TWO-DEGREE-OF-FREEDOM CONTROL SYSTEMS

THE YOULA PARAMETERIZATION APPROACH

László Keviczky
Csilla Bányász

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"WHO KNOWS WRITES, WHO READS UNDERSTANDS"

LÁSZLÓ KEVICZKY AND CSILLA BÁNYÁSZ

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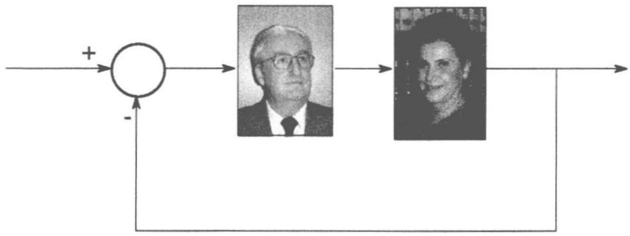
DEDICATION



We would like to express our thanks to our children, Zoltán and Tamás, who have always supported our work. Their love and patience have allowed us to achieve the results presented in this book.

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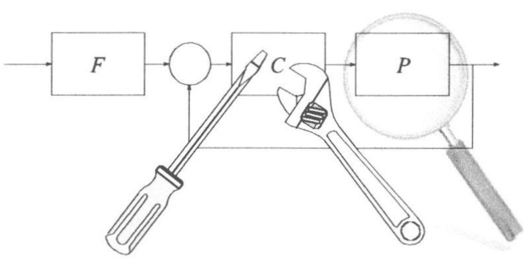

THE BEST STUDENTS

József Bokor
Jenő Hetthéssy
Róbert Haber
István Vajk

Our students are carrying the torch further. Their cooperation helped and inspired the work of the teachers. All of them have successful university carriers and they are good colleagues and friends. Apart from the relationship of parents and children, this continuity of human life is perhaps the most important one.

THE CLOSEST COWORKERS

We express our gratitude to Ruth Bars and Jenő Hetthéssy, who were our coworkers writing a former university lecture notes and they gave their permission to shortly repeat some parts of that work in this book for ease of understanding.

NOTATION

Transfer function of continuous-time systems	H
Transfer function of discrete-time systems	G
Regulator transfer function	C
Process transfer function	P
Discrete-time process pulse transfer function	G (or P_d)
Sensitivity function	S
Complementary sensitivity function	T
Transfer function of open control loop	L
Gain of control loop	K
Transfer coefficient of control loop	k
Youla parameter	Q (or $\mathbf{Q}$)
KB parameter	Q_{KB}
Continuous-time	(t)
Discrete-time	$[k]$
Laplace transform	$\mathcal{L}\{\ldots\}$
z-transform	$\mathcal{Z}\{\ldots\}$
Complex variable argument ($\mathcal{L}$ transf.)	s
Complex variable argument ($\mathcal{Z}$-transf.)	z
Reference signal	r (or y_r)
Controlled variable	y
Error signal	e
Actuating signal (or output of the regulator)	u
Input noise	y_{ni}
Output noise	y_n (or y_{no})
Vector	$\boldsymbol{a}, \boldsymbol{b}, \boldsymbol{c}, \ldots$
Row vector	$\boldsymbol{a}^T, \boldsymbol{b}^T, \boldsymbol{c}^T, \ldots$
Matrix	$\boldsymbol{A}, \boldsymbol{B}, \boldsymbol{C}, \ldots$
Transpose of a matrix	$\boldsymbol{A}^T$

