Identification of Dynamic Systems

Rolf Isermann · Marco Münchhof

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An Introduction with Applications

Springer

Prof. Dr. -Ing. Dr. h.c. Rolf Isermann
Technische Universität Darmstadt
Institut für Automatisierungstechnik
Landgraf-Georg-Straße 4
64283 Darmstadt
Germany
RIsermann@iat.tu-darmstadt.de

Dr. -Ing. Marco Münchhof, M.S./SUNY
Technische Universität Darmstadt
Institut für Automatisierungstechnik
Landgraf-Georg-Straße 4
64283 Darmstadt
Germany
MMuenchhof@iat.tu-darmstadt.de

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Preface

For many problems of the design, implementation, and operation of automatic control systems, relatively precise mathematical models for the static and dynamic behavior of processes are required. This holds also generally in the areas of natural sciences, especially physics, chemistry, and biology, and also in the areas of medical engineering and economics. The basic static and dynamic behavior can be obtained by theoretical or physical modeling, if the underlying physical laws (first principles) are known in analytical form. If, however, these laws are not known or are only partially known, or if significant parameters are not known precisely enough, one has to perform an experimental modeling, which is called process or system identification. Then, measured signals are used and process or system models are determined within selected classes of mathematical models.

The scientific field of system identification was systematically developed since about 1960 especially in the areas of control and communication engineering. It is based on the methods of system theory, signal theory, control theory, and statistical estimation theory and was influenced by modern measurement techniques, digital computations and the need for precise signal processing, control, and automation functions. The development of identification methods can be followed in wide spread articles and books. However, a significant influence had the IFAC-symposia on system identification, which were since 1967 organized every three years around the world, in 2009 a 15$^{\text{th}}$ time in Saint-Malo.

The book is intended to give an introduction to system identification in an easy to understand, transparent, and coherent way. Of special interest is an application-oriented approach, which helps the user to solve experimental modeling problems. It is based on earlier books in German, published in 1971, 1974, 1991 and 1992, and on courses taught over many years. It includes own research results within the last 30 years and publications of many other research groups.

The book is divided into eight parts. After an introductory chapter and a chapter on basic mathematical models of linear dynamic systems and stochastic signals, part I treats *identification methods with non-parametric models and continuous time signals*. The classical methods of determining frequency responses with non-periodic and periodic test signals serve to understand some basics of identification and lay ground for other identifications methods.

Part II is devoted to the determination of *impulse responses with auto- and cross-correlation functions*, both in continuous and discrete time. These correlation methods can also be seen as basic identification methods for measurements with stochastic disturbances. They will later appear as elements of other estimation methods and allow directly the design of binary test signals.

The *identification of parametric models* in discrete time like difference equations in Part III is based mainly on least squares parameter estimation. These estimation methods are first introduced for static processes, also known as regression analysis, and then expanded to dynamic processes. Both, non-recursive and recursive parameter estimation methods are derived and various modifications are described, like methods of extended least squares, total least squares, and instrumental variables. The Bayes and maximum likelihood methods yield a deeper theoretical background, also with regard to performance bounds. Special chapters treat the parameter estimation of time-variant processes and under closed-loop conditions.

Part IV now looks at *parameter estimation methods for continuous-time models*. First parameter estimation is extended to measured frequency responses. Then, the parameter estimation for differential equations and subspace methods operating with state variable filters are considered.

The *identification of multi-variable systems (MIMO)* is the focus of Part V. First basic structures of linear transfer functions and state space models are considered. This is followed by correlation and parameter estimation methods, including the design of special uncorrelated test signals for the simultaneous excitation of several inputs. However, sometimes it is easier to identify single-input multiple outputs (SIMO) processes sequentially.

Of considerable importance for many complex processes is the *identification of non-linear systems*, treated in Part VI. Special model structures, like Volterra series, Hammerstein- and Wiener-models allow applying parameter estimation methods directly. Then, iterative optimization methods are treated, taking into account multi-dimensional, non-linear problems. Powerful methods were developed based on non-linear net models with parametric models like neural networks and their derivations and look-up tables (maps) as non-parametric representations. Also, extended Kalman filters can be used.

Some *miscellaneous issues*, which are common to several identification methods, are summarized in Part VII, as e.g. numerical aspects, practical aspects of parameter estimation and a comparison of different parameter estimation methods.

Part VIII then shows the *application* of several treated identification methods *to real processes* like electrical and hydraulic actuators, machine tools and robots, heat exchangers, internal combustion engines and the drive dynamic behavior of automobiles.

The *Appendix* as Part IX then presents some mathematical aspects and a description of the three mass oscillator process, which is used as a practical example throughout the book. Measured data to be used for applications by the reader can be downloaded from the Springer web page in the Internet.

