C. James Taylor, Peter C. Young
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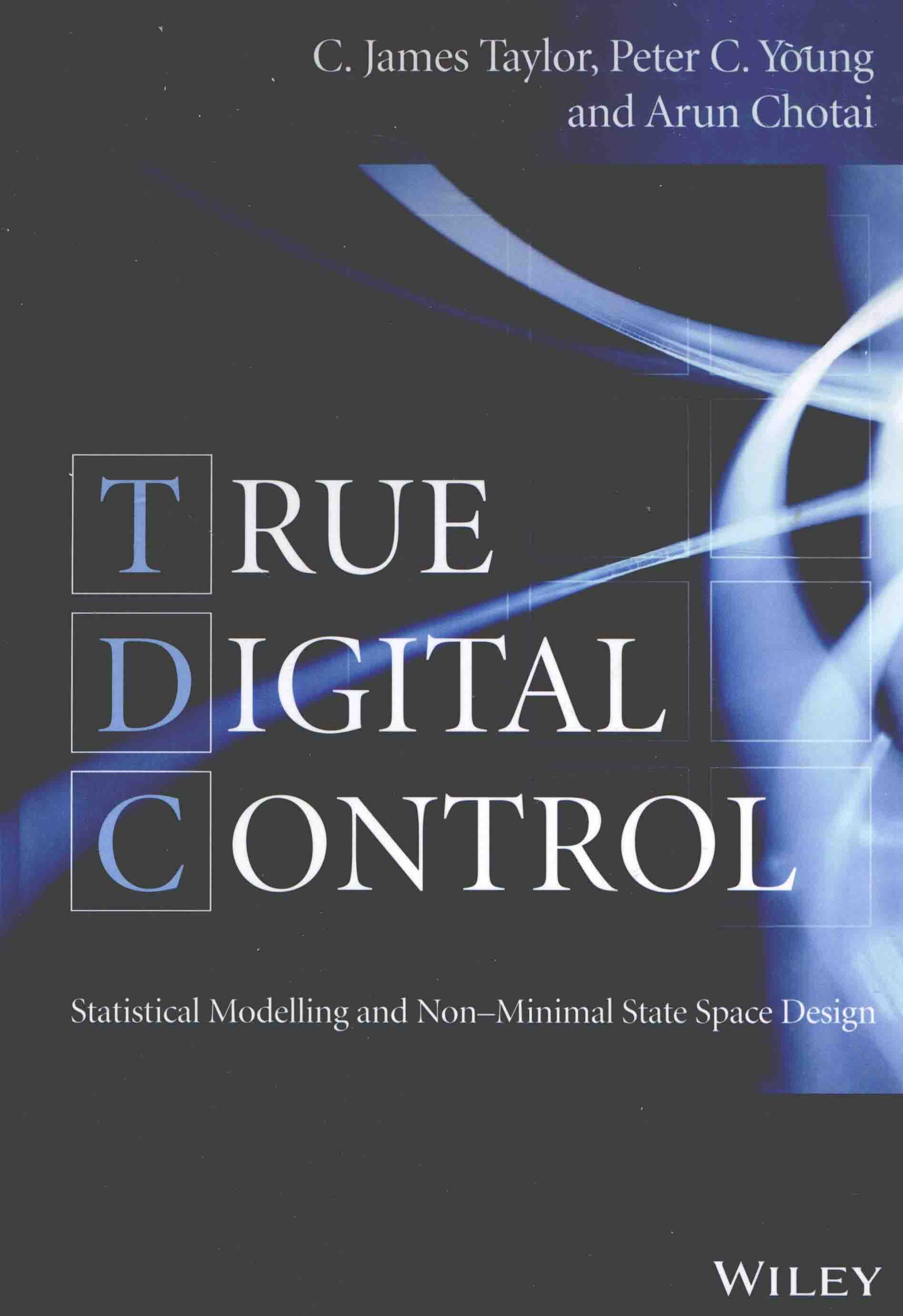

