“bursting” phenomena).
- Development of a **stability** and **robust** framework for adaptive control.
- Systematic use of Lyapunov’s approach for stability analysis of adaptive systems.
- Several seminal results were published in this period addressing control architectures and algorithms for a range of dynamical systems.
- Proof of robustness and parameters convergence through persistence of excitation.
- Robust modifications to handle non-parametric and time-varying disturbances and unmodelled dynamics.
- *Morse, Narendra, Anderson, Astrom, Wittenmark, Athans, Sastry, Ioannou, Anderson, Annaswamy, Praly, Kokotovic, …*

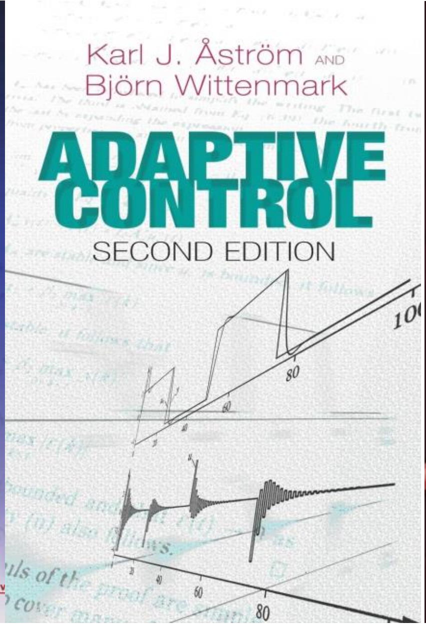
Motivation

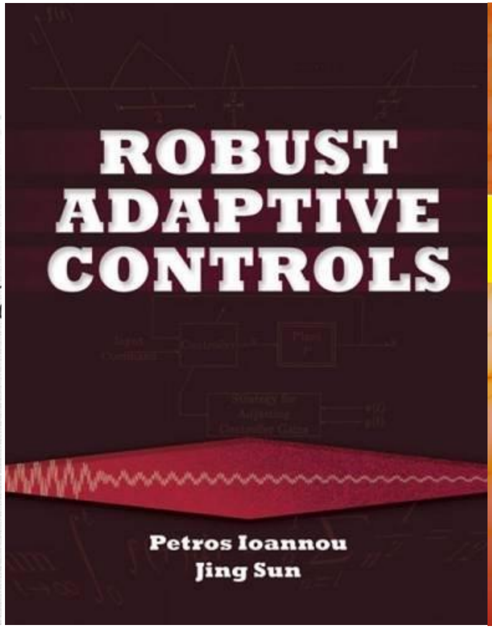
1990-today: Previous advancements published in textbooks capturing the details of various solutions (≈15 books are now available on the topic…).

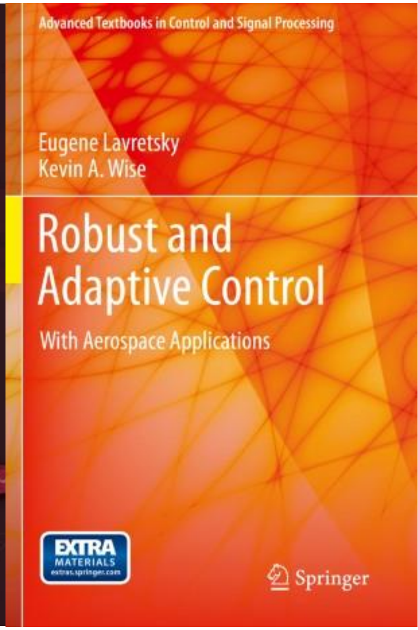












Motivation

Air Force, Navy, and NASA working with industry and academia made significant progress towards maturing adaptive control theory for aerospace applications (RESTORE program, JDAM program).