Adjunct of a matrix	$\mathbf{adj}(\boldsymbol{A})$
Determinant of a matrix	$\det(\boldsymbol{A})$ (or $\lvert\boldsymbol{A}\rvert$)
Trace of a matrix	$\mathrm{tr}(\boldsymbol{A})$
State variable	$\boldsymbol{x}$
Parameters of state equation (continuous)	$\boldsymbol{A}$, $\boldsymbol{b}$, $\boldsymbol{c}$, d (or $\mathbf{A}$, $\mathbf{B}$, $\mathbf{C}$, $\mathbf{D}$)
Parameters of state equation (discrete)	$\boldsymbol{F}$, $\boldsymbol{g}$, $\boldsymbol{c}$, d
Diagonal matrix	$\mathbf{diag}[a_{11},a_{22},\ldots,a_{nn}]$
Identity matrix	$\boldsymbol{I} = \mathbf{diag}[1,1,\ldots,1]$
Sampling time	T_s
Dead-time (continuous)	T_d
Time delay (discrete)	d
Step response function	$v(t)$
Weighting function	$w(t)$
Frequency	ω
Frequency spectrum of a continuous signal	$F(j\omega)$
Frequency spectrum of a sampled signal	$F^*(j\omega)$
Frequency spectrum of a discrete time model	$G(j\omega)$ (or $P_d(j\omega)$)
Polynomials	$\mathcal{A}$, $\mathcal{B}$, $\mathcal{C}$, $\mathcal{D}$, $\mathcal{G}$, $\mathcal{F}$, $\mathcal{R}$, $\mathcal{X}$, $\mathcal{Y}$, $\mathcal{V}$
Matrix polynomials	$\boldsymbol{\mathcal{A}}$, $\boldsymbol{\mathcal{B}}$, $\boldsymbol{\mathcal{C}}$, $\boldsymbol{\mathcal{D}}$, $\boldsymbol{\mathcal{U}}$, $\boldsymbol{\mathcal{V}}$
Parameter matrices of matrix polynomials	$\mathbf{N}_L^i, \mathbf{D}_L^i, \mathbf{T}_i, \mathbf{P}_i$
Order of a polynomial	$\deg\{\mathcal{A}\}$
Characteristic equation	$\mathcal{A}(s) = 0$
Characteristic equation (discrete)	$\mathcal{F}(z) = 0$
Limit of control output	$\mathbb{U}$
Gradient vector	$\mathbf{grad}[f(\boldsymbol{x})]$
For all ω	$\forall\omega$
Angle of a complex number or function	$\angle$ (or $\mathrm{arc}(\ldots)$)
Exponential function	$e^{(\ldots)}$ (or $\exp(\ldots)$)
Natural logarithm	$\ln(\ldots)$
Common (base 10)	$\lg(\ldots)$
Expected value	$E\{\ldots\}$
Probability limit value	$\mathrm{plim}\{\ldots\}$
Matrix exponential	$e^{\boldsymbol{A}}$
Matrix logarithm	$\ln(\boldsymbol{A})$
Set of stable linear DT processes	$\mathcal{S}_{DT}$
Set of stable linear CT processes	$\mathcal{S}_{CT}$ (or $\mathcal{S}$)

ABBREVIATIONS

CAD	Computer-aided design
CT	Continuous-time
DT	Discrete-time
ID	Process identification
DE	Diophantine equation
ELS method	Extended least squares method
GMV	Generalized minimum variance
IV	Instrumental variables
IS	Inverse stable
IU	Inverse unstable
LS method	Least squares method
MFD	Matrix fraction description
ML	Maximum likelihood
MSE	Mean square error
MV	Minimum variance
MIMO	Multiple input multiple output
ODOF	One-degree-of-freedom
ST	Self-tuning
SISO	Single input single output
SRE	Step response equivalent
SA method	Stochastic approximation method
TDOF	Two-degree-of-freedom
TFM	Transfer function matrix
YP	Youla-parameterized
PFE	Partial fractional expansion

PREFACE

From earliest times humankind has aimed to preserve its experiences and opinions and pass them on to succeeding generations. This is reflected in cave drawings, tally marks, clay boards, and papyrus rolls, as well as in books and Gutenberg technologies. The process is continued by contemporary digital methods. A person can share knowledge by describing her/his experiences, results, and opinions. This process together with genetic heritage ensures the future of humankind but the latter is much slower and is not transparent yet in practice.

