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Alfonso Baños · Antonio Barreiro

Reset Control Systems

Springer

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To Angeles and Alfonso (A. Baños)
To Rosa, María, and Marta (A. Barreiro)

Series Editors' Foreword

The series *Advances in Industrial Control* aims to report and encourage technology transfer in control engineering. The rapid development of control technology has an impact on all areas of the control discipline. New theory, new controllers, actuators, sensors, new industrial processes, computer methods, new applications, new philosophies all lead to new challenges. Much of this development work resides in industrial reports, feasibility study papers and the reports of advanced collaborative projects. The series offers an opportunity for researchers to present an extended exposition of such new work in all aspects of industrial control for wider and rapid dissemination.

The name of Isaac Horowitz is usually associated with quantitative feedback theory (QFT), but his first-order reset element (FORE) is probably not so well known. This Horowitz FORE compensator was a generalisation of the seminal Clegg Integrator (1958) in which integral control was coupled with a reset mechanism to inculcate additional performance and design benefits. These two compensators are the original inspiration and source for the results and applications reported in this *Advances in Industrial Control* monograph, *Reset Control Systems*, by Alfonso Baños and Antonio Barreiro. In fact, the authors' whole reset control research project seems to have been much motivated by original meetings in Spain with Professor Horowitz.

The monograph is a comprehensive presentation of reset control systems, covering the fundamental theoretical foundations, design rules and applications experience. The monograph has four chapters on theoretical fundamentals. Opening these is an invaluable introductory chapter (Chap. 1) that guides the reader through the historical development of reset control. This particular chapter also sets out the theoretical context of reset systems and identifies their relationship with other related theoretical fields, for example impulsive and hybrid systems. Chapters. 2 to 4 contain the core theoretical results of the monograph and set out, possibly for the first time, a complete systems analysis framework for reset control.

Design for reset control is treated in Chap. 5, where the focus is on identifying the type of systems for which reset control offers good design and performance benefits. Alongside this; sets of useful compensator tuning rules are presented for different compensator and system types. The chapter also investigates the properties of the authors' own novel PI + CI reset compensator.

In control engineering, the assessment of usefulness, effectiveness, design ease and performance gain is through real applications studies. In this respect, the case studies of Chap. 6 provide a trio of demanding "benchmark" applications. The authors expose all the steps of trying to accomplish successful reset control system designs. The applications are from process control (a pilot heat exchanger plant), control by tele-operation (a remote controlled process application that uses the Internet for communication) and utility process operations (a solar collector field control problem). This chapter allows both the practitioner and the theoretician to see how reset control works in practice, and the insights provided will undoubtedly inspire new developments for the reset control field.

This invaluable and comprehensive study of reset control systems by Professors Baños and Barreiro joins several other recent *Advances in Industrial Control* monographs that give more fundamental presentations of new potential applicable topics. One such monograph is *Process Control* by Jie Bao and Peter L. Lee (ISBN 978-1-84628-892-0, 2007) that was received enthusiastically; another is *Fractional-order Systems and Controls* by Concepción A. Monje, YangQuan Chen, Blas M. Vinagre, Dingyü Xue and Vicente Feliu (ISBN 978-1-84996-334-3, 2010), and a third is, *Internet-based Control Systems* by Shuang-Hua Yang (ISBN 978-1-84996-358-9, 2011). The industrial control engineer, the control academic or control postgraduate researcher may find these three "fundamentals with applications" texts along with, *Reset Control Systems* essential volumes for inclusion in a complete control library.

Industrial Control Centre, Glasgow, Scotland, UK M.J. Grimble
M.A. Johnson

Foreword

As part of the small community of control researchers, often referred to as the QFT-ers, I first met Alfonso Baños in 1997 at an international QFT conference in Glasgow, Scotland. We kept in touch throughout the years via emails, and in 2008 he arranged for his PhD student, Joaquín Carrasco, to spend a few months in my research lab. Joaquín's thesis focused on reset control, and he wanted to learn about our activities in that area. Since then, I continued to follow their work and have come to fully appreciate their contributions to the area of reset control.

