



# Contents

<b>Dear Student</b>	<b>xi</b>
<b>1 Introduction: Control engineering is a part of our life</b>	<b>1</b>
Wind turbine systems	3
Wastewater treatment plant control	4
Flight control systems	6
Coordinate measuring machines	8
Ship autopilot design	10
Hot strip rolling mills in the steel industry	11
Industrial heaters	14
<b>2 Tools for the control engineer</b>	<b>16</b>
How many ways of writing complex numbers are there?	17
What is the complex exponential and how do I use it?	18
I just want to know how to add, subtract, multiply and divide complex numbers. Is this easy?	20
Control engineers talk about transfer functions. What is a transfer function?	22
What are the magnitude or gain values of a complex number?	22
How do I work out the phase of a complex number?	22
I need to practise solving quadratic equations: are there some simple methods?	23
Parameter dependent complex numbers! That sounds hard – what are they?	24
How do I define a Laplace transform?	25
What is the Laplace variable $s$ and the $s$ -plane?	26
Where do the poles and zeros come from in a Laplace transform?	27
How do I use transform tables?	28
Oh dear, I need to work out Laplace transforms from first principles. How do I begin?	30
The transforms get even harder: what are the exponential–trigonometric signals?	32
When I multiply a signal by a constant, what happens to the Laplace transform?	34
I need to transform a combinations of signals. How do I do this?	34
What Laplace transform operations should I learn?	35
Why is a differentiator like multiplying by $s$ ?	36
How do we represent an integrator using Laplace transforms?	37

I need to use Laplace transforms to represent a differential equation. How do I do this?	38
My lecturer says the system is linear. What does she mean?	39
I want to know what the superposition property is. Is it useful?	42
The tutorial sheet mentions causality and physical realisability. They sound difficult. What are they?	43
Can I use partial fractions to help me with Laplace transform derivations?	44
What is the Final Value Theorem?	45
How do I use the Initial Value Theorem?	46
How do I find the frequency content of a signal?	47
<b>3 Software toolkit: MATLAB</b>	<b>52</b>
3.1 Introduction to MATLAB	52
3.2 Starting MATLAB	53
3.3 Basic operations	54
3.4 Vectors	55
3.5 Vector manipulation	56
3.6 Polynomials	57
3.7 Matrices	58
3.8 Functions	59
3.9 Help window/tips	60
3.10 Plotting	61
3.11 Transfer functions in MATLAB	64
3.12 MATLAB environment	68
3.13 M-files and functions	70
3.14 SISO Design Tool: <code>r1tool</code>	75
General MATLAB commands	78
<b>4 Software toolkit: Simulink</b>	<b>83</b>
4.1 Using Simulink for analysis	83
4.2 Detailed house model	86
4.3 Building a simple Simulink model	91
4.4 Development and analysis of the house heating model	96
<b>5 Modelling for control engineering</b>	<b>102</b>
5.1 Signals, systems and block diagrams	103
5.2 Actuator–Process–Transducer device structure	106
5.3 Modelling summary	109
5.4 Chemical process engineering: liquid level control	110
5.5 Mechanical systems: model of a shaker table	122
5.6 Modelling of a manufacturing process component	135
<b>6 Simple systems: first-order behaviour</b>	<b>147</b>
6.1 First-order system model	150
6.2 First-order step response	151
6.3 Positive and negative step signals ('up and down' step signals)	154
6.4 Use of Simulink to find the step response	155
6.5 General first-order system time response	155

6.6	System parameters and system behaviour	158
6.7	Speed of response	163
6.8	Process time delays	165
6.9	Modelling of deadtime process	167
6.10	MATLAB function: pade	168
<b>7</b>	<b>Simple systems: second-order systems</b>	<b>173</b>
7.1	Second-order systems: model of a trailer suspension system	174
7.2	Second-order system parameters	177
7.3	Second-order transfer function forms	181
7.4	Solving general second-order equations	183
7.5	Modelling of second-order systems with deadtime	189
7.6	Simulink model of second-order system with deadtime	190
<b>8</b>	<b>Feedback improves system performance</b>	<b>196</b>
8.1	Open and closed-loop systems	197
8.2	Introducing feedback into control	200
8.3	Practical closed-loop control systems	202
8.4	Block diagram manipulation	204
8.5	Feedback changes the closed-loop performance	211
<b>9</b>	<b>Design specifications on system time response</b>	<b>219</b>
9.1	Design specifications: steady state and transient behaviour	220
9.2	Steady state performance	221
9.3	Transient performance	226
9.4	Specifications for disturbance rejection	233
<b>10</b>	<b>Poles, zeros and system stability</b>	<b>242</b>
10.1	Poles and zeros	243
10.2	System parameters and their relationship to pole locations	248
10.3	The link between pole position and system step response	251
10.4	How do the zeros of a transfer function model arise?	253
10.5	Further analysis and interpretation of the role of zeros in a system	257
10.6	Open- and closed-loop poles and zeros	259
10.7	What do we mean by bounded signals?	264
10.8	System stability	267
<b>11</b>	<b>Three-term control: PID control</b>	<b>277</b>
11.1	Controller assessment framework	279
11.2	Proportional control	282
11.3	Integral control	290
11.4	Derivative control	299
11.5	PI and PID controller formula	307
<b>12</b>	<b>PID control: the background to simple tuning methods</b>	<b>312</b>
12.1	Choice of controller structure	313
12.2	Manual tuning method	318
12.3	Proportional control of a system with a first-order model	321

