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Model-Reference Robust Tuning of PID Controllers

Springer

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V. M. Alfaro dedicates the book to his wife María Amanda and to his children Alejandro, Carolina, and Sebastián.

R. Vilanova thanks his beloved wife Rosa for her love and support during the time spent in writing the book.

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,..., 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.

In an interesting recent journal paper [1], some survey evidence was presented that supported the premise that PID control continues to play a significant role as an industrial controller in a wide range of industries. For low-level loops the PID controller is simple to apply and sufficiently effective to justify its continued widespread popularity. The *Advances in Industrial Control* monograph series has always aimed to feature the most recent developments in this field. In 2012, the series published a wide ranging survey text *PID* Control in the *Third Millennium* edited by Ramon Vilanova and Antonio Visioli (ISBN 978-1-4471-2424-5, 2012). This volume demonstrated the breadth of ideas and applications appearing in the PID control field.

However, for the purposes of this Foreword it is sufficient to map the practical tools of the evolving science of PID control onto the two categories of "PID controller tuning" and "PID controller performance monitoring".

PID Controller Tuning

Controller design begins with the desired performance specification. The metrics to be achieved by the control have grown in number over recent years to take in concepts such as robustness and fragility. A subset of the design specifications are usually used by the design algorithm that can be an offline or online procedure. The particular field of automated online PID controller design is one of considerable interest to the industrial control engineer. Ultimately the PID controller design will meet only some of the possible controller specifications and then the remaining metrics can be used as controller evaluation metrics. There are a number of monographs in the *Advances in Industrial Control* series on these topics; the most recent being:

- *Control of Integral Processes* with Dead Time by Antonio Visioli and Qing-Chang Zhong (ISBN 978-0-85729-069-4, 2011);
- *Non-Parametric Tuning of PID Controllers* by Igor Boiko (ISBN 978-1-4471-4464-9, 2012); and
- *Industrial Process Identification and Control Design* by Tao Liu and Furong Gao (ISBN 978-0-85729-976-5, 2012).

PID Controller Performance Monitoring

Once a controller has been implemented, the question arises as to how to verify that it is retaining its desired performance over operational time. The idea of monitoring controller performance is a generic one and not just restricted to PID controllers. However, the possible situation of a large number of PID loops in a process plant has led to significant monitoring algorithm developments for the PID control field. An online automated performance monitoring routine is a very attractive economic proposition for industrial PID applications. The survey paper [1], cited above provides an excellent overview of the current state of the art of such methods. On this topic, the *Advances in Industrial Control* monograph series has titles that include:

- *Process Control Performance Assessment* edited by Andrzej W. Ordys, Damien Uduehi and Michael A. Johnson (ISBN 978-1-84628-623-0, 2007); and
- *Control Performance Management in Industrial Automation* by Mohieddine Jelali (ISBN 978-1-4471-4545-5, 2012).

This monograph, *Model-Reference Robust Tuning of PID Controllers*, by Victor M. Alfaro and Ramon Vilanova is clearly a contribution to the PID-controller-tuning literature. When dealing with controller design specifications and controller evaluation metrics, the authors discuss both time-domain and frequency-domain metrics and specifications. Subsumed into this assessment framework are both controller robustness and controller fragility. Whereas controller robustness measures the effect on performance and stability of changing process parameters, controller fragility inverts this to measure the effect of the variability of the controller parameters for a fixed given design process on performance and stability. Measures of controller fragility find application in controller commissioning where online tuning may move controller parameters away from design values with a concomitant change in closed-loop performance and stability. This aspect is discussed by the authors in Chap. 3, and is just one of the interesting topics found in this monograph.

The monograph reports the joint research of the authors. Professor Victor Alfaro is with the Department of Automation at the Universidad de Costa Rica. He has had a long and distinguished career in various industries as a practicing engineer before joining the academic community. Professor Ramon Vilanova is with the Department of Telecommunications and Systems Engineering at the Universitat Autònoma de Barcelona. He has made many contributions to the PID control literature. His industrial work has included important control research for wastewater treatment plants.