The wide topics of dynamic system identification are based on the research performed by many experts. Because some early contributions lay the ground for many other developments we would just like to mention a few authors from early seminal contributions. The determination of characteristic parameters of step responses was published by V. Strejc (1959). First publications on frequency response measurement with orthogonal correlation go back to Schaefer and Feissel (1955) and Balchen (1962). The field of correlation methods and ways to design pseudo-random-binary signals was essentially brought forward by e.g. Chow, Davies (1964), Schweitzer (1966), Briggs (1967), Godfrey (1970) and Davies (1970). The theory and application of parameter estimation for dynamic processes was around 1960 until about 1974 essentially promoted by works of J. Durbin, R.C.K. Lee, V. Strejc, P. Eykhoff, K.J. Åström, V. Peterka, H. Akaike, P. Young, D.W. Clarke, R.K. Mehra, J.M. Mendel, G. Goodwin, L. Ljung, and T. Söderström.

This was followed by many other contributions to the field which are cited in the respective chapters, see also Table 1.3 for an overview over the literature in the field of identification.

The authors are also indebted to many contributions for developing and applying identifications methods from researchers at our own group since 1973 until now, like M. Ayoubi, W. Bamberger, U. Baur, P. Blessing, H. Hensel, R. Kofahl, H. Kurz, K.H. Lachmann, O. Nelles, K.H. Peter, R. Schumann, S. Toepfer, M. Vogt, and R. Zimmerschied. Many other developments with regard to special dynamic processes are referenced in the chapters on applications.

The book is dedicated as an introduction to system identification for undergraduate and graduate students of electrical and electronic engineering, mechanical and chemical engineering and computer science. It is also oriented towards practicing engineers in research and development, design and production. Preconditions are basic undergraduate courses of system theory, automatic control, mechanical and/or electrical engineering. Problems at the end of each chapter allow to deepen the understanding of the presented contents.

Finally we would like to thank Springer-Verlag for the very good cooperation.

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Rolf Isermann
Marco Münchhof

Contents

Part III Identification with Parametric Models — Discrete Time Signals

List of Symbols

Only frequently used symbols and abbreviations are given.

Letter symbols

a	parameters of differential of difference equations, amplitude
b	parameters of differential or difference equations
c	spring constant, constant, stiffness, parameters of stochastic difference equations, parameters of physical model, center of Gaussian function
d	damping coefficient, direct feedthrough, parameters of stochastic difference equations, dead time, drift
e	equation error, control deviation $e = w - y$
e	number $\mathrm{e} = 2.71828\ldots$ (Euler's number)
f	frequency ($f = 1/T_\mathrm{p}$, T_p period time), function $f(\ldots)$
f_S	sample frequency
g	function $g(\ldots)$, impulse response
h	step response, undisturbed output signal for method IV, $h \approx y_\mathrm{u}$
i	index
$\mathrm{i} = \sqrt{-1}$	imaginary unit
j	integer, index
k	discrete number, discrete-time $k = t/T_0 = 0, 1, 2, \ldots$ (T_0: sample time)
l	index
m	mass, order number, model order, number of states
n	order number, disturbance signal
p	probability density function, process parameter, order number of a stochastic difference equation, parameter of controller difference equation, number of inputs, $p(x)$ probability density function
q	index, parameter of controller difference equation, time shift operator with $x(k)q^{-1} = x(k-1)$

r	number of outputs
r_{P}	penalty multiplier
s	Laplace variable $s = \delta + \mathrm{i}\omega$
t	continuous time
u	input signal change ΔU, manipulated variable
w	reference value, setpoint, weight, $w(t)$ window function
x	state variable, arbitrary signal
y	output signal change ΔY, signal
y_{u}	useful signal, response due to u
y_{z}	response due to disturbance z
z	disturbance variable change ΔZ, $\mathfrak{Z}$-transform variable $z = \mathrm{e}^{-T_0 s}$
A	denominator polynomial of process transfer function
B	numerator polynomial of process transfer function
$\mathcal{A}$	denominator polynomial of closed-loop transfer function
$\mathcal{B}$	numerator polynomial of closed-loop transfer function
C	denominator polynomial of stochastic filter equation, covariance function
D	numerator polynomial of stochastic filter equation, damping ratio
F	filter transfer function
G	transfer function
I	second moment of area
J	moment of inertia
K	constant, gain
M	torque
N	discrete number, number of data points
P	probability
Q	denominator polynomial of controller transfer function
R	numerator polynomial of controller transfer function, correlation function
S	spectral density, sum
T	time constant, length of a time interval
T_0	sample time
T_{M}	measurement time
T_{P}	period time
U	input variable, manipulated variable (control input)
V	cost function
W	complex rotary operator for DFT and FFT
Y	output variable, control variable
Z	disturbance variable
$\boldsymbol{a}$	vector
$\boldsymbol{b}$	bias

