



Dr. Partha Sarathi Khuntia

# Intelligent Control Strategies for Aircraft and Other Dynamic Systems

Intelligent Control



**LAMBERT**  
Academic Publishing

**Dr. Partha Sarathi Khuntia**

# **Intelligent Control Strategies for Aircraft and Other Dynamic Sysems**

**Intelligent Control**



**LAP LAMBERT Academic Publishing**

## **Impressum/Imprint (nur für Deutschland/ only for Germany)**

Bibliografische Information der Deutschen Nationalbibliothek: Die Deutsche Nationalbibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet über <http://dnb.d-nb.de> abrufbar.

Alle in diesem Buch genannten Marken und Produktnamen unterliegen warenzeichen-, marken- oder patentrechtlichem Schutz bzw. sind Warenzeichen oder eingetragene Warenzeichen der jeweiligen Inhaber. Die Wiedergabe von Marken, Produktnamen, Gebrauchsnamen, Handelsnamen, Warenbezeichnungen u.s.w. in diesem Werk berechtigt auch ohne besondere Kennzeichnung nicht zu der Annahme, dass solche Namen im Sinne der Warenzeichen- und Markenschutzgesetzgebung als frei zu betrachten wären und daher von jedermann benutzt werden dürften.

Coverbild: [www.ingimage.com](http://www.ingimage.com)

Verlag: LAP LAMBERT Academic Publishing AG & Co. KG  
Dudweiler Landstr. 99, 66123 Saarbrücken, Deutschland  
Telefon +49 681 3720-310, Telefax +49 681 3720-3109  
Email: [info@lap-publishing.com](mailto:info@lap-publishing.com)

Herstellung in Deutschland:  
Schaltungsdienst Lange o.H.G., Berlin  
Books on Demand GmbH, Norderstedt  
Reha GmbH, Saarbrücken  
Amazon Distribution GmbH, Leipzig  
**ISBN: 978-3-8383-8360-6**

## **Imprint (only for USA, GB)**

Bibliographic information published by the Deutsche Nationalbibliothek: The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at <http://dnb.d-nb.de>.

Any brand names and product names mentioned in this book are subject to trademark, brand or patent protection and are trademarks or registered trademarks of their respective holders. The use of brand names, product names, common names, trade names, product descriptions etc. even without a particular marking in this works is in no way to be construed to mean that such names may be regarded as unrestricted in respect of trademark and brand protection legislation and could thus be used by anyone.

Cover image: [www.ingimage.com](http://www.ingimage.com)

Publisher: LAP LAMBERT Academic Publishing AG & Co. KG  
Dudweiler Landstr. 99, 66123 Saarbrücken, Germany  
Phone +49 681 3720-310, Fax +49 681 3720-3109  
Email: [info@lap-publishing.com](mailto:info@lap-publishing.com)

Printed in the U.S.A.  
Printed in the U.K. by (see last page)  
**ISBN: 978-3-8383-8360-6**

Copyright © 2010 by the author and LAP LAMBERT Academic Publishing AG & Co. KG  
and licensors  
All rights reserved. Saarbrücken 2010

**Dr. Partha Sarathi Khuntia**

**Intelligent Control Strategies for Aircraft and Other  
Dynamic Systems**

**DEVELOPMENT OF INTELLIGENT CONTROL  
STRATEGIES FOR AIRCRAFT AND OTHER DYNAMIC  
SYSTEM APPLICATIONS**

*By*

**DR. PARTHA SARATHI KHUNTIA**

## ***ACKNOWLEDGEMENT***

First of all I thank God Almighty for His Grace and Blessings.

I wish to express my sincere thanks and indebtedness to my guides Dr. Debjani Mitra, Associate Professor, Department of Electronics and Instrumentation, Indian School of Mines University, Dhanbad for providing me an opportunity to carry out the present research work. Her guidance and encouragement have helped me in all stages of the work and have also given me the inspiration I needed to develop as a researcher.

I wish to acknowledge the ETBR & DC Division of Hindustan Aeronautics Ltd., Bangalore for allowing me training on familiarization of aircraft stability and control required for carrying out this research work.