This is why we as authors decided to publish our results, methods, experiences, and problem-solving approaches. This book is recommended for those working in and outside the subject area, students, colleagues, interested persons, and particularly, our successors. The reader is very important in this process, perhaps the most important. In general it is true that "Who knows writes, who reads understands." This is the most effective situation since the time book writing and publishing exists.

Mountain peaks can be scaled in many different ways. There are well-designed incline rails, pedestrian path, and even roads, but the real friends of nature prefer to go on trails. This book tries to offer solutions via hidden trails, hoping that the reader will understand and appreciate these methods rather more.

The majority of people rarely come across the concept of automatic control, despite the fact that they operate machines by pushing buttons, tripping switches, or using instrument panels. While being largely unaware of it, they almost always apply some kind of *Control* when using common everyday devices. In the modern technologies of the twenty-first century the basic processing, evaluating, and decision-making tasks are executed by digital *Computation*, i.e., by computers. Observation of the signals and characteristics of the real-time processes and the transfers of executive commands are made possible by digital *Communication*. These three areas (*Control–Computation–Communication* = C^3) are often considered in close synergy, sometimes extended by a fourth, not easily defined, subject area, namely built-in machine *Intelligence*. This constitutes the famous C^3I complex. Our book deals specifically with the *Control* area of this complex.

"*Navigare necesse est.*" i.e., a ship must be navigated, as the ancient Romans recognized. "*Controlare necesse est.*" i.e., a system must be controlled, something we have been saying since the technical revolution of the nineteenth century. In fact, our everyday life cannot be imagined without automatic equipment. Sometimes this fact is not transparent because everyone is used to pushing the buttons on their modern or less modern devices, switching on and adjusting screens etc., and the technology that completes the demands is hidden, invisible. One therefore does not think about how many control loops or regulatory processes are in operation when a radio, television, or CD or DVD system is activated or simple equipment such as irons, hot water boilers, or central heating systems is used. It is indeed hard to find equipment that does not contain at least one or more control tasks solved by automation for our comfort. This subject area also includes the investigation of control systems operating in different life forms, regulate the supply, and demand ratio in economics, or the environmental processes of the globe.

In an iron the temperature control system is operated by a relay, in the gas heating system the temperature is controlled, but in more sophisticated systems the temperature of the environment is also taken into consideration. In the home, modern audio–visual systems contain dozens of control tasks, e.g., the regulation of the speed of tape recorders, the start and stop operation of the equipment; CD and DVD systems use similar operation modes, not forgetting the temperature control of the processor in the 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 governed by automatic regulators. Modern aircraft typically could not fly without controllers, since their operation is a typical example of unstable systems. The number of control tasks in modern aircraft is over a hundred. The universe could not be investigated without automatic control and guidance systems for launching rockets and satellites. In Mars explorers, sophisticated high-level, so-called autonomous intelligent, equipments have been applied.

In complex, industrial processes the number of tasks to be solved is over a thousand or even ten thousand. The quantity and quality of the products and the safety of the environment cannot be guaranteed without these automatically operated systems. Launching products onto the market requires the accurate control of a number of variables (in many cases within a prescribed fidelity limit).

In almost all factory assemblies, from simple production beltways to robots, automatic control is applied.

With the development of systems biology it was discovered that in any organ, or the entire body, dozens of basic control processes are at work (e.g., governing blood pressure, body temperature, the level of blood sugar content, the level of hormones, etc.), and current technologies are approaching the point when some of these tasks can be taken over by devices in the case of illness or other problems.

Several basic economic processes (e.g., supply and demand, storage inventory, macro- and microbalance, etc.) offer possibilities for automatic control.

The discussion of control engineering methods requires many formulas. This does not mean pure mathematics, though the results and methods of mathematics are intensively used. Control engineering belongs to the technical sciences, but its results are applied from biology to economics.

Let us ascend via the trails we have found. On the way we will try to produce results that cannot be seen from anywhere else. The new view is worth the trek.

László Keviczky

Csilla Bányász