Motivation

More recent (theoretical) advancements:

- Adaptive control of nonlinear systems
  - Significantly more challenging (backstepping, adaptive observers, immersion and invariance approach, …)
  - Magnitude and rate saturation on input and states, time-delays, unmodelled dynamics, …

- Adaptive schemes guaranteeing
  - Fast adaptation and robustness
  - parameters convergence with finite-time persistence of excitation.
  - exponentially stable behavior

Motivation

Increasing number of adaptive control implementations and results in the last decade.

Flight Test of Composite Model Reference Adaptive Control (CMRAC) Augmentation Using NASA AirSTAR Infrastructure

Irene M. Gregory[1]
NASA Langley Research Center, Hampton, VA 23681

Ross Gadient[2] and Eugene Lavretsky[3]
The Boeing Company, Huntington Beach, California 92647

This paper presents flight test results of a robust without composite adaptive control augmentation. The fl NASA Generic Transport Model as part of the Airb Research system at NASA Langley Research Center.

$\mathcal{L}_1$ Adaptive Controller for Attitude Control of Multirotors

Srinath Mallikarjunan* — *Unmanned-Dynamics*
Bill Nesbitt†
Evgeny Kharisov‡ — *University of Illinois Urbana-Champaign*
Enric Xargay§ — *University of Illinois Urbana-Champaign*
Naira Hovakimyan ¶ — *University of Illinois Urbana-Champaign*
Chengyu Cao ‖ — *University of Connecticut*

In this work we show an 1 / 15 theory for attitude control of UAVs. We implement the flight control system on a multirotor to show robustness

L_1 Adaptive Control Design for NASA AirSTAR Flight Test Vehicle

Irene M. Gregory[1]
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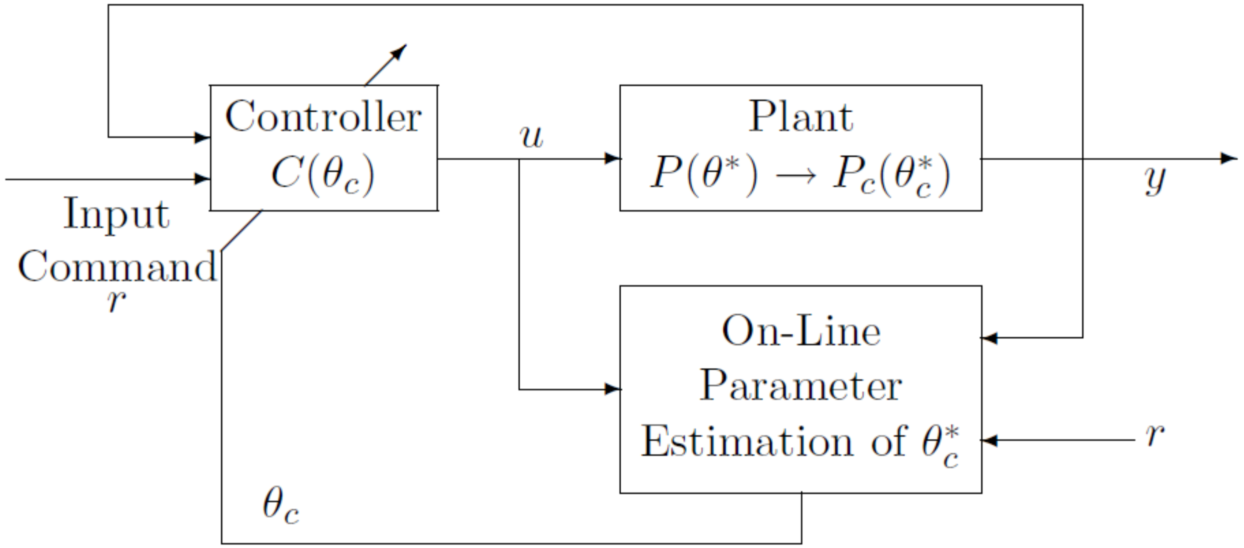
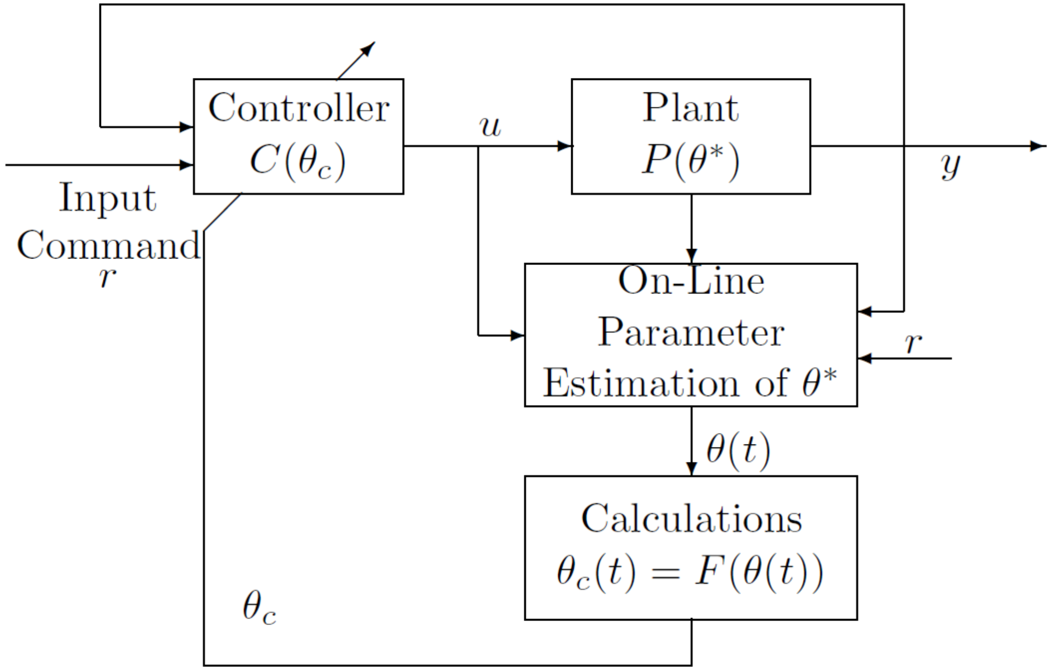
esent a new L_1adaptive control architecture that directly compensates as unmatched system uncertainty. To evaluate the L_1 adaptive