The Editors of the *Advances in Industrial Control* monograph series are very pleased to add this title to the important set of monographs in the series on all aspects of PID control.

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

Reference

1. Bauer, M., Horch, A., Xieb, L., Jelali, M., Thornhill, N.: The current state of control loop performance monitoring—A survey of application in industry, J. Process Control **38**, 1–10 (2016)

Preface

Controllers and controller design are at the heart of industrial progress. Controllers allow to keep process variables of interest at prescribed values in order to guarantee product quality as well as better production times. The controller receives information of the actual value of the process variable of interest, the controlled variable, and of the desired value for this, the controller set-point. It compares these two values to obtain the actuating error signal. Commercial controllers with a proportional integral derivative control algorithm, PID for short, were introduced back in 1940. As has been widely reported elsewhere, 75 years later it still is a more common control algorithm used in the processes industry.

The influence on the controller output signal of each one of the control modes can be adjusted setting its corresponding adjustable parameter. Although the PID control algorithm provides to the user the opportunity of combining the information of the error signal (P), its integral over time (I), and its rate of change (D), most of the controllers in operation use only the error signal and of its integral, in a proportional integral control, or simply PI control. Among this underuse of the PID capabilities, it is a well-known fact that poor controller tuning is a common situation, bearing in mind that there are many tuning rules to allow the specification of the controller parameters. One may think that, in fact, there exists an overwhelming quantity that makes it difficult to decide and apply. In addition to this great variety of tuning approaches, even though the PID controllers are of fixed structure over the years some additional capabilities have been incorporated into them: measurement and set-point signal filters, set-point weighting factors, reset windup prevention, and other features. At the controlled process side, there is a wide range of dynamic characteristics: over- and underdamped, integrating, unstable, slow, fast, nonlinear, and their possible combinations.

The control system designer faces the task of selecting the controller control algorithm parameters to restrict the controlled process variable to perform according to certain design criteria. These criteria would include, among others, evaluation of the control system performance and relative stability. The possible combinations of control algorithms, controlled process dynamics and information, design criteria, and design approaches result in the diversity of tuning relations that have been growing over the years and reveal plenty of technical publications available in this subject.

From the existing literature on PID controller design, it is easy to see that different design approaches exist depending on the controlled process dynamics and even on the way the desired performance is stated. This clearly contributes to the confusion that prevents practitioners from the application of tuning rules. As said above, the purpose of the book is to provide a comprehensive and didactical presentation of a unifying approach for controller design (in fact when applied to PID controllers it may fit into any fixed structure controller) that deals in an explicit way with the performance/robustness trade-off as one of the key points in modern PID tuning.

The proposed controller design procedure is based on the use of closed-loop transfer functions targets (the *reference models*) to obtain robust control systems, therefore is named *Model-Reference Robust Tuning* (MoReRT). As design main considerations are, in addition to the closed-loop responses shapes, the control system relative stability, its robustness to process variations, and to obtain a smooth control effort.

This book is based on the research work the authors carried out during the past few years. It is not intended to be a research report but a unified presentation of the previously referred MoReRT methodology for PI/PID controller design. As found in references, a somewhat complete set of journals can be accessed where a deeper discussion on some control topics can be found. Also the comparison of the proposed design approach with some approaches previously existing in the literature has been excluded from the book content. These comparisons can be found on the referred journal papers as the main goal of the book is to serve as a comprehensive presentation of a design approach that, in the authors opinion, deserves some extensions and particular applications, which would be difficult to forecast just by looking at the set of *disconnected* results that journal papers usually constitute.

The book comprises a total of 11 chapters and one appendix. The contents can be structured along four parts.

