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# Control Engineering

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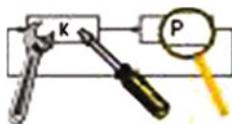
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Frigyes Csáki  
(1921–1977)

*This textbook is devoted to the memory  
of Frigyes Csáki, who was the first professor  
of control in Hungary*



# Foreword

The *Advanced Textbooks in Control and Signal Processing* series is designed as a vehicle for the systematic textbook presentation of both fundamental and innovative topics in the control and signal processing disciplines. It is hoped that prospective authors will welcome the opportunity to publish a more rounded and structured presentation of some of the newer emerging control and signal processing technologies in this textbook series. However, it is useful to note that there will always be a place in the series for contemporary presentations of foundational material in these important engineering areas.

It is currently quite a challenge to compose and write a new introductory textbook for control courses. One issue is that the electrical engineering discipline has grown and evolved immeasurably over the years. It now encompasses the fields of power systems technology, telecommunications, signal processing, electronics, optoelectronic and control systems engineering all served with a smattering of computer science. The undergraduates and postgraduates are faced with the unenviable task of selecting which subjects to study from this smorgasbord of topics.

Many academic institutions have introduced a modular semester structure to their engineering courses. This has the advantage of allowing undergraduates and postgraduates to study a set of basic modules from each of the disciplines before specializing through a selection of advanced subject modules. This means the student obtains a good foundational grounding in the electrical engineering discipline. Such an approach requires an introductory control course textbook of sufficient depth to be useful but not so advanced as to leave students bewildered given that the subject of control has a substantial mathematical content.

Other institutions have managed to retain an Automatic Control Department or Group where the main course is a first degree in control engineering per se. Such departments are also likely to offer master and Ph.D. postgraduate qualifications in the control discipline too. In these departments, the requirements of control systems theory for mathematics can be met by specific control mathematics course modules. An introductory control engineering textbook in this context can have considerably more analytical depth too.

There is one more consideration to add into this discussion of introductory control systems engineering course textbooks. The spectrum of control involves systems theory, systems modeling, control theory, control design techniques, system identification methods, system simulation and validation, controller implementation techniques, control hardware, sensors, actuators, and system instrumentation. Quite how much of each area to include in an introductory control course is something usually decided by the course lecturer, the institutional resources available, the academic level of the course, and the time available for the student to study control. But these issues will also have a considerable influence on the type, level, and structure of any introductory course textbook that is proposed.

László Keviczky, Ruth Bars, Jenő Hetthéssy, Csilla Bányász form a team of control academics who have worked in various Hungarian higher educational institutions, primarily the Department of Automation and Applied Informatics at the Budapest University of Technology and Economics, Hungary, and latterly with the Computer and Automation Research Institute of the Hungarian Academy of Science. Their introductory control course textbook presented here has evolved and been refined through many years of teaching practice. The textbook focuses on the control and systems theory, control design techniques, system simulation and validation part of the control curriculum and is supported by a substantial volume of MATLAB<sup>®</sup> exercises (ISBN 978-981-10-8320-4).

The textbook can be used by undergraduates in a first control systems course. The technical content is self-contained and provides all the signals and systems material that would be needed for a first control course. This is an obvious advantage for the student reader and also the lecturer as it avoids the need for a supplementary mathematical textbook or course. The use of the Youla parameterization approach is a distinctive feature of the text, and this approach will also be of interest to graduate students. The Youla parameterization approach has the advantage of unifying a number of control design methods.

Many popular undergraduate texts give cursory space to the PID controller yet it is a controller that is widely used in industry. In this control textbook, there is a good chapter on PID control and this will chime well with the more industrially orientated undergraduate and academic lecturer. Also valuable is the material presented in Chapter 13 on the tuning of discrete PID controllers. To close the textbook, the authors present an outlook chapter, Chapter 16, that directs the reader toward more advanced topics.

Industrial Control Centre  
Glasgow, Scotland, UK  
January 2017

M. J. Grimble  
M. A. Johnson

# Preface

“Navigare necesse est”, i.e., the ship must be navigated, said the Romans in Antiquity. “Controlare necesse est”, i.e. systems must be controlled, we have been saying since the technological revolution of the nineteenth century. Really, in our everyday life, or in our environment, one can hardly find equipment that does not contain at least one or more control tasks solved by automation instead of by us, or, more importantly, for our comfort.

