

THE CONTROL OF DYNAMICALLY INTERACTING
SYSTEMS

by

JAMES EDWARD COLGATE

S.B. in Physics, Massachusetts Institute of Technology
(1983)

S.M. in Mechanical Engineering, Massachusetts Institute of Technology
(1986)

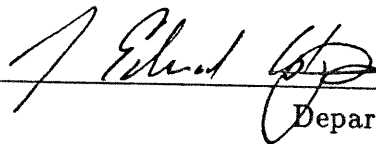
SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY IN MECHANICAL ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
August 1988

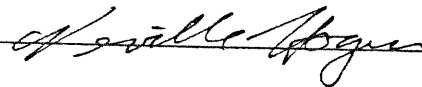
© Massachusetts Institute of Technology 1988

Signature of Author



Department of Mechanical Engineering
August 3, 1988

Certified by



Neville Hogan
Thesis Supervisor

Accepted by



Professor Ain A. Sonin
Chairman, Departmental Committee on Graduate Studies

THE CONTROL OF DYNAMICALLY INTERACTING SYSTEMS

by

JAMES EDWARD COLGATE

Submitted to the Department of Mechanical Engineering
on August 3, 1988 in partial fulfillment of the
requirements for the Degree of Doctor of Philosophy in
Mechanical Engineering

ABSTRACT

This thesis addresses the analysis and design of controllers for dynamically interacting systems. The example of a robotic manipulator which must interact with an arbitrary passive environment is considered in detail.

An approach to the design of *interaction controllers* is presented in terms of a hierarchical set of design specifications and is contrasted with an approach to servo design. It is shown that the emphasis on interaction creates a need for *coupled stability* and *interactive behavior* specifications.

Methods are developed for the analysis of coupled stability and interactive behavior. A necessary and sufficient condition for the stability of a linear, time-invariant plant coupled to an arbitrary passive environment is derived. An alternative test for coupled stability requiring the construction of two root loci, one representing interaction with springs, and one representing interaction with masses, is also developed.

Experiments performed to examine the utility of these methods are described. A variety of controllers were implemented on a two-link manipulator and a device for measuring the endpoint impedance of the manipulator was constructed. Impedance measurements of the closed-loop systems were made, and interaction with springs and masses was examined. These experiments indicate that a measurement of the impedance is an effective predictor of interactive behavior. In addition, these experiments demonstrate that systems with identical servo responses can exhibit significantly different interactive behaviors, and that contact instability can occur in the absence of force feedback.

The concepts of a *passive physical equivalent* and an *uncontrollable element* are introduced. These concepts are used to analyze the contact instability phenomenon associated with force feedback, and to make recommendations for improved force control.

Finally, approaches to the design of interaction controllers are presented and analyzed. The relative merits of various design methods, including "servo masking" and the "target model referenced controller", are discussed.

Thesis Supervisor: Neville Hogan

Title: Associate Professor of Mechanical Engineering
Department of Mechanical Engineering

MEMBERS OF THE COMMITTEE

Dr. Neville Hogan (Chairman)
Associate Professor
Department of Mechanical Engineering

Dr. J. Karl Hedrick
Professor
Department of Mechanical Engineering

Dr. Warren P. Seering
Associate Professor
Department of Mechanical Engineering

Dr. John L. Wyatt
Associate Professor
Department of Electrical Engineering and Computer Science

Acknowledgements

I would like to thank Neville Hogan for introducing me to this field of research, and for doing well those things an advisor should do—providing essential guidance and support. However, I am grateful to Neville for much more—for allowing me the latitude to pursue my own, sometimes off-beat notions; for sparking lively discussion one-on-one, in group meetings, or over beer; and most of all, for managing to transcend the more petty concerns (like thesis-writing) that threaten to control the life of an academic, thereby providing frequent reminder of what was so attractive about this field in the first place.

I am also grateful to the other members of my committee, Karl Hedrick, Warren Seering, and John Wyatt. As individuals, they offered encouragement and sage consultation. As a group, they trounced my pre-conceived notions of the ineffectiveness of committees.

Among my fellow students, Bill Murray stands out. In five years as an officemate, Bill was always a source of help, humor, and discussion. He also set a standard of quality in all aspects of research from which I and the entire Newman Lab have benefitted.