My foray into reset control research was somewhat accidental. While working on challenging industrial robust control problems, we 'stumbled' upon a series of papers from the 1970s written by the late professor I. Horowitz, the founder of QFT, and his students. I recall that right away we noticed something unique about these papers. Horowitz presented nontraditional solutions to overcome the limitations of linear, time-invariant (LTI) control. Horowitz was already familiar with Clegg-integrator and similar concepts that were introduced a few decades earlier on purely empirical grounds. Horowitz's results on Clegg-integrator and First-Order Reset Element (FORE) offered the practicing control engineer a systematic and transparent procedure for using such nonlinear elements in feedback control design. In our own work, we initially attempted to use these ideas in experiments, and motivated by successful results, we decided to investigate if one can explain such results theoretically. Orhan Beker, a PhD student of CV Hollot and I, was able to prove for the first time that reset control can overcome classic LTI performance limitations in a feedback system comprising a plant with an integrator. I believe that these encouraging results may have spurned other groups, including Baños's and Barreiro's, to probe deeper into this area which falls under the more general subjects of hybrid control systems and impulsive control.

This book presents a compilation of numerous results derived by the authors and colleagues. The material is written in self-contained manner and offers the interested reader an exposition of current state-of-the-art results. The authors present stability theory in progression starting from reset-times independent results and reset-times dependent results, to the more general passivity-based results. A whole chapter is devoted to time-delay systems where LTI limitations are especially harsh and stability conditions take the form of linear matrix inequalities. Numerical examples are sprinkled throughout the presentation so to bring life into the theory.

In addition to the book's theoretical focus, the authors appear to have made deliberate effort to remain true to the original motivation behind Horowitz's original work to provide the control engineer with a practical technique for design of reset control systems in applications. They achieve this goal using describing function analysis as a design tool, extend the notion of reset to a partial reset compensator where only some of the compensator states are reset, and introduce a new reset compensator that consists of a PI compensator whose integrator is reset only at a fraction of Clegg integrator reset times. An entire chapter presents experimental applications of reset control systems in a temperature control of a heat exchanger, a bilateral teleoperation, and a temperature control of a solar collector field.

In closing, I would like to thank the authors for asking me to write this forward. This well written book strikes a fine balance between sophisticated theory and engineering design and therefore should be accessible to most readers. In writing this book, the authors have succeeded in continuing Horowitz's philosophy for feedback control research.

Amherst, USA Yossi Chait

Preface

Although the origin of reset control systems goes back to 1958 with the founding work of Clegg, the subject is still in its infancy. The seminal works of Horowitz and coworkers in the 1970s were the first attempts to build a synthesis theory for basic reset compensators such as the Clegg integrator or the FORE (first-order reset element), but the lack of a control theory, approaching basic questions such as well-posedness and stability, for several decades has put aside of the mainstream further developments in reset control, both in theory and applications. It is not until the late 1990s that reset control starts to develop with the works of Chait, Hollot and coworkers, giving a significative impetus to the field. In the meantime, the area of hybrid control systems and impulsive control also give numerous results, having clear connections with reset control. For the last decade, a number of international groups have been working actively on reset control, and fortunately, reset control has started to be seen as an attractive control design technique with a significant potential for practical control applications.

The first direct contact of the authors with reset control was in September 2000, when Isaac Horowitz was visiting our group in Spain. We were actively working in nonlinear QFT at that time, that uses linear compensation, and in several fruitful discussions he gave us clear arguments for the many benefits of using nonlinear/reset compensation to attack the "nonlinear tiger" and also to overcome fundamental limitations of LTI systems. We started to seriously work on reset control in 2006, and since then our goal has been to develop a formal theory to cover basic theoretical aspects, and also to define simple compensator structures and tuning rules for them, with the focus on some practical problems, including applications in process control and teleoperation, and in general systems with time-delays.

The first chapter of the book is an introduction to reset control systems, pursuing two objectives. The first objective is to give a quick and simple description of what a reset control is, and to provide basic explanations on why and when it is convenient to use this strategy. This objective is covered by the first two sections and is summarized in this key idea: *a reset control is a simple nonlinear control technique very effective for linear plants subject to fundamental design limitations*. The second objective of the chapter is to give a brief survey on the literature on analysis and design of reset control systems. The historical perspective begins with the early ideas on reset control, including the popular Clegg integrator and the first-order reset element (FORE) introduced by Horowitz and coworkers. In addition, the first series of rigorous results on analysis and design of reset controllers using a state-space description are given, including full reset and partial reset compensators. In addition, relationships between reset control and the wider field of impulsive and hybrid control systems will be analyzed from different points of view.