TRUE DIGITAL CONTROL

Statistical Modelling and Non–Minimal State Space Design

WILEY

TRUE DIGITAL CONTROL

STATISTICAL MODELLING AND NON-MINIMAL STATE SPACE DESIGN

C. James Taylor, Peter C. Young and Arun Chotai
Lancaster University, UK

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TRUE DIGITAL CONTROL

To Ting-Li

To Wendy

In memory of Varsha

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Preface

This book develops a *True Digital Control* (TDC) design philosophy that encompasses data-based (statistical) model identification, through to control algorithm design, robustness evaluation and implementation. Treatment of both stochastic system identification and control design under one cover highlights the important connections between these disciplines: for example, in quantifying the model uncertainty for use in closed-loop stochastic sensitivity analysis. More generally, the foundations of linear state space control theory that are laid down in early chapters, with *Non-Minimal State Space* (NMSS) design as the central worked example, are utilised subsequently to provide an introduction to other selected topics in modern control theory. MATLAB®[1] functions for TDC design and MATLAB® scripts for selected examples are being made available online, which is important in making the book accessible to readers from a range of academic backgrounds. Also, the CAPTAIN Toolbox for MATLAB®, which is used for the analysis of all the modelling examples in this book, is available for free download. Together, these contain computational routines for many aspects of model identification and estimation; for NMSS design based on these estimated models; and for offline signal processing. For more information visit: http://www.wiley.com/go/taylor.

The book and associated software are intended for students, researchers and engineers who would like to advance their knowledge of control theory and practice into the state space domain; and control experts who are interested to learn more about the NMSS approach promoted by the authors. Indeed, such non-minimal state feedback is utilised throughout this book as a unifying framework for generalised digital control system design. This includes the *Proportional-Integral-Plus* (PIP) control systems that are the most natural outcome of the NMSS design strategy. As such, the book can also be considered as a primer for potentially difficult topics in control, such as optimal, stochastic and multivariable control.

As indicated by the many articles on TDC that are cited in this book, numerous colleagues and collaborators have contributed to the development of the methods outlined. We would like to pay particular thanks to our good friend Dr Wlodek Tych of the Lancaster Environment Centre, Lancaster University, UK, who has contributed to much of the underlying research and in the development of the associated computer algorithms. The first author would also like to thank Philip Leigh, Matthew Stables, Essam Shaban, Vasileios Exadaktylos, Eleni Sidiropoulou, Kester Gunn, Philip Cross and David Robertson for their work on some of the practical examples highlighted in this book, among other contributions and useful discussions while they studied at Lancaster. Philip Leigh designed and constructed the Lancaster forced

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[1] MATLAB®, The MathWorks Inc., Natick, MA, USA.

ventilation test chamber alluded to in the text. Vasileios Exadaktylos made insightful suggestions and corrections in relation to early draft chapters of the book. The second author is grateful to a number of colleagues over many years including: Charles Yancey and Larry Levsen, who worked with him on early research into NMSS control between 1968 and 1970; Jan Willems who helped with initial theoretical studies on NMSS control in the early 1970s; and Tony Jakeman who helped to develop the *Refined Instrumental Variable* (RIV) methods of model identification and estimation in the late 1970s. We are also grateful to the various research students at Lancaster who worked on PIP methods during the 1980s and 1990s, including M.A. Behzadi, Changli Wang, Matthew Lees, Laura Price, Roger Dixon, Paul McKenna and Andrew McCabe; to Zaid Chalabi, Bernard Bailey and Bill Day, who helped to investigate the initial PIP controllers for the control of climate in agricultural glasshouses at the Silsoe Research Institute; and to Daniel Berckmans and his colleagues at the University of Leuven, who collaborated so much in later research on the PIP regulation of fans for the control of temperature and humidity in their large experimental chambers at Leuven.