I am also grateful to my colleague Mr. Milind Thomas of the Department of Electronics and Communication Engineering, New Horizon College of Engineering, Bangalore-560087 for his goodwill and effort to help me during my work.

I am especially grateful to my father Mr. Niranjan Khuntia, who has been a constant source of inspiration and support and my wife Mrs. Diptirani Jena and son Krishna Kumar Khuntia who has always kept me cheerful. I thank all my family members for their love, support and sacrifice in providing me time and opportunity to work for and prepare this work.

## LIST OF FIGURES

Figure No.	Title of the Figure	Page No.
Figure 1.1	Control Surfaces of the Aircraft	6
Figure 1.2	Axes of Rotation of the Aircraft	8
Figure 1.3	Orientation of Gravity Vector $m\vec{g}$ with Body Axis System	12
Figure 1.4	Angular Orientation and Velocities of Gravity Vector $m\vec{g}$ Relative to Body Axis	13
Figure 1.5	Orientation of Relative Wind with Body Axis System	18
Figure 2.1	The Step Responses With Different Time Constants	27
Figure 2.2	The Unit Step Responses of $y_1(t)$ , $y_2(t)$ and $y_3(t)$	29
Figure 2.3	Poles and Zeros of $G_1(s)$ , $G_2(s)$ , $G_3(s)$	30
Figure 2.4	The Unit Step Responses of $y_1(t)$ , $y_2(t)$ and $y_3(t)$	33
Figure 2.5	Step Responses for $\alpha = 1.5$ and $\beta = 1$	35
Figure 2.6	Step Responses for $\alpha = 2.0$ and $\beta = 1$	35
Figure 2.7	Step Responses for $\alpha = 2.5$ and $\beta = 1$	36
Figure 2.8	Frequency Magnitude of Butterworth Filters	37
Figure 2.9	Unit Step Responses of Butterworth Filters	38
Figure 2.10	Block Diagram of Two Parameter Controller	40
Figure 2.11	Step Response for Different Values of $\alpha$ (alpha)	43
Figure 2.12	The Pitch Control System of an Aircraft	45
Figure 2.13	Step Response of Pitch Control System	46
Figure 3.1	A Schematic Diagram of a General Control System	52
Figure 3.2	Classical Feedback Control	53
Figure 3.3	Decomposition of the Plant Inputs and Outputs	53
Figure 3.4	Decomposition of Plant	54
Figure 3.5	The Closed Loop Regulator	55
Figure 3.6	Block Diagram of the Control System	56
Figure 3.7	Step Response of $z_1 w(t)$ with $K$ and $\hat{K}$	58
Figure 3.8	Step Response of $z_2 w(t)$ with $K$ and $\hat{K}$	58
Figure 3.9	Step Response of $H_{\lambda}(s)$ from 'w' to 'z <sub>1</sub> ' for Various Values of $\lambda$	59
Figure 3.10	Step Response of $H_{\lambda}(s)$ from 'w' to 'z <sub>2</sub> ' for Various Values of $\lambda$	60
Figure 3.11	Block Diagram of Pitch Control System	61
Figure 3.12	Step Response with Controllers $K$ and $\hat{K}$	64
Figure 3.13	Step Response of the Pitch Controller for Various Values of $\lambda$	65
Figure 3.14	The Bode Plot of $H_{0.5}(s)$	66
Figure 3.15	Step Response of the Original Model and Reduced Models(5 <sup>th</sup> order)	71
Figure 3.16	Step Response of the Original Model and Reduced Models(4 <sup>th</sup> Order)	71
Figure 4.1	Scalar Quadratic Function, $J(\beta, j) = \beta^2$	76
Figure 4.2	Individual Representation as a String	78
Figure 4.3	Crossover Operation	82