Main adaptive architectures and algorithms: direct vs indirect schemes

Direct approach

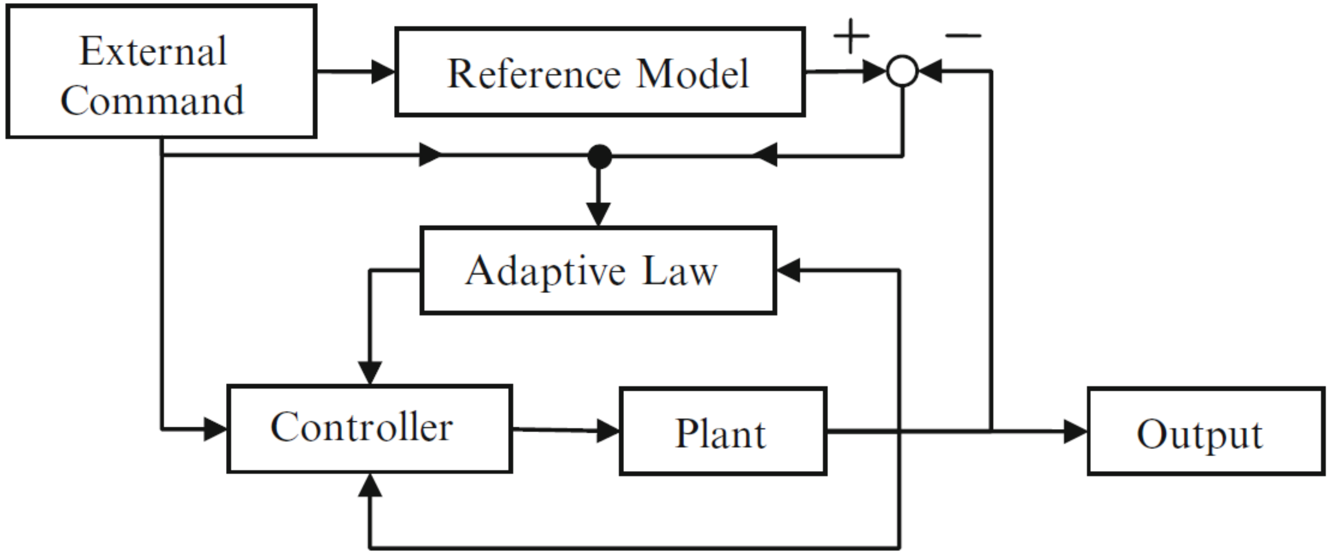


Indirect approach



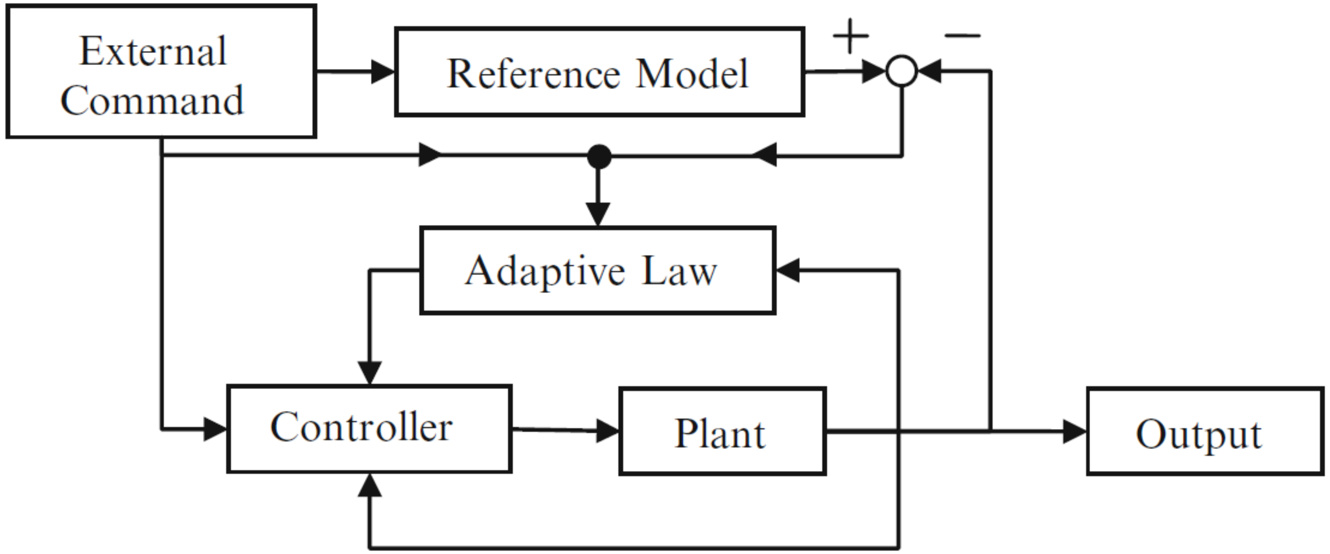
Model Reference Adaptive Control (direct&indirect)

Objective: make the closed-loop system behave as a reference model which embeds control design requirements.