I would like to thank Dov Adelstein for his irreverence, which helped me keep things in perspective, and for the bull sessions with Bill and others that were usually just too entertaining. Dov also wrote and gave me access to the data analysis software used in this thesis.

Thanks to Ian, wherever he is, for his work on the two-link manipulator; to Andre, for the rousing discussions of force control; to Crispin and Ernie, for affording me a glimpse of thought on other, higher planes; to Cary, Joey B., Dave (the story-teller), and John W., who have found life beyond MIT; to Eric and Dawei, for mezzanine banter; to Keita, for nursing the microVAX and keeping me in business with Matrix-x, and to J.B., for nursing the laser printer and seeing to the purchase of Matrix-x. And thanks to the rest of the members of the Newman Lab for collectively making it a fine place to be.

I am grateful to Emilio Bizzi for allowing me to use the equipment in his lab, and to Sandro Mussa-Ivaldi, for helping me first to learn, and then to maintain the two-link manipulator.

Thanks to Bob Samuel for the good times in the machine shop, and to Deborah Faust for helping me out of many a tight spot.

Thanks to Cliff and Greg, roommates of long-standing, and all-around pals who helped me realize that there is more to life than the lab. Thanks to Marissa, who may yet convince me that there is more to life than engineering.

Finally, it would be fruitless to try to find a sentence or two that would properly acknowledge the love and support of my parents (fortunately, we're family, so they won't mind if I don't).

This research was performed in the Eric P. and Evelyn E. Newman Laboratory for Biomechanics and Human Rehabilitation at M.I.T. Partial support was supplied by a National Science Foundation Fellowship, NSF grants number ECS-8307461 and EET-8613104, NIDRR grant number G000830074, and the Whitaker Foundation.

To Mom and Dad

Contents

Title Page	1
Abstract	2
Members of the Committee	4
Acknowledgements	5
Table of Contents	8
List of Figures	12
List of Tables	16
Nomenclature	17
1 Introduction	20
1.1 Statement of Purpose	20
1.2 Background	21
1.2.1 Physical Systems Modeling	21
1.2.2 Physical Equivalence	22
1.2.3 Control Theory and Network Analysis	23
1.3 Context	24
1.3.1 Manipulation	24
1.3.2 Impedance Control	25
1.3.3 Departures from the Ideal	27
1.3.4 Force Control	28
1.4 An Approach to the Control of Interaction	28
1.4.1 A Heirarchy of Design Specifications	28
1.4.2 Structure of Interaction Controllers	31
1.5 Terminology	33
1.6 Summary of Remaining Chapters	35

2	Passivity	36
2.1	Thermodynamic Concepts	36
2.2	Active Models	39
2.3	General State Space Concepts of Passivity	42
2.4	Passivity of Linear Systems	46
2.4.1	Input/Output Passivity Criteria	48
2.4.2	Network Synthesis	55
2.4.3	State-Space Passivity Criteria	56
2.5	An Alternative Criterion for Positive Real Functions	60
3	Coupled Stability	64
3.1	Approaches to Coupled Stability	64
3.2	1-Port Interaction	70
3.3	n -Port Interaction	76
3.4	The "Worst" Environment	82
3.5	Extensions to the Coupled Stability Analysis	84
3.6	Contact Stability	86
3.7	Summary	87
4	Examples of the Coupled Stability Criterion	88
4.1	Impedance Controllers	88
4.1.1	Feedback Linearized Impedance Control	89
4.1.2	A Linearized Impedance Controller for a Two-Link Manipulator	89
4.1.3	The Addition of First-Order Decoupled Actuator Dynamics	94
4.2	Force Feedback	98
4.3	PID Control	103
4.3.1	SISO Example	103
4.3.2	Two-Link Manipulator Implementation	106
4.4	LQG/LTR Control	113
5	Experimental Investigation of the Interactive Behavior of a Two-Link Manipulator	117
5.1	Overview	117
5.2	Measurement of the Driving Point Impedance	118
5.2.1	Approach	118
5.2.2	Apparatus	121
5.2.3	Data Acquisition	124
5.2.4	Data Analysis	125
5.2.5	Error Analysis	131
5.3	Interaction Tests	134