In Chap. 2, a definition of a reset control system, or a reset system in general, is given. In general, as it is common in impulsive systems, reset systems may exhibit different types of solutions, in particular having complex patterns such as beating, deadlock, and Zenoness. In control practice, this type of behavior is considered pathological and thus several conditions will be given for reset control systems to be well-posed. On the other hand, important properties of reset systems may be derived by analyzing the reset instants that correspond to a given initial condition. These patterns will be also analyzed, and their relationship with the observability and reachability of the base linear system will be shown.

Chapter 3 is devoted to the stability problem of reset control systems with finite-dimensional base systems. The stability problem is addressed from different, complementary points of view: (i) internal or Lyapunov stability, (ii) external or input–output stability with passivity analysis, and (iii) stability by the describing function method. Internal stability techniques are subdivided into techniques giving rise to stability conditions that do not depend directly on the reset instants (reset-times independent), or alternatively, are reset-times dependent. The first case is obtained directly using continuous time Lyapunov functions (that gives rise to the so-called H_β condition), while the second case (reset-times dependent) requires a discretization at the after-reset values and a subsequent discrete-time Lyapunov analysis. Then, the input–output $\mathscr{L}_2$ stability is studied, and a number of results are presented in connection with passivity and dissipativity properties of reset feedback loops. Finally, the standard describing function tool is used for approximately predicting the appearance or absence of oscillations.

Stability of time-delay systems under reset control is approached in Chap. 4. Since reset control is able to overcome fundamental limitations, and time-delay is one source of such limitations, then it is of great interest to study the problem of delayed reset systems. The stability is addressed by choosing an appropriate Lyapunov–Krasovskii functional, and by imposing that the functional should decrease in the continuous and reset modes. The resulting conditions take the form of linear matrix inequalities, and, depending on the chosen functional, these LMIs can be delay-dependent or delay-independent. In both cases, those LMIs, derived from time-domain stability conditions, are translated into equivalent frequency-domain conditions by means of adequate tools, like the Kalman–Yakubovich–Popov lemma, or passivity techniques. From the latter frequency-domain conditions, useful interpretations are exhibited regarding the achieved robustness, in terms of scaled small-gain or positive realness of certain subsystems. Finally, several examples illustrate the application of the stability conditions, showing the potentials of reset control when applied to time-delay systems.

In Chap. 5, reset compensation has been used to overcome limitations of LTI compensation. In this chapter, a new reset compensator, referred to as PI + CI, is introduced. It basically consists of adding a Clegg integrator to a PI compensator, with the goal of improving the closed loop response by using the nonlinear characteristic of this element. It turns out that by resetting a percentage of the integral term in a PI compensator, a significant improvement can be obtained over a well-tuned PI compensator in some relevant practical cases, such as systems with dominant lag and integrating systems. The main goal is the development of PI + CI tuning rules for basic dynamic systems in a wide range of applications, including first- and higher-order plus dead time systems. In addition, a number of design improvements such us the use of a fixed or variable reset band, the integration with QFT, and the use of a variable reset percentage are discussed.

Finally, in Chap. 6, several practical applications of reset control systems will be developed, all based on the PI + CI compensator: a temperature control system of a heat exchanger, a bilateral teleoperation control system, and finally, a temperature control of a solar collector field. The first two applications have been tested by means of experiments in plants, while the third has been tested by using a (well-proven) simulator of the field.

This book is a compendium of the several works developed by our groups in the last five years. These works have been performed in collaboration with Joaquín Carrasco, Angel Vidal, Alejandro Fernández, Juan Ignacio Mulero, Sebastián Dormido, José Carlos Moreno, Manuel Berenguel, and Arjan van der Schaft. In fact, they are responsible for many parts of this book. The authors also acknowledge the support of 'Ministerio de Ciencia e Innovación' (Spanish government) under the joint projects DPI2004-07670, DPI2007-66455, and DPI2010-20466.

Thus, the book has been planned as a means to systematize and make available to a wider audience a number of publications that are disseminated over several journals and conference proceedings. It is intended for control researchers interested in a solid introduction to reset control, including the several approaches available in the literature, and also for control engineers interested in application of simple and efficient control techniques that may overcome fundamental limitations of the universally used PI/PID compensators.

Murcia, Spain — Alfonso Baños
Vigo, Spain — Antonio Barreiro

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