$\boldsymbol{b}, \boldsymbol{B}$	input vector/matrix
$\boldsymbol{c}, \boldsymbol{C}$	output vector/matrix
$\boldsymbol{e}$	error vector
$\boldsymbol{g}$	vector of inequality constraints with $\boldsymbol{g}(\boldsymbol{x}) \leq \boldsymbol{0}$
$\boldsymbol{h}$	vector of equality constraints with $\boldsymbol{h}(\boldsymbol{x}) = \boldsymbol{0}$
$\boldsymbol{n}$	noise vector
$\boldsymbol{s}$	search vector
$\boldsymbol{u}$	manipulated variables for neural net
$\boldsymbol{v}$	output noise
$\boldsymbol{w}$	state noise
$\boldsymbol{x}$	vector of design variables
$\boldsymbol{y}$	output vector
$\boldsymbol{z}$	operating point variables for neural net
$\boldsymbol{A}$	arbitrary matrix, state matrix
$\boldsymbol{C}$	covariance matrix, matrix of measurements for TLS
$\boldsymbol{D}$	direct feedthrough matrix
$\boldsymbol{G}$	transfer function matrix
$\boldsymbol{G}_\nu$	noise transfer function matrix
$\boldsymbol{H}$	Hessian matrix, Hadamard matrix
$\boldsymbol{I}$	identity matrix
$\boldsymbol{K}$	gain matrix
$\boldsymbol{P}$	correlation matrix, $\boldsymbol{P} = \boldsymbol{\Psi}^{\mathrm{T}}\boldsymbol{\Psi}$
$\boldsymbol{S}$	Cholesky factor
$\boldsymbol{T}$	similarity transform
$\boldsymbol{U}$	input matrix for subspace algorithms
$\boldsymbol{W}$	weighting matrix
$\boldsymbol{X}$	state matrix
$\boldsymbol{Y}$	output matrix for subspace algorithms
$\boldsymbol{A}^{\mathrm{T}}$	transposed matrix
α	factor, coefficients of closed-loop transfer function
β	factor, coefficients of closed-loop transfer function
γ	activation function
δ	decay factor, impulse function, time shift
ε	correlation error signal, termination tolerance, small positive number
ζ	damping ratio
η	noise-to-signal ratio
θ	parameter
λ	forgetting factor, cycle time of PRBS generator
μ	membership function, index, time scaling factor for PRBS, order of controller transfer function
ν	index, white noise (statistically independent signal), order of controller transfer function

ξ	measurement disturbance
π	number $\pi = 3.14159\ldots$
ϱ	Step width factor for stochastic approximation algorithms
τ	time, time difference
φ	angle, phase
ω	angular frequency, $\omega = 2\pi/T_P$; T_P period, rotational velocity $\omega(t) = \dot{\varphi}(t)$
ω_0	undamped natural frequency
Δ	change, deviation
Π	product
Σ	sum
Φ	validity function, activation function, weighting function
Ψ	wavelet
$\boldsymbol{\gamma}$	correction vector
$\boldsymbol{\psi}$	data vector
$\boldsymbol{\theta}$	parameter vector
$\boldsymbol{\Delta}$	augmented error matrix
$\boldsymbol{\Sigma}$	covariance matrix of a Gaussian distribution, matrix of singular values
$\boldsymbol{\Phi}$	transition matrix
$\boldsymbol{\Psi}$	data matrix

Mathematical abbreviations

$\exp(x) = e^x$	exponential function
dim	dimension
adj	adjoint
$\angle$	phase (argument)
arg	argument
cond	condition number
cov	covariance
det	determinant
lim	limit
max	maximum (also as index)
min	minimum (also as index)
plim	probability limit
tr	trace of a matrix
var	variance
Re{...}	real part
Im{...}	imaginary part
$\boldsymbol{Q}_S$	controllability matrix
$\boldsymbol{Q}_{Sk}$	extended reversed controllability matrix

