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★**$\mathcal{L}_1$ adaptive control theory.**
Guaranteed robustness with fast adaptation.
With a foreword by Karl Johan Åström.
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Society for Industrial and Applied Mathematics (SIAM), Philadelphia, PA, 2010. *xx*+319 *pp.* $85.00. *ISBN* 978-0-898717-04-4

The book presents the theory of $\mathcal{L}_1$ adaptive control for a broad audience of readers. The architectures of $\mathcal{L}_1$ adaptive control decouple estimation from control, and with that allow for increasing the rates of adaptation arbitrarily, subject only to CPU limitations. The low-pass filtering structure decides the tradeoff between performance and robustness, which can be addressed by well-known methods from linear and robust control. The book has six chapters, and several appendices, where some required mathematical facts are presented.

Chapter 1 presents a historical overview of adaptive control theory. Two equivalent architectures of model reference adaptive control (MRAC) are analyzed. A scalar system with constant disturbance is used to introduce the main idea of the $\mathcal{L}_1$ adaptive controller. Two features are analyzed in detail: the closed-loop system phase margin and the uniform bound for the control signal. The uniform bounds for the system state and control signals are written in terms of the system impulse response, which leads to the name "$\mathcal{L}_1$ adaptive controller".

Chapter 2 presents an $\mathcal{L}_1$ adaptive controller for systems with matched uncertainties. The idea of decoupling adaptation from robustness is well explained here. First, it is shown that with fast adaptation, the state and the input signals of the closed-loop nonlinear adaptive system follow the same signals of a bounded linear time-invariant reference system, which naturally ensures a scaled response for the system signals in the presence of fast adaptation. Next, it is shown that the response of this linear system can be made arbitrarily close to the response of a desired system by tuning the low-pass filter. This step is the key to the tradeoff between performance and robustness, and can be addressed by tuning the structure and the bandwidth of a stable, strictly proper bandwidth-limited linear filter. The performance bounds of the nonlinear $\mathcal{L}_1$ adaptive controller are decomposed into two distinct terms: the first one is inversely proportional to the square root of the rate of adaptation, while the second one depends upon the bandwidth of a linear filter. This decoupling between adaptation and robustness is the key feature of the $\mathcal{L}_1$ adaptive controller.

The chapter extends the methodology to accommodate an uncertain system input gain, time-varying parameters, and disturbances. A rigorous proof for a lower bound of the time-delay margin of the closed-loop $\mathcal{L}_1$ adaptive system is provided in the case of open-loop linear systems with unknown constant parameters. The chapter also considers unmodeled actuator dynamics, as well as nonlinear systems in the presence of unmodeled dynamics, and uses the well-known Rohrs example to provide further insights into the $\mathcal{L}_1$ adaptive controller. Other benchmark applications are also discussed. An overview of tuning methods for the design of this filter for the performance/robustness trade-off is presented towards the end and, as an example, an LMI-based solution is described with certain (conservative) guarantees.

Chapter 3 presents an $\mathcal{L}_1$ adaptive controller for systems with unmatched uncertainties. Nonlinear strict-feedback systems are considered, and the $\mathcal{L}_1$ adaptive backstepping scheme is presented. Then, multi-input multi-output (MIMO) nonlinear systems are considered, in the presence of general unmatched uncertainties. Two different adaptive laws are introduced, one of which is directly related to the sampling parameter of the CPU and updates according to a piecewise constant adaptive law. This MIMO architecture has been applied to NASA's Generic Transport Model (GTM), which is part of the AirSTAR system.

Chapter 4 presents the output feedback solution. Two separate cases are considered for the desired reference system behavior. Reference systems of first order are considered first, which naturally verify the strict positive real (SPR) assumption for their transfer function. The methodology is later extended to accommodate non-SPR reference systems. The proposed methodology leads to uniform performance bounds for both state and control signals of the system with respect to the same signals of the non-SPR reference systems. The most important feature of this output feedback solution is that it does invert the system and, therefore, it can be applied to systems with non-minimum phase zeros.

Chapter 5 presents an extension for linear time-varying (LTV) reference systems. This extension is essential for practical applications with wide operational envelope. Flight control is a good application example for this solution, when the performance specifications at different operational conditions are specified by different parameters. This process leads to a time-varying reference system, the analysis of which cannot be captured by the tools developed in prior chapters. Appropriate mathematical tools for addressing this class of systems are presented in the appendices. The chapter also presents a complete solution for nonlinear systems in the presence of unmodeled dynamics. The uniform performance bounds of the system state and the control signal are computed with respect to the corresponding signals of a linear time-varying reference system, which meets different transient specifications at different points of the operational envelope. These bounds can be uniformly reduced by increasing the rate of adaptation.

Chapter 6 summarizes some of the further extensions not captured within this book, gives an overview of the applications and the flight tests that have used this theory, and states the open problems and challenges for future work. The book concludes with appendices, where basic mathematical facts are presented to support the main proofs. The book contains numerous examples that are worked out to help the reader gain insights. It can serve as a reference book for a graduate-level special topics course in robust adaptive control. Control engineers working in industry can find the methods and solutions presented in this book to be very useful.

Reviewed by *Bożenna Pasik-Duncan*