Preface

This book addresses both the problems of stability analysis and stabilization of linear systems when subject to control saturation. It is well known that actuator saturation is present in practically all control systems. The magnitude of the signal that an actuator can deliver is usually limited by physical or safety constraints. This limitation can be easily identified in the most common devices used in the process industry, such as proportional valves, heating actuators, power amplifiers, and electromechanical actuators. Common examples of such limits are the deflection limits in aircraft actuators, the voltage limits in electrical actuators and the limits on flow volume or rate in hydraulic actuators. While such limits obviously restrict the performance achievable in the systems of which they are part, if these limits are not treated carefully and if the relevant controllers do not account for them appropriately, peculiar and pernicious behaviors may be observed. In particular, actuator saturation both in magnitude and rate have been implicated in various aircraft crashes [8] and the meltdown of the Chernobyl nuclear power station [330]. Hence, an in-depth understanding of the phenomena caused by saturation is key to solve and avoid problems in industrial control. Actually, the operation problems which can be induced by actuator saturations are well known in industry. This is the reason why, frequently, the actuators are oversized with respect to the energy necessary to control the system and the control gains are limited with respect to what could be accepted while preserving the stability. The engineering solutions intend to avoid, as much as possible, occurrence of saturation during operation. Then, the study of saturated systems is of a real interest for engineers in various domains due to its potential to provide, for example:

- Reduction of validation costs of control laws;
- Better use of actuator (and/or sensor) capacity;
- The possibility for control engineers to become involved in the design process at a much earlier stage in order to help choose actuators/sensors which have a reduced size, mass etc.

Motivated by these practical issues, the actuator saturation problem has deservedly received the attention of many researchers since the second part of the twentieth century. An excellent overview on saturated systems has been published in 1995 by Bernstein and Michel [25]. More recently, great advances were made on this subject. This is attested by the large number of publications on this topic that can be found in important conferences and journals of control systems and applied mathematics.

Although an extensive literature in the form of articles can be found, only a small number of books devoted to this subject is available. Examples are the books edited by two of ourselves [346, 361] and the one edited by Kapila and Grigoriadis [208]. The former three books are presented in the form of a collection of chapters, written by different authors, with the particular aim of presenting new trends and specific advanced topics on the analysis and synthesis of control systems subject to actuator saturation. We believe now it is timely to write a textbook on the problem of control saturation, but given the diversity of approaches, it is certainly a challenge. To write a book addressing all the approaches and aspects related to this problem is a nearly impossible task. The main challenge then is to choose a set of specific topics or approaches and present them in a coherent and self-contained way. We think that this has been successfully achieved, for instance, in the book of Saberi et al. [310], where the main focus concerns the structural conditions for the solvability of many problems involving systems with input constraints. Other examples are the books [127, 188].

Roughly speaking, there are two approaches which one could adopt to avoid saturation problems in systems which are known to have actuator limits (i.e. the vast majority of practical systems). One approach, which we shall refer to as the one step approach is, as its name implies, an approach to controller design where a (possibly nonlinear) controller is designed “from scratch”. This controller then attempts to ensure that all nominal performance specifications are met while also handling the saturation constraints imposed by the actuators. Let us emphasize that Part II of this book is dedicated to present several solutions in the scope of this approach in both analysis and synthesis frameworks.

An alternative approach to the above is to perform some separation in the controller such that one part is devoted to achieving nominal performance and the other part is devoted to control constraint handling. This is the approach taken in anti-windup compensation, which is the subject of Part III of this book. In anti-windup compensation, a linear controller which does not explicitly take into account the saturation constraints is first designed, usually using standard linear design tools. Then, after this controller has been designed, a so-called anti-windup compensator is designed to handle the saturation constraints. The anti-windup compensator is designed to ensure that stability is maintained (at least in some region near the origin) and that less performance degradation occurs than when no anti-windup is used.

The primary goal of the present work is to provide basic concepts and tools that we consider fundamental for the analysis and synthesis of linear systems subject to actuator saturation. Additionally, we aim to present in a formal, but also didactic way, some recent developments on the subject. As pointed out above, we do not intend to cover exhaustively all the approaches and the results on the subject. Naturally, we mainly focus on topics directly related to our own research in the field. In this sense, we consider a state space approach and we focus on the problems of stability analysis and synthesis of stabilizing control laws both in local and global contexts. In particular, different ways of modeling the saturation term and the behavior of the nonlinear closed-loop system are explored. Also, different kinds of Lyapunov functions such as polyhedral, quadratic and Lure type, are considered in order to present different stability and stabilization conditions. Results considering uncertain systems and performance in the presence of saturation are also presented. Associated with the different theoretical results, we propose methods and algorithms for computing estimates of the basin of attraction and for designing control systems taking into account, a priori, the control bounds and the saturation possibility. These methods and algorithms are mainly based on the use of linear programming and convex optimization problems with LMI constraints. Thus, they can easily be implemented with widely known mathematical software packages. We believe we address some aspects that are not yet covered, or not discussed in-depth, in the books currently available on this subject.

Finally, we hope this book will be a valuable reference for engineers (mainly aeronautical, electrical, mechanical and chemical), working on control applications, as well as graduate students and researchers interested in the development of new tools and theoretical results concerning systems with saturation. Due to its structure, it can also be used as a textbook in a specific course on saturation or as a complementary text in classical courses on control systems. The background required for the reader consists of basic concepts of linear and nonlinear systems, including linear algebra and matrix theory, differential equations, state space methods, and robust control theory, which can be found, for example, in classics like the books of Chen [64], Kailath [205], Khalil [215], Luenberger [252], O'Reilly [277], Sontag [327], Vidyasagar [385], Colaneri et al. [74], Zhou et al. [414], Skogestad and Postlethwaite [323]. Some familiarity with linear programming, convex analysis and LMIs is also desirable. As additional references for all these topics we can recommend the books of Maciejowski [255], Boyd et al. [45] and Zaccarian and Teel [406].

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