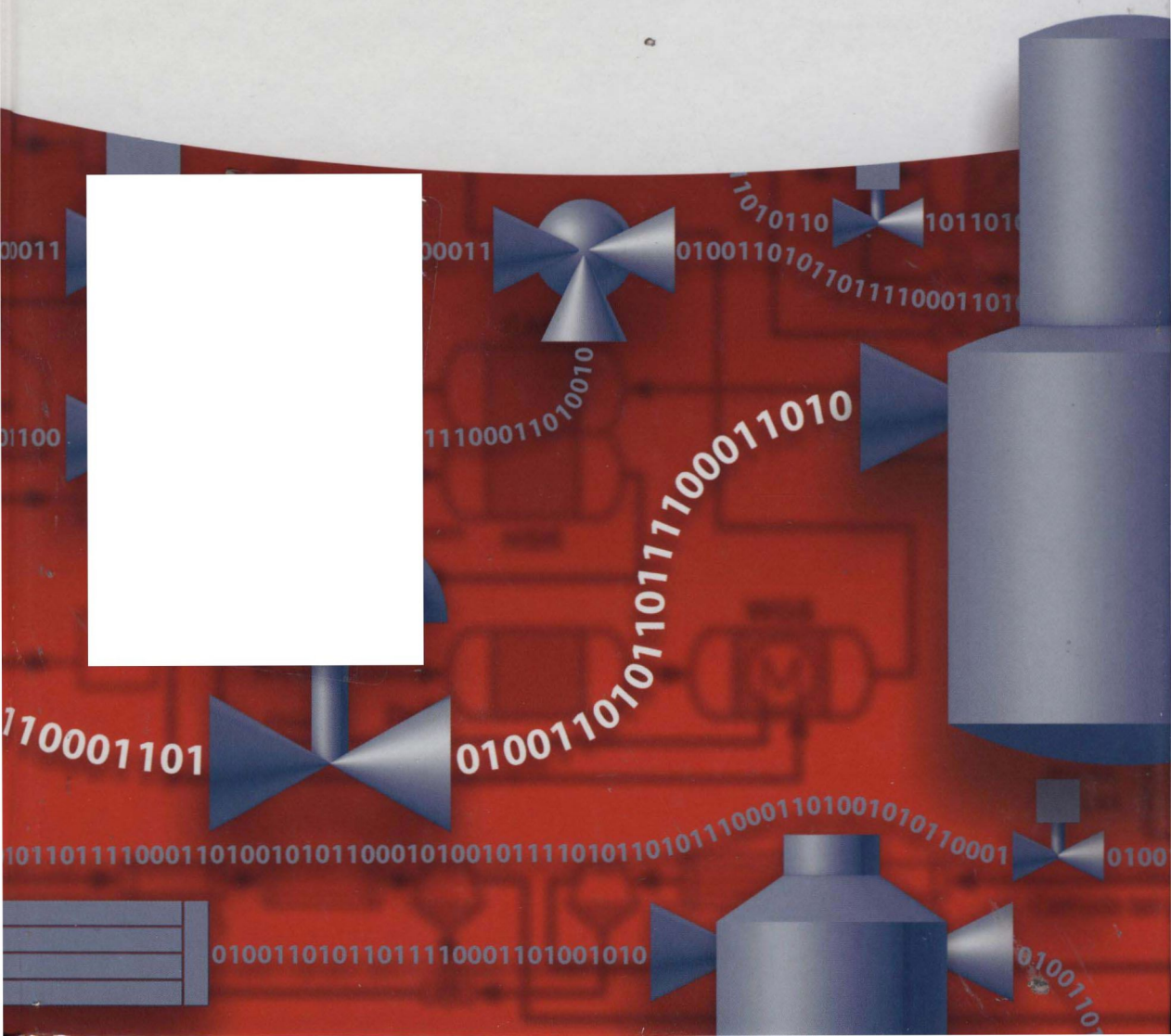


Michael Mulholland

Applied Process Control

Essential Methods



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Author

Professor Michael Mulholland
University of KwaZulu-Natal
Chemical Engineering
4041 Durban
South Africa

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Preface

Material in this book is sequenced for the process engineer who needs ‘some’ background in process control (Chapters 1–5) through to the process engineer who wishes to *specialise* in advanced process control (Chapters 1–9). The theory needed to properly understand and implement the methods is presented as succinctly as possible, with extensive recourse to linear algebra, allowing multi-input, multi-output problems to be interpreted as simply as single-input, single-output problems.

