Preface

Feedback control systems are designed to achieve desirable objectives under physical constraints and adversary conditions. Fundamental control limitations address the intrinsic constraints and limits that transcend over specific systems and methods and hence can neither be overcome nor be circumvented by feedback, defining boundaries separating what can be achieved and what cannot. One seeks to understand and answer questions in the spirit such as: What system characteristics may impose inherent constraints to design and implementation? What inherent limitations may exist regardless of control design? What kind of tradeoffs are to be made to mitigate the limitations? What are the performance limits achievable under the constraints? Needless to say, issues of this kind are commonplace in science and engineering. Analogies can be made, for example, to Shannon’s theorems in communications theory, the Cramer-Rao bound in statistics, and Heisenberg’s uncertainty principle in quantum mechanics.

Systematic investigation and understanding of fundamental control limitations dates back to the classical work of Bode in the 1940s on logarithmic sensitivity integrals, known as the Bode integral relations. Bode’s work has had a lasting impact on the theory and practice of control, and has inspired continued research effort dated most recently and resulted in a variety of extensions and new results that seek to quantify design constraints and performance limitations by logarithmic integrals of Bode and Poisson type. Performance limitation of feedback systems has also been extensively studied in lieu of optimal control problems, in search for the best achievable performance, leading to the discovery of fundamental performance limits defined under various criteria. Traditionally, performance limitation studies have been carried out based on frequency domain techniques, under the assumption that the system components exchange information in an ideal, perfect manner, neglecting all too conveniently the effect of communication on control. Both results and techniques are largely confined to linear time-invariant systems.

Bode integral relations and Shannon’s information theory are the twin pillars of control and information sciences, and they laid the very foundation for the design of control systems and communication systems, respectively. As today’s technological world is increasingly more information-rich and performance-driven, there has been
growing recognition that control and communication, the two cornerstones of modern technologies, may and should be integrated ever more closely, and that the design of new engineering systems and networks can benefit from the fusion of control and communication theories. This recognition has become ever more so acute, with the recent rise of attention to networked feedback and cyber-physical systems. Networked feedback systems differ from the conventional control systems and usher in novel challenges unexplored in the past: in a networked control system, the sensor measurement and control actuator signals are transmitted through certain communication links. Since information transmission cannot be ideal and is in general noisy and constrained, the communication constraints and transmission losses are likely to impede control performance; in other words, other than the plant itself, communication channels in the feedback loop will also impose limitations. A central task in designing networked control systems, therefore, is to explicitly acknowledge and incorporate communication constraints in controller design. Yet unfortunately, the existing information and control theories fail to reconcile: while intrinsically interrelated, they are nonetheless grounded on utterly different conceptual paradigms and mathematical constructs, neither of which can be readily applied to another. That a networked system often exhibits nonlinear, time-varying behaviors also poses a formidable technical barrier, which requires new mathematical tools than conventional frequency domain analysis.

This book is an attempt toward bridging information and control theories for the study of performance limitations of networked control systems, where communication constraints and information limits emerge as a salient feature. We develop a general information-theoretic framework for analyzing the limitations and tradeoffs imposed by communication channels on feedback control performance, by developing new information measures compatible to control system analysis and new Bode-type integral relations applicable to information-constrained networked feedback systems.

The book consists of nine chapters. Chapter 1 provides a brief introduction to the main contents of this book together with a survey of the field literature. Chapter 2 presents the necessary mathematical background on information measures and spectral analysis for the subsequent derivations of control performance limitations. Chapter 3 is devoted to control performance measures, including the $\mathcal{H}_\infty$ norm and power gain, as well as discussions on their properties. Chapter 4 introduces the notion of channel blurredness and the “fire-quenching” power allocation policies it leads to. Chapter 5 develops Bode-type integrals for single-input, single-output (SISO) networked feedback systems. Chapter 6 discusses bounds on power gain and henceforth the intrinsic performance limits of SISO networked feedback systems. Chapter 7 derives Bode-type integrals and power gain bounds for multiple-input, multiple-output (MIMO) networked feedback systems. Chapter 8 examines performance in the context of estimation systems. Chapter 9 considers continuous-time systems and presents the continuous-time versions of the information measures, Bode-type integrals, and bounds on power gain.

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