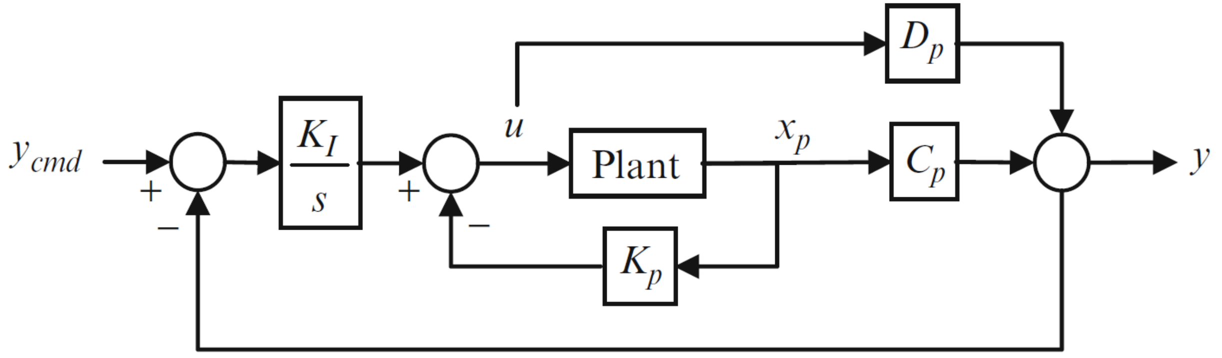


Model Reference Adaptive Control (direct&indirect)

Objective: make the closed-loop system behave (asymptotically) as a reference model, which embeds control design requirements.

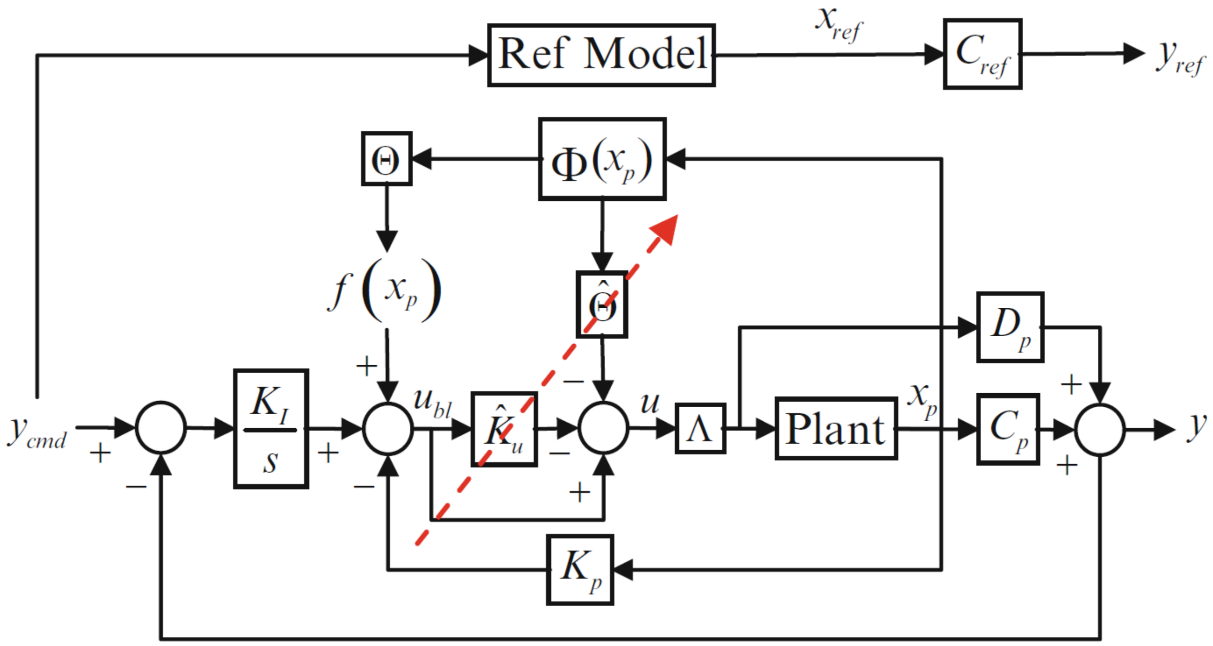


MRAC augmentation of an Optimal Baseline Controller



The adaptive action is <u>added</u> to the baseline control output $u = u_{bl} + u_{ad}$

Idea: the reference model is based on the closed-loop system resulting from the baseline controller and the nominal plant.