Before moving on to the more advanced algorithms, an essential practical background is laid out on plant instrumentation and control schemes (Chapters 2, 4 and 5). Chapter 3 builds modelling abilities from the simplest time-loop algorithm through to discrete methods, transfer functions, automata and fuzzy logic. By the end of Chapter 5, the engineer has the means to design simple controllers on the basis of his or her models, and to use more detailed models to test these controllers. Moreover, ability has been developed in the use of the multi-element control schemes of ‘advanced process control’.

Chapter 6 focuses on observation. Whereas Chapter 3 reveals the tenuous chain of preparation of plant signals, Chapter 6 aims to make sense of them. Important issues on the plant are signal conditioning, data reconciliation, identification of model parameters and estimation of unmeasured variables.

Chapter 7 addresses more advanced control algorithms, drawing on a wide range of successful modern methods. To a large extent, continuous and discrete versions of an algorithm are presented in parallel, usually in multi-input, multi-output formats – which simply devolve to the single-input, single-output case if required. State–space, input–output, fuzzy, evolutionary, artificial neural network and hybrid methods are presented. There is a strong emphasis on model predictive control methods which have had major industrial benefits.

A review of the classical methods of stability analysis is delayed until Chapter 8. This has been kept brief, in line with reduced application in the processing industries. One recognises that stability criteria, such as pole locations, do underlie some of the design techniques of Chapter 7. Certainly, frequency domain concepts are part of the language of control theory, and essential for advanced investigation. But with the slower responses and inaccurate models of processing plants, controllers are not predesigned to ‘push the limits’ and tend to be tuned up experimentally online.

A review of a range of optimisation techniques and concepts is given in Chapter 9. Although not a deep analysis, this imparts a basic working knowledge, enabling the development of simple applications, which can then later be built upon. Topics covered include *linear*, *integer*, *mixed*, and *non-linear* programming, search techniques, global optimisation, simulated annealing, genetic algorithms and multi-objective optimisation. These methods, and *dynamic programming*, underlie the

predictive control and optimal scheduling topics in Chapter 7, and are also important as static optimisers in such applications as supply chain, product blending/distribution and plant economic optimisers.

This book tries to make the methods practically useful to the reader as quickly as possible. However, there is no shortcut to reliable results, without a basic knowledge of the theory. For example, one cannot make proper use of a Kalman filter, without understanding its mechanism. Complex multi-input, multi-output applications will require a good theoretical understanding in order to trace a performance problem back to a poorly calibrated input measurement. Hence, an adequate theoretical background is provided.

A few distinctions need to be clarified:

- 1) Modelling is a particular strength of the process engineer, and is a basis of all of the algorithms – especially model predictive control. The reader needs to distinguish *state-based* models versus *input–output* models. The state-based models can predict forward in time knowing only the initial state and future inputs. Some algorithms rely on this. In contrast, *input–output* models will need additional information about past inputs and outputs, in order to predict future outputs. To use state-based algorithms on these, a state observer algorithm (e.g. Kalman filter) will be required to estimate the states.
- 2) The forward shift operator $z = e^{Ts}$ is used to relate discrete versions of systems to their transfer function forms $G(s)$ in the s (Laplace/frequency) domain. In a lot of what follows, this theoretical connection is not significant, and the data sampling shift parameter q could be used, but sometimes it is not in this text.
- 3) The text consistently uses bold characters to signify matrices $[A]$, vectors $[\mathbf{x}]$ and matrix transfer functions $[G(s), G(z)]$. Non-bold characters are used for scalars.