5.3.1	Mass Interaction	134
5.3.2	Spring Interaction	136
5.4	Results	136
5.4.1	No Control	136
5.4.2	Impedance Control	139
5.4.3	PID Control	146
5.4.4	LQG/LTR Control	161
5.5	Summary	165
6	An Application of Network Synthesis to the Analysis of Interactive Behavior	179
6.1	Passive Physical Equivalents	179
6.2	Network Synthesis Procedures	183
6.3	Difficulties	195
6.4	Uncontrollable Elements	198
7	Force Feedback as an Example of Interaction Control	201
7.1	Background	201
7.2	Analysis of Lumped Models	206
7.3	Analysis of a Distributed Model	210
7.4	Dynamic Compensation	213
7.5	Non-Uniform Manipulators	217
7.6	The Effect of a Computational Delay	220
7.7	Summary: Improving Force Control	221
8	Techniques for the Design of Interaction Controllers	225
8.1	Review of Available Techniques	228
8.2	A Naive Approach	232
8.3	Servo-Masking	239
8.4	The Target Model Referenced Controller	245
8.5	The Role of Inherent Dynamics	257
8.6	Summary	259
9	Conclusions and Discussion	261
9.1	Conclusions	261
9.2	Related Areas of Research	264
9.3	Future Directions	268
A	Counterclockwise Loops in Nyquist Plots	276
B	The LQG/LTR Design Procedure	278
C	An Example of Passive Physical Equivalent Synthesis	284

D Preservation of Relative Order	286
Bibliography	292

List of Figures

1.1	Bond graph representation of an impedance controlled manipulator. . .	26
1.2	Design specifications for a servo controller.	29
1.3	Design specifications for an interaction controller.	30
1.4	Structure of manipulator/environment system.	31
1.5	Structure of the manipulator/environment system; control divided into state-dependent and state-independent parts.	32
1.6	Network representation of manipulator/environment system.	32
2.1	Thermodynamic system interacting with an atmosphere; the reversible engine will extract the maximum useful work from this system for any change in state. Adapted from [48].	37
2.2	Passive system with an active linearized model	40
2.3	Two-dimensional mass-spring system	41
2.4	n -Port	46
2.5	Locus of points for evaluation of $Re\{Z(\sigma + j\omega)\}$	63
3.1	Systems which interact at a single port.	70
3.2	Block diagram representation of coupled system.	71
3.3	An example mapping of the Nyquist contour.	73
3.4	Nyquist plots of systems which fail to satisfy the coupled stability criterion	75
3.5	The plant A coupled to a spring.	84
3.6	Coupling of active systems.	85
4.1	Two-link manipulator	91
4.2	Simple impedance controller. Nyquist plot of $Y_{xx}(s)$	93
4.3	Closed loop control system, taken from [44].	95
4.4	Bode plots of target and closed loop admittances (example 1, case 1 from [44]	96
4.5	Nyquist plots of target and closed loop behavior (example 1, case 1 from [44]	97
4.6	Rigid body manipulator.	99
4.7	Manipulator with non-colocated actuation and sensing.	99
4.8	Nyquist plots of a force controlled manipulator's admittance.	101
4.9	Worst environment root loci for a force controlled manipulator.	102