In an iron, a temperature control system is operated by a relay, in a gas-heating system the temperature is also controlled, and in more sophisticated systems the temperature of the environment is also taken into consideration. In our homes, modern audio-visual systems contain dozens of control tasks, e.g., the regulation of the speed of the tape recorders, the start and stop operation of the equipment; similar operation modes of the CD and DVD systems; the temperature control of the processor in our PC, the positioning of the hard disks’ heads, etc. In cars, the quantity of petrol used and the harmonized operation of the brakes are all controlled by automatic controllers. An aircraft could not fly without controllers, since its operation is a typical example of an unstable system. The number of control tasks in modern aircraft is more than one hundred. The universe could not have been investigated by humankind without the automatic control and guidance systems used at launching rockets, satellites, and ballistic missiles. In the recent Mars explorers, sophisticated high-level, so-called intelligent components, have been employed.

In complex, industrial processes the number of tasks to be solved is over a thousand or ten thousand. The quantity and quality of the products, as well as the safety of the environment, could not be guaranteed without these automatically operated systems. Launching products in the market requires the accurate control of a number of variables.

In almost all assembly factories—from simple production beltways to robots—automatic control is applied.

With the development of medical biology, it was discovered that in any organ, and so in human beings, dozens of basic control processes are at work (i.e., the control of the blood pressure, the body temperature, the level of the blood-sugar content, the level of hormones) and the present techniques are approaching the level when some of these tasks can be taken over in case of illnesses or some problems.

Several basic processes of economics (e.g., supply and demand, storage–inventory, macro- and micro-balance) afford possibilities for automatic control.

The everyday person hardly meets directly with the concept of automatic control, even though they operate several pieces of equipment by pushing buttons, switches, or using instrument panels. That is why control is often considered to be a hidden technology. This phenomenon used to be the reason for the ignorant opinion that there is no need for studying the theory of control and regulation, since it comes embedded in the equipment. But do not forget that such equipment has to be designed and produced, and brought to the market. Only those countries can be considered “developed” ones, that are in the front ranks in the development of these kinds of instruments and processes.

In the modern technologies of the twenty-first century, the basic processing, evaluating and decision-making tasks are executed by computers. The observation of the signals and characteristics of real-time processes, the transfer of executive commands, are made by digital communication. The above three areas (***Control–Computation–Communication = C<sup>3</sup>***) are often considered to be in close synergy.

The goal of this book is to summarize the knowledge required in the introductory courses of university education in these subjects. Each chapter, of course, can have different priorities, but they try to provide useful, basic knowledge in order to continue studies of the higher levels of control theory.

This textbook deals with single variable (single input, single output), linear, constant parameter systems, so, with the simplest systems. Multivariable, nonlinear, varying parameters, stochastic systems are not considered. (Similarly, the theory of the modern adaptive, optimal, and robust controllers is not discussed.) It has to be admitted that the real world is more complex, i.e., multivariable, nonlinear; thus, the material of this textbook is only the first step in studying the control methods of real systems. It also has to be mentioned though that several practical tasks can be solved with quite good results by applying these simplified approaches.

In this book, relatively great attention is devoted to the subject of “Signals and Systems” essential in the basic courses of control theory. In the Appendices, important mathematical fundamentals are summarized. The reason for this is to provide a comprehensive source for students and readers, not requiring additional textbooks to understand this textbook. If anyone’s knowledge of certain fields is doubtful, it can be refreshed in the corresponding chapters.

There are many formulas in this textbook. This subject area, this field requires them, which sometimes is threatening to students. The complexity of the necessary computations, however, never exceeds the complexity of engineering computations, but where it cannot be performed by hand, the necessary computational resources and softwares are referred to. It has to be noted that this level is a basic requirement for the engineers employed by companies working for international markets. It has

to be added, however, that the theoretical knowledge can really become useful only with many years of practical experience.

Nothing is more practical than a good theory!

The authors believe that this textbook provides a suitable basis for the basic level (B.Sc.) education of those faculties, where control theory is to be taught, and where the goal is to prepare a master's level (M.Sc.) education.