A number of examples are presented in this book in order to clarify the methods. In addition, the separate accompanying book *Applied Process Control: Efficient Problem Solving* presents 226 solved problems, using the methods of this text. These often make use of MATLAB® code which is arranged in obvious time loops, allowing easy translation to the real-time environment. There will, however, be the challenge to provide additional routines such as matrix inversion.

A simple interactive simulator program has been made available at <https://sourceforge.net/projects/rtc-simulator/>. It includes 20 different applications for such aspects as PID and DMC controller tuning, advanced level control, Smith prediction, Kalman filtering and control strategies for a furnace, a boiler and a hybrid system. No support is available for the simulator.

Although I have personally used a variety of methods on industrial and research applications, in writing this book I have been fascinated to discover the brilliant ideas of many other workers in the field. To all of those people who get excited about process control, I wish you an optimal trajectory.

University of KwaZulu-Natal
March, 2016

Michael Mulholland

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Many of the problems in this book are dealt with using the MATLAB[®] program, which is distributed by the MathWorks, Inc. They may be contacted at

The MathWorks, Inc.

3 Apple Hill Drive
Natick, MA 01760–2098, USA
Tel: 508-647-7000
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A few problems are dealt with in the GAMS[®] optimisation environment, distributed by

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Contact: sales@gams.com

Some problems make use of the LPSOLVE mixed integer linear programming software which is hosted on the SourceForge Web site at

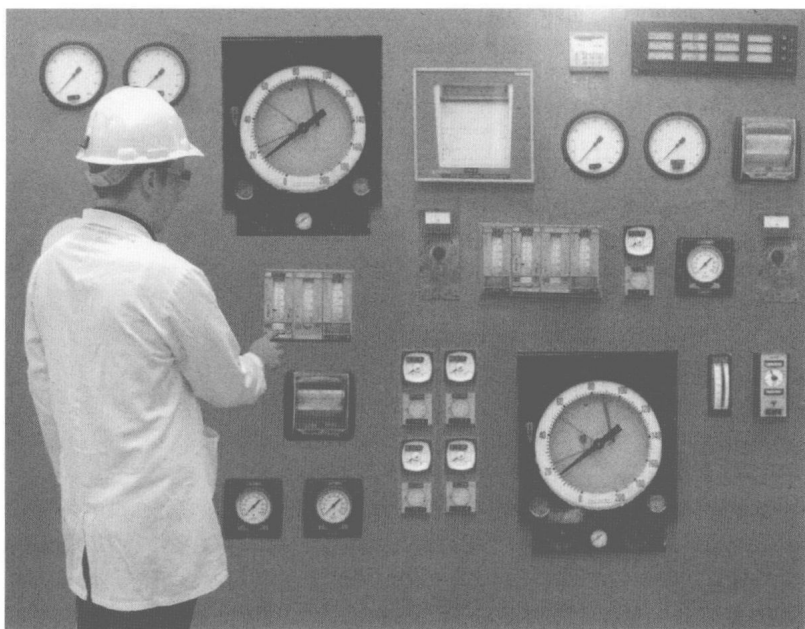
<http://sourceforge.net/projects/lpsolve/>