The first part comprises Chaps. 1–3. These chapters provide a generic description of the control system under study as well as some particular insights into PID controllers formulations and metrics to evaluate its performance. These topics could be general to any other approach to PID controller design. Specifically, the feedback control design problem and the evolution over time of the considerations taken for PID tuning are briefly presented in Chap. 1. The two-degree-of-freedom proportional integral derivative (2DoF PID) control algorithm structures and their conversion relations are presented in Chap. 2. Parameter conversion formulas take into consideration the derivative filter constant. This chapter is innovative enough to be of interest in its own because in the PID controller literature the equivalence and conditions that make such equivalence possible are not found. Particular results for PID control are usually presented by adopting one of the multiple PID formulations. In Chap. 3 the indices used for performance, robustness, and control system fragility evaluation are presented. Control system robustness is evaluated using the maximum of the sensitivity function (maximum sensitivity).

The second part of the book contains Chaps. 4 and 5, where the methodological formulations of the MoReRT are presented. Chapter 4 describes the basis of the proposed model-reference robust tuning (MoReRT) design methodology and how the model-reference closed-loop transfer functions are selected, the cost functional stated for optimization, and the available free design parameters. This proposal is to be applied to a variety of process dynamics in order to derive the corresponding tuning rules. However, application will consider normalized models for controlled process and controller. This will ensure to satisfy the so-called time-scaling property. Therefore, before proceeding to the derivation of the robust tuning rules, normalized controlled process models and controllers equations used in the design are presented in Chap. 5. The use of normalized controlled process models and normalized control algorithms allows to obtain dimensionless controller tuning rules.

The third part of the book contains the development of tuning rules for all the considered process dynamics. It can therefore be considered the core part of the book. The MoReRT control of overdamped controlled processes is presented in Chap. 6, where controllers with 2DoF PI and PID control algorithms are used for robust control of first- and second-order controlled process models. A comparison of the achievable performance, under the same robustness, is done by using a PI or a PID controller and also by the fact that designing a controller is by using a first- or a second-order process model. The robust control of inverse response processes is described in Chap. 7. Here it is stated that the right-half plane zero position impose constrains to the achievable control system robustness. In Chap. 8 MoReRT control of first- and second-order integrating processes is presented. For first-order integrating models, the MoReRT design results in a very simple tuning for the normalized controller parameters. In Chap. 9 the MoReRT design is used to tune 2DoF PI and PID controllers for unstable processes. The unstable pole position imposes severe constraints on the achievable control system robustness. One of the detectable points in all the developments shows how MoReRT allows to face the PI/PID design problem from the same point of view.

The fourth part of the book describes potential extensions of the method as well as considerations for its practical applications. Three possible extensions of the MoReRT methodology are presented in Chap. 10. First of all, it is used in the case where the purpose is to design the profile of the manipulated variable instead of, as usual, the controlled variable. Second, a more general MoReRT design is applied in the case where the dynamics of the disturbance to the controlled variable is different from the dynamics of the manipulated variable to the controlled variable. This makes the design problem a little bit more complex, and the fact of facing multiple dynamics makes it not possible to derive general tuning rules. Instead, it is shown how MoReRT can be formulated and applied. Third, the use of the MoReRT design in robust tuning of a Smith predictor type dead-time compensating PI controller, including the predictor model parameters, is presented. As a source of practical considerations, the book ends with the description of the 2DoF PID control algorithms available in some commercial controllers, programmable logic controllers, and digital control systems. A condensed reference of the MoReRT tuning relations is also presented with its applicability ranges and constraints. A general outline for the implementation of a MoReRT design procedure and the application of the proposed tuning method to control a typical industrial process are provided in Chap. 11.

The book ends with an appendix describing a software package developed for MATLAB® in order to facilitate the implementation of the MoReRT approach. The provided routines just require the user to input the process information data and the desired controller structure. The software will perform the required optimizations and show the closed-loop responses for the obtained controller.

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