This textbook has been written by a working group of the Department of Automation and Applied Informatics, Budapest University of Technology and Economics. The group is headed by László Keviczky. This material is based on, long experience and textbooks used by the department, but, of course, it is not comparable with those in goals and coverage. The following members of the group played primary roles in writing the different chapters:

- Chapter 1. Ruth Bars
- Chapter 2. Ruth Bars
- Chapter 3. László Keviczky
- Chapter 4. Ruth Bars
- Chapter 5. Ruth Bars
- Chapter 6. László Keviczky and Ruth Bars
- Chapter 7. László Keviczky
- Chapter 8. László Keviczky and Ruth Bars
- Chapter 9. László Keviczky
- Chapter 10. László Keviczky
- Chapter 11. Jenő Hetthéssy
- Chapter 12. László Keviczky and Csilla Bányász
- Chapter 13. László Keviczky and Jenő Hetthéssy
- Chapter 14. László Keviczky
- Chapter 15. László Keviczky
- Chapter 16. László Keviczky and Csilla Bányász
- Appendix. László Keviczky, Ruth Bars, Jenő Hetthéssy and Csilla Bányász

In the typographical preparation of this textbook, Csilla Bányász had the determining role. The figures were prepared partly with the help of the Ph.D. students Ágnes Bogárdi-Mészöly, Zoltán Dávid, and Gábor Somogyi.

An essential part of this textbook is the practical laboratory material published in a separate volume (MATLAB<sup>®</sup> Exercises), as well as several examples, helping the students in a good preparation for exams.

Budapest, Hungary

László Keviczky  
Ruth Bars  
Jenő Hetthéssy  
Csilla Bányász

# Contents

<b>Foreword</b> .....	ix
<b>Preface</b> .....	xi
<b>Contents</b> .....	xv
<b>Notations</b> .....	xxiii
<b>1 Introduction</b> .....	1
1.1 Basic Concepts.....	5
1.1.1 The Basic Elements of a Control Process.....	6
1.1.2 Signals and Their Classification.....	7
1.1.3 Representation of System Engineering Relationships.....	7
1.1.4 Open- and Closed-loop Control, Disturbance Elimination.....	9
1.1.5 General Specifications for Closed-Loop Control Systems.....	15
1.1.6 Simple Control Examples.....	17
1.2 On the History of Control.....	21
1.3 Systems and Models.....	24
1.3.1 Types of Models.....	25
1.3.2 The Properties of a System.....	26
1.3.3 Examples of the Transfer Characteristics of Some Simple Systems.....	27
1.3.4 Linearization of Static Characteristics.....	29
1.3.5 Relative Units.....	33
1.4 Practical Aspects.....	34

<b>2</b>	<b>Description of Continuous Linear Systems in the Time, Operator and Frequency Domain</b> . . . . .	<b>37</b>
2.1	Description of Continuous Systems in the Time Domain . . . . .	38
2.1.1	Solution of an $n$ -th Order Linear Differential Equations in the Time Domain . . . . .	38
2.1.2	State Space Representation of Linear Differential Equations . . . . .	43
2.1.3	Typical Input Excitations, Unit Impulse and Step Responses . . . . .	45
2.1.4	System Response to an Arbitrary Input Signal . . . . .	46
2.1.5	Solution of a First-Order Differential Equation . . . . .	49
2.2	Transformation from the Time Domain to the Frequency and Operator Domains . . . . .	51
2.2.1	FOURIER series, FOURIER integral, FOURIER transformation . . . . .	51
2.2.2	The LAPLACE Transformation . . . . .	57
2.2.3	The Transfer Function . . . . .	60
2.2.4	Basic Connections of Elementary Blocks, Block-Scheme Algebra, Equivalent Block Manipulations . . . . .	66
2.3	Investigation of Linear Dynamical Systems in the Frequency Domain . . . . .	72
2.3.1	Graphical Representations of the Frequency Functions . . . . .	74
2.4	Transfer Characteristics of Typical Basic Blocks . . . . .	76
2.4.1	Ideal Basic Blocks . . . . .	77
2.4.2	Lag Blocks . . . . .	81
2.4.3	Proportional, Integrating and Differentiating Lag Blocks . . . . .	92
2.4.4	Influence of the Zeros of the Transfer Function . . . . .	95
2.4.5	Non-minimum Phase Systems . . . . .	99
2.4.6	Quick Drawing of Asymptotic BODE Diagrams . . . . .	101
2.4.7	Influence of Parameter Changes . . . . .	102
2.5	Approximate Descriptions . . . . .	104
2.5.1	Dominant Pole Pair . . . . .	104
2.5.2	Approximation of Higher Order Plants by First- and Second-Order Time Lag Models with Dead-Time . . . . .	105
2.5.3	Approximation of a Dead-Time by Rational Transfer Functions . . . . .	105
2.6	Examples of the Description of Continuous-Time Systems . . . . .	108
2.6.1	Direct Current (DC) Motor . . . . .	109
2.6.2	Modeling of a Simple Liquid Tank System . . . . .	116
2.6.3	A Simple Two Tank System . . . . .	119