Finally, we would like to express our sincere gratitude to the UK Engineering and Physical Sciences, Biotechnology and Biological Sciences, and Natural Environmental Research Councils for their considerable financial support for our research and development studies at Lancaster University.

C. James Taylor, Peter C. Young and Arun Chotai
Lancaster, UK

List of Acronyms

ACF	AutoCorrelation Function
AIC	Akaike Information Criterion
AML	Approximate Maximum Likelihood
AR	Auto-Regressive
ARIMAX	Auto-Regressive Integrated Moving-Average eXogenous variables
ARMA	Auto-Regressive Moving-Average
ARMAX	Auto-Regressive Moving-Average eXogenous variables
ARX	Auto-Regressive eXogenous variables
BIC	Bayesian Information Criterion
BJ	Box–Jenkins
CAPTAIN	Computer-Aided Program for Time series Analysis and Identification of Noisy systems
CLTF	Closed-Loop Transfer Function
CT	Continuous-Time
DARX	Dynamic Auto-Regressive eXogenous variables
DBM	Data-Based Mechanistic
DC	Direct Current
DDC	Direct Digital Control
DF	Directional Forgetting
DT	Discrete-Time
DTF	Dynamic Transfer Function
EKF	Extended or generalised Kalman Filter
EWP	Exponential-Weighting-into-the-Past
FACE	Free-Air Carbon dioxide Enrichment
FIR	Finite Impulse Response
FIS	Fixed Interval Smoothing
FPE	Final Prediction Error
GBJ	Generalised Box–Jenkins
GPC	Generalised Predictive Control
GRIVBJ	Generalised RIVBJ or RIVCBJ
GRW	Generalised Random Walk
GSRIV	Generalised SRIV or SRIVC
IPM	Instrumental Product Matrix
IRW	Integrated Random Walk

IV	Instrumental Variable
IVARMA	Instrumental Variable Auto-Regressive Moving-Average
KF	Kalman Filter
LEQG	Linear Exponential-of-Quadratic Gaussian
LLS	Linear Least Squares
LLT	Local Linear Trend
LPV	Linear Parameter Varying
LQ	Linear Quadratic
LQG	Linear Quadratic Gaussian
LTR	Loop Transfer Recovery
MCS	Monte Carlo Simulation
MFD	Matrix Fraction Description
MIMO	Multi-Input, Multi-Output
MISO	Multi-Input, Single-Output
ML	Maximum Likelihood
MPC	Model Predictive Control
NEVN	Normalised Error Variance Norm
NLPV	Non-Linear Parameter Varying
NMSS	Non-Minimal State Space
NSR	Noise–Signal Ratio
NVR	Noise Variance Ratio
PACF	Partial AutoCorrelation Function
PBH	Popov, Belevitch and Hautus
PEM	Prediction Error Minimisation
PI	Proportional-Integral
PID	Proportional-Integral-Derivative
PIP	Proportional-Integral-Plus
PRBS	Pseudo Random Binary Signal
RBF	Radial Basis Function
RIV	Refined Instrumental Variable
RIVAR	Refined Instrumental Variable with Auto-Regressive noise
RIVBJ	Refined Instrumental Variable for Box–Jenkins models
RIVCBJ	Refined Instrumental Variable for hybrid Continuous-time Box–Jenkins models
RLS	Recursive Least Squares
RML	Recursive Maximum Likelihood
RW	Random Walk
RWP	Rectangular-Weighting-into-the-Past
SD	Standard Deviation
SDARX	State-Dependent Auto-Regressive eXogenous variables
SDP	State-Dependent Parameter
SE	Standard Error
SISO	Single-Input, Single-Output
SP	Smith Predictor
SRIV	Simplified Refined Instrumental Variable
SRIVC	Simplified Refined Instrumental Variable for hybrid Continuous-time models
SRW	Smoothed Random Walk

SVF	State Variable Feedback
TDC	True Digital Control
TF	Transfer Function
TFM	Transfer Function Matrix
TVP	Time Variable Parameter
YIC	Young Information Criterion

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