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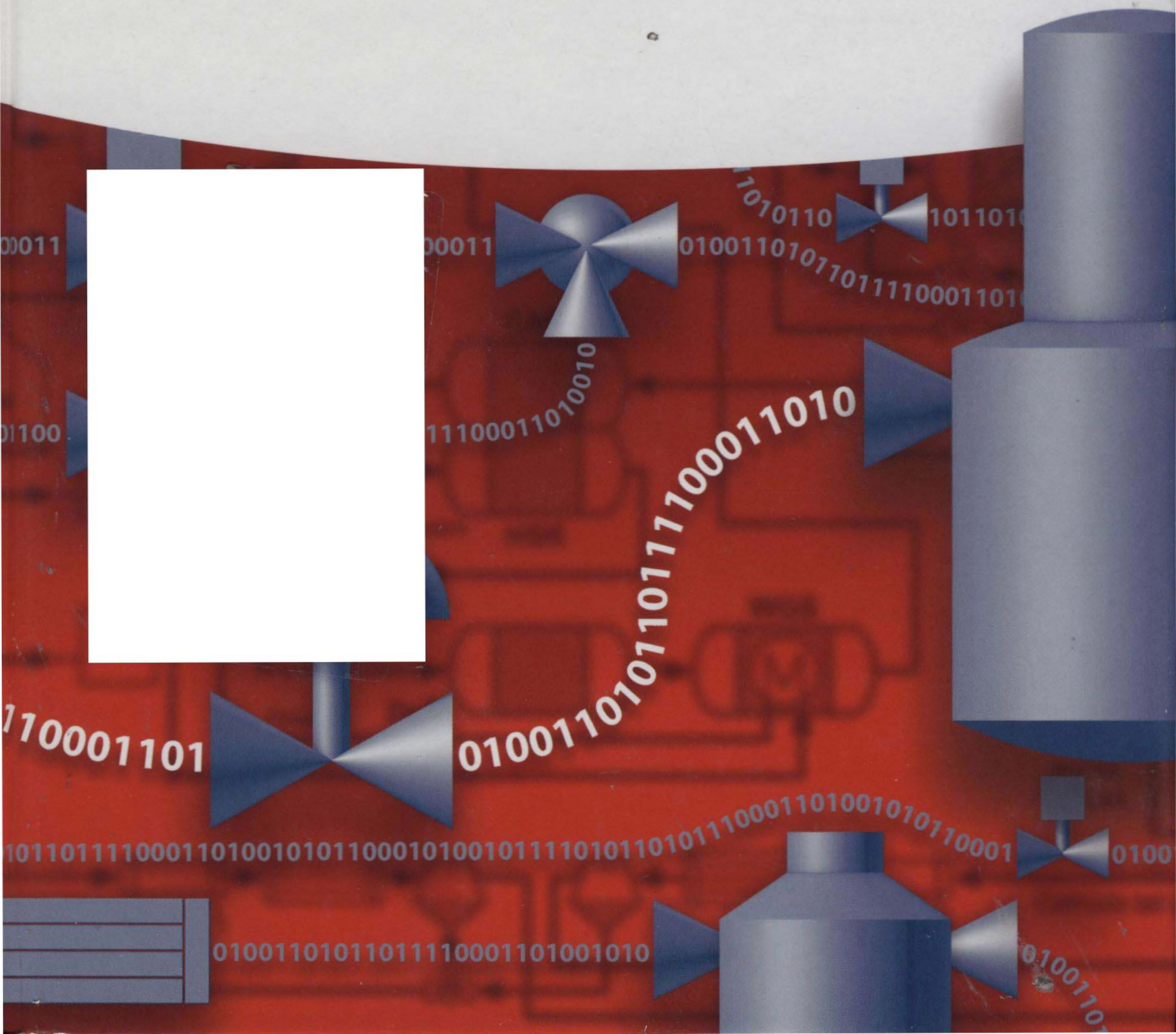
Michael Mulholland

# Applied Process Control

## Essential Methods



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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 [$\boldsymbol{A}$], vectors [$\boldsymbol{x}$] and matrix transfer functions [$\boldsymbol{G}(s)$, $\boldsymbol{G}(z)$]. 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* Michael Mulholland
March, 2016