4.10	PID control of a second order system.	104
4.11	Second order system with a PID compensator: interaction with springs (left) and masses (right).	105
4.12	Discrete representation of a driving point admittance.	109
4.13	Driving point admittance, $Y_{zz}(s)$. All three PID controlled systems. . .	111
4.14	Driving point admittance, $Y_{yy}(s)$. All three PID controlled systems. . .	112
4.15	Closed loop singular values, LQG/LTR control.	114
4.16	Nyquist plot of closed loop admittance ($Y_{yy}(s)$). LQG/LTR control. . .	115
4.17	Bode plots of closed loop admittance ($Y_{yy}(s)$). LQG/LTR control. . . .	116
5.1	Two-link manipulator.	119
5.2	The spinner.	123
5.3	Data acquisition scheme	125
5.4	(a) Interrupt service routine. (b) Analysis of a single set of raw data. . .	126
5.5	Example of the position and force data.	127
5.6	Expanded view of the position and force data.	128
5.7	Phase of the force transducer pre-filter.	133
5.8	Mass interaction experiment.	135
5.9	Spring interaction experiment.	137
5.10	Phase of $Y(j\omega)$: no control data.	138
5.11	Magnitude of $Y(j\omega)$: no control data and original model.	140
5.12	Magnitude of $Y(j\omega)$: no control data and improved model.	141
5.13	Magnitude of $Y(j\omega)$: simple impedance controller, data and model. . .	143
5.14	Phase of $Y(j\omega)$: simple impedance controller, data and model.	144
5.15	Nyquist plots of Y_{11} , Y_{22} , and D : simple impedance controller.	145
5.16	Examples of interactive behavior: simple impedance controller.	147
5.17	Position and force behavior during a contact task: simple impedance controller.	148
5.18	Magnitude of $Y(j\omega)$: PID controller, Case 1, data and model.	149
5.19	Phase of $Y(j\omega)$: PID controller, Case 1, data and model.	150
5.20	Nyquist plots of Y_{11} , Y_{22} , and D : PID controller, Case 1.	151
5.21	Magnitude of $Y(j\omega)$: PID controller, Case 2, data and model.	152
5.22	Phase of $Y(j\omega)$: PID controller, Case 2, data and model.	153
5.23	Nyquist plots of Y_{11} , Y_{22} , and D : PID controller, Case 2.	154
5.24	Magnitude of $Y(j\omega)$: PID controller, Case 3, data and model.	155
5.25	Phase of $Y(j\omega)$: PID controller, Case 3, data and model.	156
5.26	Nyquist plots of Y_{11} , Y_{22} , and D : PID controller, Case 3.	157
5.27	Nyquist plots of Y_{11} : PID controllers, Cases 1, 2, and 3.	159
5.28	Nyquist plots of Y_{22} : PID controllers, Cases 1, 2, and 3.	160
5.29	Ramp responses of PID controllers, Cases 1, 2, and 3.	166
5.30	Circle tracking performance when coupled to masses: PID control, Case 1: $B_1 = 2.0$, $B_2 = 0.92$	167

5.31	Circle tracking performance when coupled to masses: PID control, Case 2: $B_1 = 1.0$, $B_2 = 0.46$	168
5.32	Circle tracking performance when coupled to masses: PID control, Case 3: $B_1 = 0.5$, $B_2 = 0.23$	169
5.33	Nyquist plot of $Y_{22}(s)$, corrected inertial parameters: LQG/LTR controller.	170
5.34	Magnitude of $Y(j\omega)$: LQG/LTR controller, data and model.	171
5.35	Phase of $Y(j\omega)$: LQG/LTR controller, data and model.	172
5.36	Nyquist plots of Y_{11} , Y_{22} , and D : LQG/LTR controller.	173
5.37	Circle tracking performance when coupled to masses: LQG/LTR control.	174
5.38	Ramp response when coupled to springs (x -direction): LQG/LTR control.	175
5.39	Ramp response when coupled to springs (y -direction): LQG/LTR control.	176
5.40	Effect of speed on the stability of a ramp response: LQG/LTR control.	177
5.41	Endpoint position and (y -force) during the execution of a contact task: LQG/LTR control.	178
6.1	An example of a passive physical equivalent.	183
6.2	First Foster form.	185
6.3	Second Foster form.	186
6.4	First Caue form.	187
6.5	Second Caue form.	188
6.6	The Brune element.	191
6.7	Mechanical equivalent to Brune element.	192
6.8	Dual of mechanical equivalent.	194
7.1	(a) Rigid body robot model. (b) Passive physical equivalent for $u = -GF$	207
7.2	Manipulator with non-colocated actuation and control.	208
7.3	Passive physical equivalent of the two-mass model.	209
7.4	Passive physical equivalents of three-mass and four-mass uniform beam models.	211
7.5	Uniform distributed model of a robot.	211
7.6	Passive physical equivalent of the uniform beam model.	212
7.7	Worst environment root loci for first-order lag force feedback compensator.	214
7.8	Two-mass model for the analysis of integral force control.	216
7.9	Non-uniform distributed beam model.	217
7.10	Passive physical equivalent to non-uniform beam model.	218
7.11	Two-mass model with damping to ground to illustrate the effect of joint friction.	219
7.12	Plot of G versus α	219
8.1	Single-axis, linear, flexible joint robot model.	230
8.2	Structure of Kazerooni's impedance controller.	232