- 2.6.4 A Simple Heat Process . . . . . 122
- 2.6.5 The Moving Inverted Pendulum . . . . . 124
- 3 Description of Continuous-Time Systems in State-Space . . . . . 127**
  - 3.1 Solution of the State-Equations in the Complex Frequency Domain . . . . . 130
  - 3.2 Solution of the State-Equations in the Time Domain . . . . . 132
  - 3.3 Transformation of the State-Equations, Canonical Forms . . . . . 133
    - 3.3.1 Diagonal Canonical Form . . . . . 134
    - 3.3.2 Controllable Canonical Form . . . . . 136
    - 3.3.3 Observable Canonical Form . . . . . 138
  - 3.4 The Concepts of Controllability and Observability . . . . . 140
    - 3.4.1 The KALMAN Decomposition . . . . . 147
    - 3.4.2 The Effect of Common Poles and Zeros . . . . . 148
    - 3.4.3 The Inverted Pendulum . . . . . 152
- 4 Negative Feedback . . . . . 155**
  - 4.1 Control in Open- and Closed-Loop . . . . . 155
  - 4.2 The Basic Properties of the Closed Control Loop . . . . . 157
  - 4.3 The Feedback Operational Amplifier . . . . . 162
  - 4.4 The Transfer Characteristics of the Closed Control Loop . . . . . 164
  - 4.5 The Static Transfer Characteristics . . . . . 168
  - 4.6 Relationships Between Open- and Closed-Loop Frequency Characteristics . . . . . 174
    - 4.6.1 The  $M - \alpha$  and  $E - \beta$  Curves . . . . . 176
  - 4.7 The Sensitivity of a Closed Control Loop to Parameter Uncertainties . . . . . 181
  - 4.8 Requirements for Closed-Loop Control Design . . . . . 184
  - 4.9 Improving the Disturbance Elimination Properties of the Closed-Loop . . . . . 188
    - 4.9.1 Disturbance Elimination Scheme (Feedforward) . . . . . 189
    - 4.9.2 Cascade Control Schemes . . . . . 190
  - 4.10 Compensation by Feedback Blocks . . . . . 194
  - 4.11 Control with Auxiliary Manipulated Variables . . . . . 195
- 5 Stability of Linear Control Systems . . . . . 197**
  - 5.1 The Concept of Stability . . . . . 197
  - 5.2 Stability of the Closed-Loop System . . . . . 200
  - 5.3 Mathematical Formulation of the Stability of Continuous Time Linear Control Systems . . . . . 202
  - 5.4 Analytical Stability Criteria . . . . . 204
    - 5.4.1 Stability Analysis Using the ROUTH Scheme . . . . . 205
    - 5.4.2 Stability Analysis Using the HURWITZ Determinant . . . . . 206