## Acknowledgements

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
Fax: 508-647-7001
E-mail: info@mathworks.com
Web: mathworks.com
How to buy: http://www.mathworks.com/store

A few problems are dealt with in the GAMS® optimisation environment, distributed by

**GAMS Development Corporation**
1217 Potomac Street, NW
Washington, DC 20007, USA
General Information and Sales: (+1) 202 342-0180
Fax: (+1) 202 342-0181
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

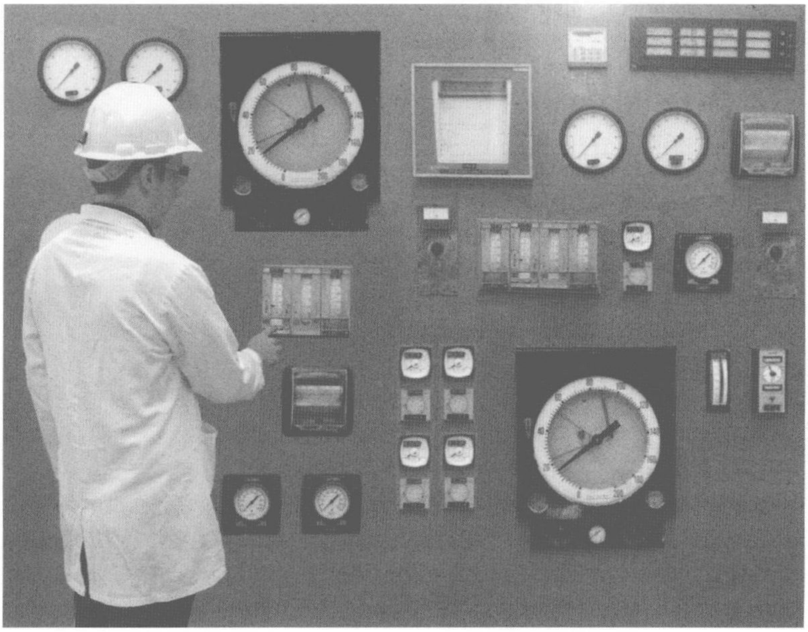
http://sourceforge.net/projects/lpsolve/

## Abbreviations

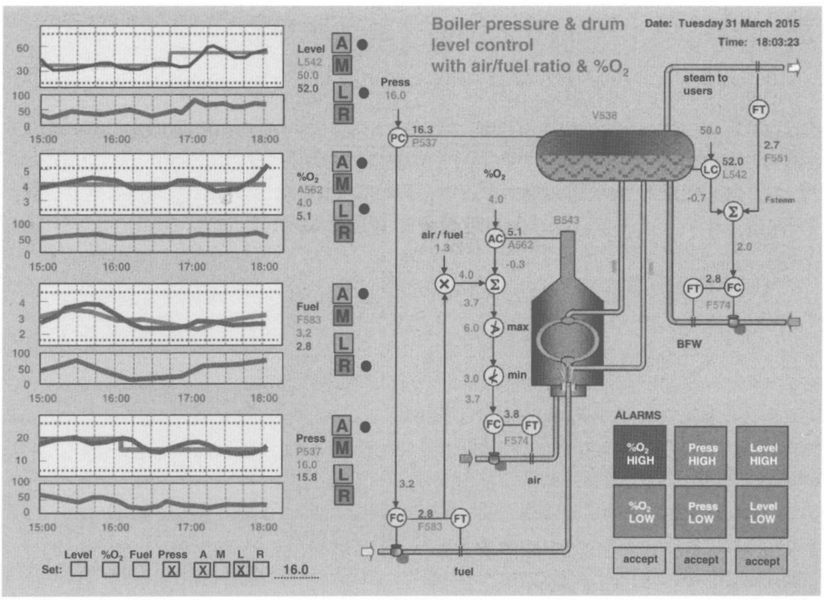
| | |
|---|---|
| A/D | analogue to digital |
| AC/FO | air to close/fail open |
| ANN | artificial neural network |
| AO/FC | air to open/fail closed |
| APC | advanced process control |
| ARIMAX | autoregressive integrated moving average exogenous |
| ARMAX | autoregressive moving average exogenous |
| 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{ . . . } | 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

# Essential Methods Contents