8.3	Linear manipulator with actuator and transmission dynamics.	233
8.4	Inequality constraints which yield closed loop and coupled stability. . . .	235
8.5	Target model.	236
8.6	Command following performance: naive controller.	237
8.7	Interactive behavior: naive controller.	238
8.8	Block diagram of "servo-masking" interaction controller.	242
8.9	Command following performance: servo-masking controller.	243
8.10	Interactive behavior: servo-masking controller.	244
8.11	Block diagram of the target model referenced controller.	246
8.12	Bode plots of TMRC behavior, $\rho = 10^{-6}$	248
8.13	Bode plots of TMRC behavior, $\rho = 10^{-11}$	250
8.14	Nyquist plots of closed loop admittance, TMRC.	251
8.15	Nyquist plots of $C_s(s)Y_t(s)$ and $Y_s(s)$	251
8.16	Bode plots of TMRC behavior, target model with reduced magnitude. . .	254
8.17	Nyquist plot of closed loop admittance, target model with reduced mag- nitude.	255
9.1	The "standard block diagram".	270
9.2	Block diagram of a generalized interaction controller.	270
B.1	Model-based compensator.	279
B.2	The LQG/LTR target loop.	280
B.3	Block diagram of LQG/LTR controller for the two-link manipulator. . .	281
C.1	Synthesis of a passive physical equivalent.	285
D.1	System with relative order 2.	289
D.2	Block diagram of a general input and state feedback controller with dynamic compensation.	289

List of Tables

5.1	Minimum masses which cause instability, predicted from experimental Nyquist plot and observed: PID control.	158
5.2	Minimum masses which cause instability, predicted from experimental Nyquist plot and observed: LQG/LTR control.	162
5.3	Minimum stiffnesses which cause instability, predicted from experimental Nyquist plot and observed: LQG/LTR control.	163

Nomenclature

General Notation

a	scalar
\mathbf{a}	vector
A	matrix or scalar, as indicated by context
A_c	matrix corresponding to closed loop system
A_s	matrix corresponding to servo system
A_t	matrix corresponding to target system
a_0	reference value

Acronyms

LHP	left half s -plane
LTI	linear time-invariant
PD	positive definite
PSD	positive semi-definite
RHP	right half s -plane
TMRC	target model referenced controller

Mathematical Symbols

a^*	complex conjugate of a
\mathbf{a}', A'	transpose of \mathbf{a} or A
\mathbf{a}^H, A^H	complex conjugate transpose (Hermitian) of \mathbf{a} or A .
$\ \mathbf{a}\ , \ \mathbf{a}\ $	Euclidean norm ($\sqrt{\mathbf{a}^* \mathbf{a}}, \sqrt{\mathbf{a}^H \mathbf{a}}$)
$\langle \mathbf{a}, \mathbf{b} \rangle$	inner product
$\sigma(A)$	singular value of A
$Re\{a\}, \Re a$	real part of a
$Im\{a\}, \Im a$	imaginary part of a
j	$\sqrt{-1}$

Bond Graph Symbols

0	common effort junction
1	common flow junction
S_e	effort source
S_f	flow source
I	admittance causality storage (e.g., inertia, inductor)
C	impedance causality storage (e.g., spring, capacitor)
R	dissipator (e.g., damper, resistor)
TF	transformer
GY	gyrator

Miscellaneous

A	state matrix
b, B	viscous damping coefficient
B	input matrix
C	output matrix
$C(s)$	closed loop transfer function
D	feedforward matrix, determinant term
e	effort, error
E	energy
f	flow
F	force
G	force feedback gain
$G(s)$	plant transfer function
$G_{xx}(\omega), G_{xy}(\omega), G_{xFx}(\omega), G_{xFy}(\omega)$	auto- and cross-spectral densities
$H_x(\omega), H_y(\omega)$	transfer functions from x position to x and y forces
I	inertia matrix
J	jacobian matrix
k, K	stiffness
L	environmental input matrix
m, M	mass
P	power, PD matrix in energy function
r	reference
s	Laplace variable ($\sigma + j\omega$)
S	scattering matrix
$S(\omega)$	transfer function from x position to y position
t	time
T	time delay

u, U	control effort
v	velocity
x, X, y	positions
$Y(s)$	admittance
$Z(s)$	impedance
α	amplification factor
β	two-link manipulator damping coefficient
γ	coherence
ε	error
ω	imaginary part of s , joint angular velocity
σ	real part of s
τ	time constant
θ	joint angle
Θ	state vector of two-link manipulator