Abbreviations

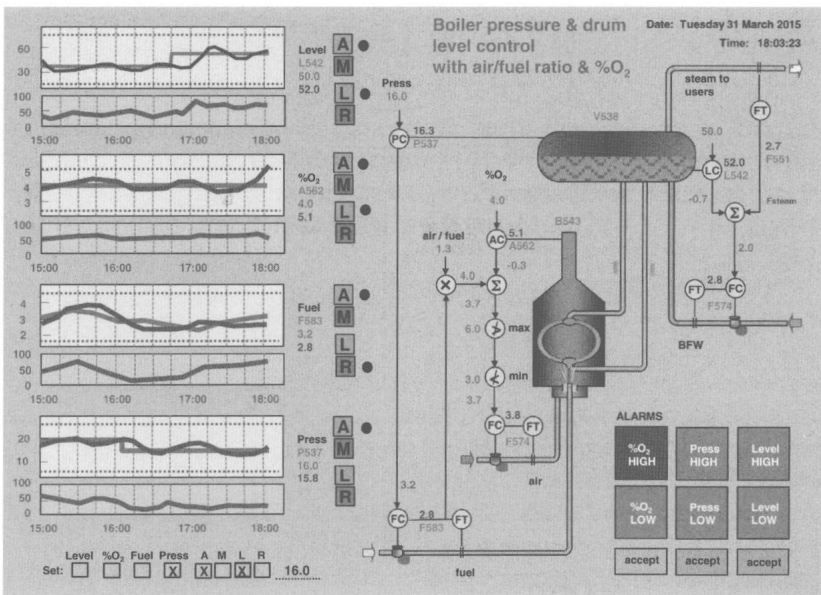
A/D	analogue to digital
AC/FO	air to close/fail open
ANN	artificial neural network
AO/FC	air to open/fail closed
APC	advanced process control
ARIMAX	autoregressive integrated moving average exogenous
ARMAX	autoregressive moving average exogenous
ARX	autoregressive exogenous
BB	branch and bound
BFW	boiler feedwater
BIDP	backward iterative dynamic programming
CEM	cause and effect matrix
CRT	cathode ray tube
CV	controlled variable
CVP	control variable parameterisation
CW	cooling water
D/A	digital to analogue
DAE	differential and algebraic equations
DCS	distributed control system
DMC	dynamic matrix control
DP	differential pressure
DV	disturbance variable
$E\{ \dots \}$	expectation of . . .
EKF	extended Kalman filter
ES	evolutionary strategy
FFT	fast Fourier transform
FIDP	forward iterative dynamic programming
FIMC	fuzzy internal model controller
FIR	finite impulse response
FRM	fuzzy relational model
FRMBC	fuzzy relational model-based control
FSQP	feasible sequential quadratic programming

Fuzzy	fuzzy logic
GA	genetic algorithm
GAMS	General Algebraic Modelling System®
GM	gain margin
GPC	generalised predictive control
HP	high pressure (port)
HS	high select
I	identity matrix
I/O	input–output
I/P	current to pressure (pneumatic) converter
IAE	integral of absolute error
IDP	iterative dynamic programming
IMC	internal model control
INA	inverse Nyquist array
IO	input–output
IP	integer programming
ISE	integral of squared error
KO	knockout (separation drum)
LAN	local area network
LBT	lower block triangular
LCD	liquid crystal display
LDMC	linear dynamic matrix control
LP	linear programming
LP	low pressure (port)
LPG	liquefied petroleum gas
LPSOLVE	MILP program (http://sourceforge.net/projects/lpsolve/)
LQR	linear quadratic regulator
LS	low select
LS	least squares
MATLAB	MATLAB® program, distributed by the MathWorks, Inc.
MEK	methyl ethyl ketone
MIDO	mixed integer dynamic optimisation
MILP	mixed integer linear programming
MIMO	multi-input, multi-output
MINLP	mixed integer nonlinear programming
MIP	mixed integer programming
MIQP	mixed integer quadratic programming
MLD	mixed logical dynamical
MM	molecular mass
MPC	model predictive control
MRI	Morari resiliency index
MTBF	mean time between failures
MV	manipulated variable
NC	normally closed
NLP	nonlinear programming
NO	normally open

NSGA-II	fast non-dominated sorting genetic algorithm II
OA	outer approximation
ODE	ordinary differential equation
OHTC	overall heat transfer coefficient
P	proportional
P/I	pressure (pneumatic) to current converter
PCA	principal components analysis
PDE	partial differential equation
PI	proportional integral
PID	proportional integral derivative
PLC	programmable logic controller
PM	phase margin
PV	process variable
QDMC	quadratic dynamic matrix control
RAID	redundant array of independent discs
RGA	relative gain array (Bristol array)
RLS	recursive least squares
RTD	resistance temperature detector
RTO	real-time optimisation
SCADA	supervisory control and data acquisition
SG	specific gravity
SISO	single-input single-output
SP	setpoint
SQP	sequential quadratic programming
VPC	valve position control
WABT	weighted average bed temperature
WAN	wide area network (e.g. using telecommunication, radio)
WG	water-gauge
ZOH	zero-order hold



Old analogue control panel



Modern digital control display

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