Instability issues

Adaptive controllers are designed to control real physical systems.

In real systems, one must consider the presence of both parametric and non-parametric uncertainties

- unmodeled dynamics (e.g., flexibility, friction, actuators and sensor dynamics)
- exogenous disturbances
- actuator saturation
- measurement noise
- sampling delays

Course contents

The combined presence of these effects, together with lack of persistence of excitation (PE), can lead to

- estimated parameters drift slowly as time goes on, and suddenly diverge sharply.
- adaptation has difficulty in distinguishing parameter information from noise.

The use of large adaptive gains to compensate for the lack of PE is not recommended in practice, as the control action

- can excite high-frequency unmodelled dynamics;
- can reach saturation bounds of the actuators.

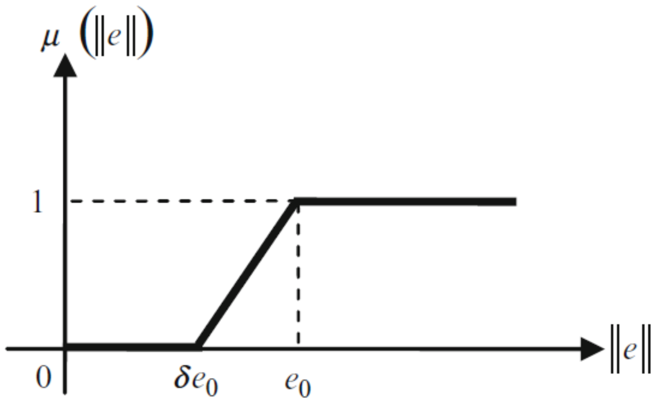
➢ Increasing too much the adaptive gains can lead to performance degradation, or worse, instability.

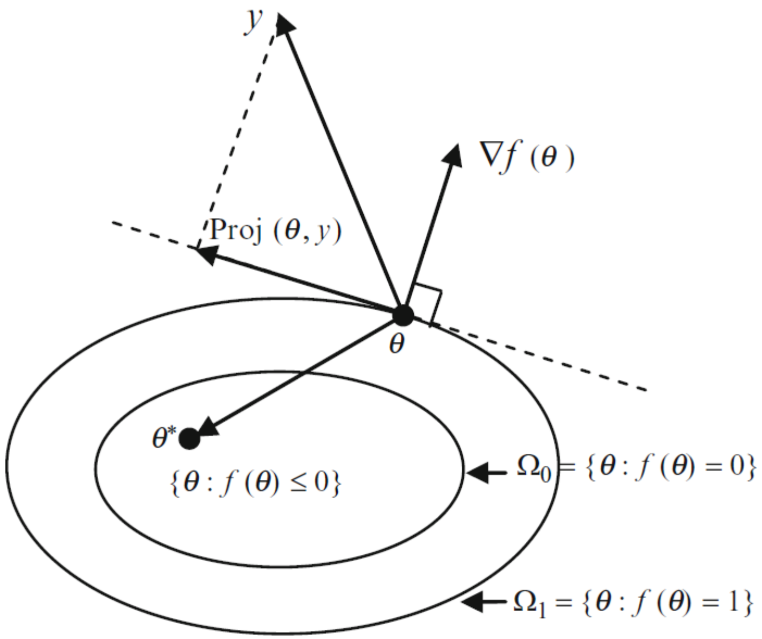
Robust modifications

Several methods have been proposed to counteract the effect of exogenous disturbances.