- 5.5 Stability Analysis Using the Root Locus Method . . . . . 207
  - 5.5.1 Basic Relationships of the Root Locus Method . . . . . 208
  - 5.5.2 Rules for Drawing Root Locus . . . . . 210
  - 5.5.3 Examples of the Root Locus Method . . . . . 212
  - 5.5.4 Root Locus in the Case of Varying a Parameter  
Different from the Gain . . . . . 216
- 5.6 The NYQUIST Stability Criteria . . . . . 217
  - 5.6.1 Illustration of the Evolution of Undamped  
Oscillations in the Frequency Domain . . . . . 217
  - 5.6.2 The Simple NYQUIST Stability Criterion . . . . . 218
  - 5.6.3 The Generalized NYQUIST Stability Criterion . . . . . 221
  - 5.6.4 Examples of the Application of the NYQUIST  
Stability Criteria . . . . . 225
  - 5.6.5 Practical Stability Measures . . . . . 228
  - 5.6.6 Structural and Conditional Stability . . . . . 232
  - 5.6.7 Stability Criteria Based on the BODE Diagrams . . . . . 234
- 5.7 Robust Stability . . . . . 237
- 6 Regulator Design in the Frequency Domain . . . . . 241**
  - 6.1 On the Relationships Between Properties in the Time- and  
Frequency-Domain . . . . . 242
  - 6.2 Quality Requirements in the Frequency Domain . . . . . 243
  - 6.3 Methods to Shape the Open-Loop Frequency Characteristics . . . . . 246
- 7 Control of Stable Processes . . . . . 253**
  - 7.1 The YOULA-Parameterization . . . . . 254
  - 7.2 The SMITH Controller . . . . . 264
  - 7.3 The TRUXAL-GUILLEMIN Controller . . . . . 266
  - 7.4 The Effect of a Constrained Actuator Output . . . . . 267
  - 7.5 The Concept of the Best Reachable Control . . . . . 270
    - 7.5.1 General Theory . . . . . 270
    - 7.5.2 Empirical rules . . . . . 275
- 8 Design of Conventional Regulators . . . . . 277**
  - 8.1 The PID Regulator Family and Design Methods . . . . . 278
    - 8.1.1 Tuning of P Regulators . . . . . 283
    - 8.1.2 Tuning of I Regulators . . . . . 284
    - 8.1.3 Tuning of PI Regulators . . . . . 284
    - 8.1.4 Tuning of PD Regulators . . . . . 286
    - 8.1.5 Tuning of PID Regulators . . . . . 287
    - 8.1.6 Influence of the Dead-Time . . . . . 290
    - 8.1.7 Realization of PID Regulators . . . . . 291

- 8.2 Design of Residual Systems . . . . . 293
  - 8.2.1 Simple Residual System with Dead-Time and Integrator . . . . . 293
  - 8.2.2 Simple Residual System with Integrator and Time Lag . . . . . 297
- 8.3 Empirical Regulator Tuning Methods . . . . . 300
  - 8.3.1 Methods of ZIEGLER and NICHOLS . . . . . 300
  - 8.3.2 Method of OPPELT . . . . . 301
  - 8.3.3 Method of CHIEN-HRONES-RESWICK . . . . . 302
  - 8.3.4 Method of STREJC . . . . . 302
  - 8.3.5 Relay Method of ÅSTRÖM . . . . . 303
  - 8.3.6 Method of ÅSTRÖM-HÄGGLUND . . . . . 305
- 8.4 Handling Amplitude Constraints: “*Anti-Reset Windup*” . . . . . 306
- 8.5 Control of Special Plants . . . . . 308
  - 8.5.1 Control of a Double Integrator . . . . . 308
  - 8.5.2 Control of an Unstable Plant . . . . . 312
- 8.6 Regulator Design Providing a 60° Phase Margin by Pole Cancellation . . . . . 317
- 9 Control Systems with State Feedback . . . . . 325**
  - 9.1 Pole Placement by State Feedback . . . . . 327
  - 9.2 Observer Based State Feedback . . . . . 331
  - 9.3 Observer Based State Feedback Using Equivalent Transfer Functions . . . . . 335
  - 9.4 Two-Step Design Methods Using State Feedback . . . . . 338
  - 9.5 The *LQ* Controller . . . . . 340
- 10 General Polynomial Method for Controller Design . . . . . 343**
- 11 Sampled Data Control Systems . . . . . 351**
  - 11.1 Sampling . . . . . 354
  - 11.2 Holding . . . . . 357
  - 11.3 Description of Discrete-Time Signals, the *z*-Transformation and the Inverse *z*-Transformation . . . . . 361
    - 11.3.1 Basic Properties of the *z*-Transformation . . . . . 361
    - 11.3.2 The *z*-Transformation of Elementary Time Series . . . . . 363
    - 11.3.3 The Inverse *z*-Transformation . . . . . 365
    - 11.3.4 Initial and Final Value Theorems . . . . . 368
  - 11.4 Description of Sampled Data Systems in the Discrete-Time and in the Operator and Frequency Domain . . . . . 368
    - 11.4.1 The State-Space Model . . . . . 369
    - 11.4.2 Input-Output Models Based on the Shift Operator . . . . . 372
    - 11.4.3 Modeling Based on the *z*-Transformation . . . . . 375
    - 11.4.4 Analysis of DT Systems in the Frequency Domain . . . . . 381