12.4	Proportional and integral control of a system with a first-order model	327
12.5	Proportional and derivative control procedures	331
12.6	PID controller design by pole placement	340
<b>13</b>	<b>Root locus for analysis and design</b>	<b>351</b>
13.1	The relationship between the poles and system dynamic response: a summary	352
13.2	Introducing the root locus	353
13.3	Preliminary MATLAB root locus investigations	358
13.4	Some useful root locus rules	360
13.5	Second-order system performance: root locus contours	362
13.6	Effects of adding a pole or a zero to the root locus of a second-order system	364
13.7	Time delays and inverse response systems	368
13.8	Parameter root locus	370
13.9	Using MATLAB <code>r1tool</code> and <code>r1ocus</code> routines	375
<b>14</b>	<b>The frequency domain</b>	<b>383</b>
14.1	Identification of magnitude and phase values from a sinusoidal signal	386
14.2	Frequency and logarithmic frequency scales	390
14.3	Presentation of gain and phase information	392
14.4	The frequency response and system features	397
14.5	Special frequency points	405
14.6	Interpretation of frequency response plot	409
14.7	Performance specification: gain and phase margins	410
<b>15</b>	<b>Frequency response using Bode plot presentation</b>	<b>426</b>
15.1	The Bode plot	428
15.2	Gain and phase calculation without using a computer	428
15.3	Using computers to form a frequency response plot	430
15.4	What are low, middle and high frequencies?	432
15.5	Transfer function components	434
15.6	Magnitude and phase of transfer function components	436
15.7	Introducing a sketching table	439
15.8	Elementary examples	445
15.9	Second-order underdamped system	451
15.10	Effect on gain and phase plots of increasing the damping ratio	454
15.11	Further examples using MATLAB plots	457
15.12	Magnitude plots of closed-loop and sensitivity transfer functions	461
<b>16</b>	<b>Controller design using the Bode plot</b>	<b>469</b>
16.1	Design specifications	470
16.2	Design example 1: proportional control with lag term added	471
16.3	Design example 2: PI control	477
16.4	Phase lag and phase lead elements	482
16.5	Phase lag controller	486

16.6	Phase lead control design	491
16.7	Design is iterative: a cautionary tale	498
16.8	Summary of the effects of phase lag and phase lead controllers on system responses	500
<b>17</b>	<b>Analysis and simple design using the Nichols chart</b>	<b>505</b>
17.1	Adding closed loop information to a Nichols plot	507
17.2	The Nichols chart	513
17.3	Design specifications on the Nichols chart	516
17.4	Reading gain and phase margins from the Nichols plot	517
17.5	Altering the loop gain to achieve design specifications	519
<b>18</b>	<b>The practical aspects of PID control</b>	<b>529</b>
18.1	Understanding common notation for industrial PID controllers	531
18.2	Industrial PID control technology	535
18.3	The issues in implementing an industrial PID controller	538
18.4	Integral wind-up and anti-wind-up circuits	539
18.5	Implementing the derivative term	545
18.6	Industrial PID controller structures	547
18.7	Different forms of industrial PID controllers	553
18.8	Reverse acting controllers	556
18.9	Digital PID control	565
<b>19</b>	<b>PID controller tuning methods</b>	<b>577</b>
19.1	Understanding PID tuning procedures	579
19.2	Process reaction curve PID tuning method	584
19.3	Sustained oscillation PID tuning	592
19.4	Damped oscillation or quarter amplitude decay PID tuning procedure	600
19.5	The relay experiment	605
19.6	Conclusions; or is the PID tuning problem solved?	613
<b>20</b>	<b>Introducing a state variable description of a system</b>	<b>620</b>
20.1	What is a state variable?	621
20.2	State vectors and matrices of coefficients	622
20.3	General procedure for writing a state variable representation	623
20.4	State variable diagram	629
20.5	MATLAB–Simulink representation of state variable models	630
20.6	Example of the development of a state variable model	632
20.7	State variable free and forced responses	635
20.8	Modelling and simulation in Simulink using an ABCD form	640
20.9	State variable model to transfer function model	643
20.10	MATLAB function ss2tf: state space to transfer function conversion	645
20.11	From transfer function to state space model	647
20.12	MATLAB command tf2ss: transfer function to state space conversion	653

<b>21</b>	<b>Linearisation of systems from the real nonlinear world</b>	<b>659</b>
21.1	What do we mean by <i>linear</i> ?	660
21.2	Nonlinear examples	662
21.3	Working regions and operating points	664
21.4	Linear approximation through Taylor series	667
21.5	Where do we apply linearisation?	668
21.6	Linearisation of a simple nonlinear dynamic equation	670
21.7	Linearising the model equations for a liquid level process	673
21.8	Linearisation of a more general nonlinear state variable model	675
21.9	Linearising a nonlinear state variable model to produce a linear ABCD model	676
<b>22</b>	<b>Analysis of state variable systems</b>	<b>683</b>
22.1	Matrix revision	684
22.2	Eigenvalues and eigenvectors	688
22.3	Poles, eigenvalues and system stability	691
22.4	More on state variable system time responses	696
22.5	Case study: Eigenvalues, eigenvectors and time responses	699
<b>23</b>	<b>An introduction to control using state variable system models</b>	<b>710</b>
23.1	State variable system structure	711
23.2	State variable controller structure	712
23.3	A state variable investigation of output feedback	713
23.4	Pole placement design with output feedback	716
23.5	Investigating state feedback: using the state vector directly	722
23.6	At the signpost of advanced control	733
	<b>Answers to multiple choice questions</b>	<b>738</b>
	<b>Answers to selected questions</b>	<b>740</b>
	<b>Index</b>	<b>745</b>
	<b>MATLAB and Simulink index</b>	<b>751</b>