Control of Linear Systems With Regulation and Input Constraints—Ali Saberi, Anton A. Stoorvogel, and Peddapullaiah Sannuti (New York: Springer-Verlag, 1999) *Derong Liu*

Over the past decade, several books have been published that deal with the subject of control systems with constraints, whether the constraints are on the states of the system or on the control inputs of the system (see, e.g., [2]–[5]). The present book studies in detail the problem of output regulation under constrained and unconstrained inputs for linear systems. Constraints for the inputs are specified in the form of actuator amplitude saturation as well as actuator rate saturation. In the classical control formulation (e.g., tracking control) of output regulation problems, constrained inputs are considered, while in the optimal control formulation (H_2 and H_∞), output regulation itself is considered as a constraint. In the former formulation, the objectives of controller design include "internal stability" and "output regulation" under actuator and rate saturation, while in the latter, the objectives of controller design become "internal stability," "optimal performance measure," and "output regulation." Both continuous-time systems and discrete-time systems are considered in the book.

When the states of a linear system are subjected to saturation-type effects/nonlinearities, the system is in fact a nonlinear system. However, when such type of effects are only present on the control signals, such as the case considered in the book under review, the system is still a linear system. Earlier works related to actuator saturation have dealt with control systems with constrained or bounded controls (e.g., [5]–[9]). In practice, all control actuation devices are subject to amplitude and rate saturation. Every conceivable physical control input in every conceivable application is ultimately limited due to the limited power that can be provided by the actuator. Examples of such control inputs include force, torque, thrust, stroke, voltage, current, and flow rate. In fact, the importance of actuator saturation was recognized and reflected in the original formulation of many fundamental control problems, including controllability and optimal control. Control problems that involve hard nonlinearities such as actuator and rate saturation, however, turn out to be difficult to deal with. As a result, even though there have been continual efforts in addressing actuator saturation (see the chronological bibliography [1] and the references cited therein), its effects have not been addressed thoroughly in the modern control literature. On the other hand, output regulation has been one of the central topics in the development of control theory. This is the problem of designing a feedback controller that internally stabilizes a system and at the same time guarantees the output of the systems to track a certain reference signal. The authors of the book have published numerous results on new developments of output regulation in the past decade. This book is their newest addition that provides a treatise on the output regulation problem for linear systems under actuator and rate saturation as well as under optimal transient requirements.

Chapter 1 provides a brief introduction to the book. Notation and terminology including the system description are introduced.

Chapter 2 concerns the classical exact output regulation problem under no constraints on the actuators. The control objective is to have the output of the system track a reference signal that is produced by an exosystem. The problem formulation also includes an exosystem that generates a disturbance for the system and, thus, disturbance rejection is also part of the control objective. The chapter first reviews state feedback and output feedback solutions under no constraints on the actuators. It then clarifies and extends several facts of output regulation such as well-posedness of the output regulation problem, internal model principle, and structural stability.

The *first major theme of the book* concerns the classical exact output regulation when the actuators are subject to amplitude and rate saturation, which is covered in Chapters 3–5. Chapters 3 and 4 consider the case when the actuators are subject to only amplitude saturation for continuous and discrete-time systems, respectively. State feedback and output feedback controllers are obtained with low-gain and low-and-high-gain options. Chapter 5 deals with the general case of both amplitude and rate saturation of inputs for both continuous-time and discrete-time systems. Again, state feedback and output feedback controllers are obtained with low-gain and low-and-high-gain options.

Chapter 6 studies exact output regulation along with optimal transient performance requirements. The systems in this chapter are not subject to input constraints. It studies some performance issues in the linear quadratic regulator problem including the determination of the infimum of the performance measure, solvability conditions for optimal and suboptimal output regulation problems, as well as construction of optimal and suboptimal output regulators. This chapter fits the title of the book since output regulation is considered as a constraint.

The *second major theme of the book* concerns general performance and robustness issues with output regulation constraints which is addressed in Chapters 7–12. Some key results are developed in Chapter 7 which are then used in the development of subsequent chapters. The problem of achieving a desired performance with output regulation constraint is formulated and translated to an unconstrained optimal control problem. Specific cases of performance measures are considered in Chapters 8–11. Chapters 8 and 9 investigate H_2 optimal control and suboptimal control for continuous-time and discrete-time systems, respectively. In addition to stability and output regulation requirements, an H_2 optimal/suboptimal controller minimizes the H_2-norm of the closed-loop transfer function. Chapters 10 and 11 study the same under H_∞-norm, for continuous-time and discrete-time systems, respectively. In Chapter 12, the notion of robust output regulation in the presence of structured model uncertainties is introduced. This chapter is a short chapter that motivates further research rather than providing solutions. For example, the "robust almost output regulation problem" is one of the open problems.

The *third major theme of the book* concerns the generalization of the classical output regulation problem which is addressed in Chapters 13–16. In Chapter 13, the topic of exact output regulation introduced in Chapter 2 is generalized in several ways including output regulation with arbitrary reference signals and almost output regulation. Results presented in this chapter are all under no constraints on the actuators. In Chapters 14 and 15, the generalized output regulation problem is studied for linear systems with actuators subject to amplitude saturation for continuous-time and discrete-time systems, respectively. Both state feedback and output feedback controller designs are considered. In Chapter 16, the same problem is studied for both continuous-time and discrete-time systems with actuators subject to amplitude and rate saturation.

In Chapter 17, the issue of what can be done if classical output regulation is not possible is considered. Output regulation in the sense of minimizing the power of the error signal is suggested as an option.

Finally, an Epilogue is provided to pose some open problems in the field. In particular, some problems left open in some of the chapters in the book are summarized.

The book reads very well. The topics chosen are of interest to practicing control engineers, graduate students, and researchers. Results in this book make great contributions to the important research area of

The reviewer is with Department of Electrical and Computer Engineering, University of Illinois at Chicago, Chicago, IL 60637 USA (e-mail: dliu@ece.uic.edu).

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control systems with output regulation and input constraints. However, several chapters in this book are very short, indicating incomplete work and potential for future developments.

REFERENCES

[1] D. S. Bernstein and A. N. Michel, "A chronological bibliography on saturating actuators," *Int. J. Robust Nonlinear Control*, vol. 5, pp. 375–380, 1995.

[2] T. Hu and Z. Lin, *Control Systems With Actuator Saturation: Analysis and Design*. Boston, MA: Birkhäuser, 2001.

[3] V. Kapila and K. M. Grigoriadis, Eds., *Actuator Saturation Control*. New York: Marcel Dekker, 2002.

[4] Z. Lin, *Low Gain Feedback*. New York: Springer-Verlag, 1998.

[5] D. Liu and A. N. Michel, *Dynamical Systems with Saturation Nonlinearities: Analysis and Design*. New York: Springer-Verlag, 1994.

[6] L. Pandolfi, "Linear control systems: controllability with constrained controls," *J. Optim. Theory Applicat.*, vol. 19, pp. 577–585, 1976.

[7] W. E. Schmitendorf and B. R. Barmish, "Null controllability of linear systems with constrained controls," *SIAM J. Control Optim.*, vol. 18, pp. 327–345, 1980.

[8] E.D. Sontag, "An algebraic approach to bounded controllability of linear systems," *Int. J. Control*, vol. 39, pp. 181–188, 1984.

[9] R. P. VanTil and W. E. Schmitendorf, "Constrained controllability of discrete-time systems," *Int. J. Control*, vol. 43, pp. 943–956, 1986.