11.4.5	Transformation of Zeros . . . . .	384
11.5	Structural Properties of State Equations . . . . .	385
<b>12</b>	<b>Sampled Data Controller Design for Stable Discrete-Time Processes . . . . .</b>	<b>393</b>
12.1	The YOULA Controller for Sampled Data Systems . . . . .	393
12.2	The SMITH Controller for Sampled Data System . . . . .	397
12.3	The TRUXAL-GUILLEMIN Regulator for Sampled Data Systems . . . . .	399
12.4	Design of Regulators Providing Finite Settling Time . . . . .	400
12.5	Predictive Controllers . . . . .	408
12.6	The Best Reachable Discrete-Time Control . . . . .	411
12.6.1	General Theory . . . . .	411
12.6.2	Empirical Rules . . . . .	412
<b>13</b>	<b>Design of Conventional Sampled Data Regulators . . . . .</b>	<b>413</b>
13.1	Design Methods for the Discrete-Time <i>PID</i> Regulator Family . . . . .	416
13.1.1	Tuning of Sampled Data <i>PI</i> Regulators . . . . .	417
13.1.2	Tuning of Sampled Data <i>PD</i> Regulators . . . . .	418
13.1.3	Tuning of Sampled Data <i>PID</i> Regulators . . . . .	420
13.2	Other Design Methods . . . . .	422
13.2.1	Design of an Intermediate Continuous-Time Regulator and its Discretization . . . . .	424
13.2.2	Design of Discrete-Time Regulators Using Discrete-Time Process Models . . . . .	435
13.2.3	Design of Discrete-Time Regulators Using Continuous-Time Process Models . . . . .	435
13.3	Design of Discrete-Time Residual Systems . . . . .	439
13.3.1	Continuous-Time Second Order Process with Two Time Lags and Dead-Time . . . . .	439
13.3.2	The TUSCHÁK Method . . . . .	441
13.3.3	Discrete-Time Second Order Process with Time Lag and Dead-Time . . . . .	444
<b>14</b>	<b>State Feedback in Sampled Data Systems . . . . .</b>	<b>447</b>
14.1	Discrete-Time Pole-Placement State Feedback Regulator . . . . .	449
14.2	Observer Based Discrete-Time Pole Placement State Feedback Regulator . . . . .	451
14.3	Two-Step Design Methods Using Discrete-Time State Feedback . . . . .	455
14.4	Discrete-Time <i>LQ</i> State Feedback Regulator . . . . .	457