The corresponding adaptive laws are called robust adaptive laws:

- Projection-based
- Deadzone modification
- σ-modification
- e-modification

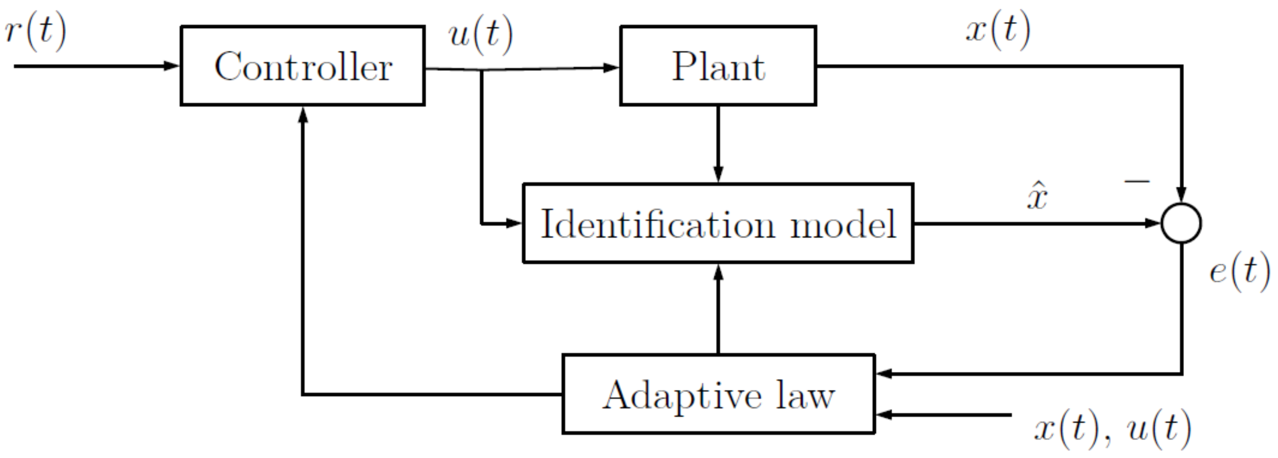




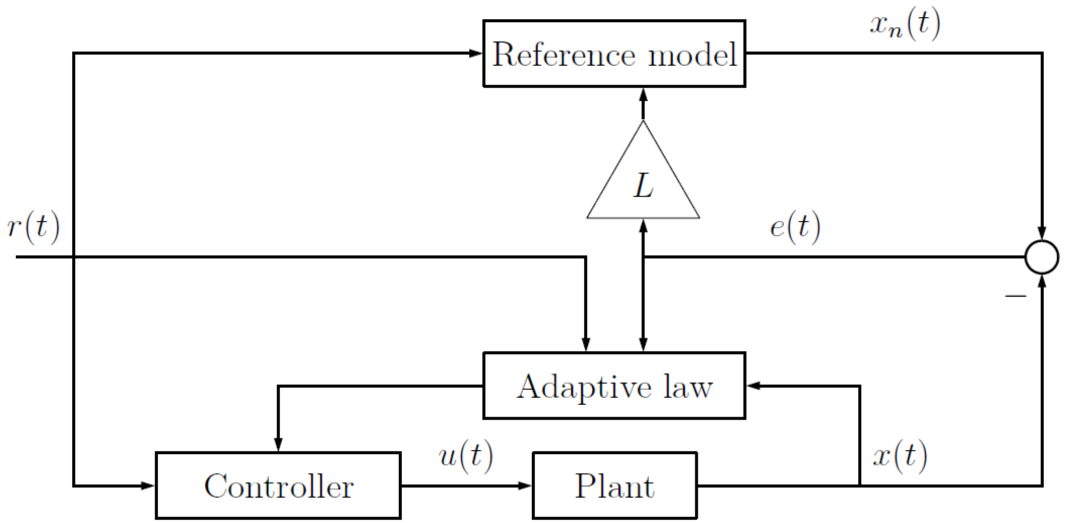
Transient improvements

The oscillations in the transient phase of standard MRAC can be mitigated by employing different architectures

Predictor-based MRAC



Closed-loop reference model MRAC



L1 adaptive control

Based on PMRAC scheme with the inclusion of a low-pass filter filter

Objective: compensation of only the low-frequency content of the uncertainty within the bandwidth of the control channel.

Effective decoupling adaptation and robustness