$\mathrm{E}\{\ldots\}$	expected value of a statistical variable
$\mathfrak{F}$	Fourier transform
H	Hermitian matrix
$\boldsymbol{\mathcal{H}}$	Hankel matrix
$\mathfrak{H}(f(x))$	Hilbert transform
$\mathcal{H}$	Heaviside function
$\mathfrak{L}$	Laplace transform
$\boldsymbol{Q}_{\mathrm{B}}$	observability matrix
$\boldsymbol{Q}_{\mathrm{Bk}}$	extended observability matrix
$\mathfrak{z}$	z transform directly from s transform
$\boldsymbol{\mathcal{T}}$	Markov parameter matrix, Töplitz matrix
$\mathfrak{Z}$	z transform
$G(-\mathrm{i}\omega)$	conjugate complex, sometimes denoted as $G^*(\mathrm{i}\omega)$
$\lVert\cdot\rVert_2$	2-norm
$\lVert\cdot\rVert_{\mathrm{F}}$	Frobenius norm
$V_{\boldsymbol{\theta}}$	first derivative of V with respect to $\boldsymbol{\theta}$
$V_{\boldsymbol{\theta\theta}}$	second derivative of V with respect to $\boldsymbol{\theta}$
$\nabla f(\boldsymbol{x})$	gradient of $f(\boldsymbol{x})$
$\nabla^2 f(\boldsymbol{x})$	Hessian matrix of $f(\boldsymbol{x})$
$\hat{x}$	estimated or observed variable
$\tilde{x}$	estimation error
$\bar{x}$	average, steady-state value
$\dot{x}$	first derivative with respect to time t
$x^{(n)}$	n-th derivative with respect to time t
x_0	amplitude or true value
x_{00}	value in steady state
$\overline{x}$	mean value
x_{S}	sampled signal
x_δ	Dirac series approximation
x^*	normalized, optimal
x_{d}	discrete-time
x_{00}	steady state or DC value
$\boldsymbol{A}^\dagger$	pseudo-inverse
$\boldsymbol{f}/\boldsymbol{A}$	orthogonal projection
$\boldsymbol{f}/_{\boldsymbol{B}}\boldsymbol{A}$	oblique projection

Abbreviations

ACF	auto-correlation function, e.g. $R_{\mathrm{uu}}(\tau)$
ADC	analog digital converter
ANN	artificial neural network
AGRBS	amplitude modulated GRBS
APRBS	amplitude modulated PRBS
AR	auto regressive
ARIMA	auto regressive integrating moving average process

ARMA	auto regressive moving average process
ARMAX	auto regressive moving average with external input
ARX	auto regressive with external input
BLUE	best linear unbiased estimator
CCF	cross-correlation function, e.g. $R_{\mathrm{uy}}(\tau)$
CDF	cumulative distribution function
CLS	bias corrected least squares
COR-LS	correlation analysis and method of least squares
CWT	continuous-time wavelet transform
DARE	differential algebraic Riccatti equation
DFT	discrete Fourier transform
DSFC	discrete square root filter in covariance form
DSFI	discrete square root filter in information form
DTFT	discrete time Fourier transform
DUDC	discrete UD-factorization in covariance form
EIV	errors in variables
EKF	extended Kalman filter
ELS	extended least squares
FFT	Fast Fourier Transform
FIR	finite impulse response
FLOPS	floating point operations
FRF	frequency response function
GLS	generalized least squares
GRBS	generalized random binary signal
GTLS	generalized total least squares
IIR	infinite impulse response
IV	instrumental variables
KW	Kiefer-Wolfowitz algorithm
LLM	local linear model
LPM	local polynomial model
LOLIMOT	local linear model tree
LPVM	linear parameter variable model
LQR	linear quadratic regulator
LRGF	locally recurrent global feedforward net
LS	least squares
M	model
MA	moving average
MIMO	multiple input, multiple output
ML	maximum likelihood
MLP	multi layer perceptron
MOESP	Multi-variable Output Error State sPace
N4SID	Numerical algorithms for Subspace State Space IDentification
NARX	non-linear ARX model
NDE	non-linear difference equation
NFIR	non-linear FIR model

NN	neural net
NOE	non-linear OE model
ODE	ordinary differential equation
OE	output error
P	process
PCA	principal component analysis
PDE	partial differential equation
PDF	probability density function $p(x)$
PE	prediction error
PEM	prediction error method
PRBS	pseudo-random binary signal
RBF	radial basis function
RCOR-LS	recursive correlation analysis and method of least squares
RGLS	recursive generalized least squares
RIV	recursive instrumental variables
RLS	recursive least squares
RLS-IF	recursive least squares with improved feedback
RML	recursive maximum likelihood
SISO	single input, single output
SNR	signal to noise ratio
SSS	strict sense stationary
STA	stochastic approximation
STFT	short time Fourier transform
STLS	structured total least squares
SUB	subspace
SUMT	sequential unconstrained minimization technique
SVD	singular value decomposition
TLS	total least squares
WLS	weighted least squares
WSS	wide sense stationary
ZOH	zero order hold