**15 General Polynomial Method for the Design of Discrete-Time Controllers** . . . . . 459

**16 Outlook** . . . . . 465

    16.1 Norms of Control Engineering Signals and Operators . . . . . 465

        16.1.1 Norms of Signals . . . . . 466

        16.1.2 Operator Norms . . . . . 466

    16.2 Basic Methods of the Numerical Optimization . . . . . 469

        16.2.1 Direct Seeking Methods . . . . . 469

        16.2.2 Gradient Based Methods . . . . . 471

    16.3 Introduction to Process Identification . . . . . 474

        16.3.1 Identification of Static Processes . . . . . 474

        16.3.2 Identification of Dynamic Processes . . . . . 477

        16.3.3 Discrete-Time to Continuous-Time Transformation . . . . . 480

        16.3.4 Recursive Parameter Estimation . . . . . 481

        16.3.5 Model Validation . . . . . 482

    16.4 Iterative and Adaptive Control Schemes . . . . . 484

**Appendix** . . . . . 485

**Authors** . . . . . 521

**Pictures of Some of the Scientists Cited in This Book** . . . . . 523

**References** . . . . . 525

**Index** . . . . . 527

# Notations

$H$	Transfer functions of continuous-time systems
$G$	Transfer functions of discrete-time systems
$C$	Controller transfer function
$P$	Process transfer function
$G$ (or $P_d$ )	Discrete-time process pulse transfer function
$S$	Sensitivity function
$T$	Complementary sensitivity function
$L$	Transfer function of an open control loop
$K$	Gain of a control loop
$k$	Transfer coefficient of a control loop
$Q$	YOUVA parameter
$(t)$	Continuous time
$[k]$	Discrete time
$\mathcal{L}\{\dots\}$	LAPLACE transform
$\mathcal{F}\{\dots\}$	FOURIER transform
$\mathcal{Z}\{\dots\}$	z-transform
$s$	Complex variable ( $\mathcal{L}$ transformation)
$z$	Complex variable ( $\mathcal{Z}$ transformation)
$r$ (or $y_r$ )	Reference signal
$y$	Controlled variable
$e$	Error signal
$u$	Actuating signal (or output of the regulator)
$y_{ni}$	Input noise
$y_n$ (or $y_{no}$ )	Output noise
$y_z$	Measurement noise
$\mathbf{a}, \mathbf{b}, \mathbf{c}, \dots$	Vector
$\mathbf{a}^T, \mathbf{b}^T, \mathbf{c}^T, \dots$	Row vector
$\mathbf{A}, \mathbf{B}, \mathbf{C}, \dots$	Matrix
$\mathbf{A}^T$	Transpose of a matrix
$\mathbf{adj}(\mathbf{A})$	Adjunct of a matrix

$\det(\mathbf{A})$ (or $ \mathbf{A} $ )	Determinant of a matrix
$\mathbf{x}$	State variable
$\mathbf{A}, \mathbf{b}, \mathbf{c}, d$	Parameters of the state equation (continuous)
$\mathbf{F}, \mathbf{g}, \mathbf{h}, d$ (or $\mathbf{F}, \mathbf{g}, \mathbf{c}, d$ )	Parameters of the state equation (discrete)
$\mathbf{diag}[a_{11}, a_{22}, \dots, a_{nn}]$	Diagonal matrix
$\mathbf{I} = \mathbf{diag}[1, 1, \dots, 1]$	Unit matrix
$T_s$	Sampling time
$T_d$	Dead time (continuous)
$d$	Time delay (discrete)
$T_h$	Additional time delay
$v(t)$	Step response function
$w(t)$	Weighting function
$\omega$	Frequency
$\omega_c$	Crossover (cut-off) frequency
$F(j\omega)$	Frequency spectrum of a continuous signal
$F^*(j\omega)$	Frequency spectrum of a sampled signal series
$G(j\omega)$ (or $P_d(j\omega)$ )	Frequency spectrum of a discrete-time model
$\mathcal{A}, \mathcal{B}, \mathcal{C}, \mathcal{D}, \mathcal{G}, \mathcal{F}, \mathcal{R}, \mathcal{X}, \mathcal{Y}, \mathcal{V}$	Polynomials
$\deg\{\mathcal{A}\}$	Order of a polynomial
$\mathcal{A}(s) = 0$	Characteristic equation
$\mathbb{U}$	Limit of the control output
$\mathbf{grad}[f(\mathbf{x})]$	Gradient vector
$\forall \omega$	For all $\omega$
$\angle$ (or $\text{arc}(\dots)$ )	Angle of a complex number or functions
$e^{(\dots)}$ (or $\exp(\dots)$ )	Exponential function
$\ln(\dots)$	Natural logarithm
$\lg(\dots)$	Base 10 logarithm
$E\{\dots\}$	Expected value
$\text{plim}\{\dots\}$	Probability limit value
$e^{\mathbf{A}}$	Matrix exponential
$\ln(\mathbf{A})$	Matrix logarithm
CT	Continuous time
DT	Discrete time
SRE	Step response equivalent
PFE	Partial fractional expansion
■	End of example