Figure 4.4	Flow chart of GA Optimization	84
Figure 4.5	Design of Discrete PID Controller	85
Figure 4.6	Step Response of Pitch Control System using SDGA (at Different Iterations)	87
Figure 4.7	Block Diagram of GA Optimized PID Controller for Pitch Control System	88
Figure 4.8	The Parameters of GA Based PID Controller (using MSE Objective Function)	91
Figure 4.9	The Parameters of GA Based PID Controller (using ISE Objective Function)	91
Figure 4.10	The Parameters of GA Based PID Controller (using IAE Objective Function)	92
Figure 4.11	The Parameters of GA Based PID Controller (using ITAE Objective Function)	92
Figure 4.12	Step Responses of Different Objective Functions ( $t=0.5$ second)	93
Figure 4.13	Comparison of Step Responses of SDGA and GA for Pitch Control System	94
Figure 4.14	Electric Circuit of DC Motor	95
Figure 4.15	Step Response of DC Motor using SDGA (after 10 Iterations)	96
Figure 4.16	Step Response using SDGA (after 50 Iterations, Speed control of DC Motor)	97
Figure 4.17	Step Response using GA (after 10 Generations)	97
Figure 4.18	Step Response using GA (after 50 Generations)	98
Figure 4.19	Step Response of Different Objective Functions ( $t=0.5$ second)	98
Figure 4.20	Responses of GA and SDGA for DC Motor Control	99
Figure 4.21	Initial, Destination and Obstacles Position of the Vehicle	100
Figure 4.22	Autonomous Vehicle Guidance	101
Figure 4.23	Obstacle Function $J_0(x, y)$	102
Figure 4.24	Obstacle Function Contour	103
Figure 4.25	Contour Form of Goal Function $w_2 J_g(x, y)$ , Initial and Destination Position	104
Figure 4.26	Multiobjective Function, $J(x, y)$	105
Figure 4.27	Vehicle Path While Avoiding Obstacles and Reaching the Goal	107
Figure 4.28	Vehicle Trajectory at Each Iteration ( $x$ -solid, $y$ -dash)	107
Figure 5.1	Fuzzy Model Reference Learning Controller for Aircraft Pitch Control	112
Figure 5.2	Membership Function for $e(kT)$ and $e_c(kT)$ for Fuzzy Controller	115
Figure 5.3	Membership Function of Out put $\delta(kT)$ of Fuzzy Controller	115
Figure 5.4	Shifting of Centers of MFs of Controller Output $\delta(kT)$	119
Figure 5.5	Results of Simulation (Case-1)	123
Figure 5.6	Results of Simulation (Case-2)	124,125
Figure 5.7	Results of Simulation (Case-3)	126,127
Figure 5.8	Results of Simulation (Case-4)	128,129
Figure 5.9	Control Surface of Simulation(Case-4)	130



Figure 6.1	Radial Basis Function Network Model	134
Figure 6.2	RBFNC for Aircraft Pitch Control	136
Figure 6.3	Receptive Field Unit Centers	138
Figure 6.4	Receptive Field $R_{r3}(e(k), e_c(k))$	138
Figure 6.5	Scaling and Addition of Receptive Fields	139
Figure 6.6	Response of Simulation(Case-1)	142
Figure 6.7	Response of Simulation(Case-2)	143
Figure 6.8	Response of Simulation (Case-3)	144,145
Figure 6.9	Response of Simulation (Case-4)	146
Figure 6.10	Control Surface at t=2 seconds	147
Figure 6.11	Control Surface at t=10 seconds	147
Figure 6.12	Control Surface at t=14.999 seconds	148
Figure 6.13	Control Surface at t=15 seconds	148
Figure 6.14	Control Surface at t=40 seconds at the End of Simulation	149
Figure 6.15	Control Surface Difference between t=40 seconds and t= 15 second	149
Figure 6.16	Contour Map	150
Figure 6.17	Comparative Analysis of RBFNC, FMRLC and Convex Pitch Controller	150

## LIST OF TABLES

Table No.	Title of the Table	Page No.
Table 1.1	Stability Derivatives of Longitudinal Dynamics of FOXFORT Aircraft	22
Table 2.1	Transfer Function, Overshoot and Settling Time for Different Values of $\alpha$	44
Table 2.2	Roots of the Characteristic Equation of Pitch Control System	49
Table 3.1	Roots of Characteristic Equation for Optimally Convex Pitch Control System	68
Table 4.1	Genetic Algorithm Parameters	90
Table 4.2	PID Controller Parameters for Different Objective Functions (for 50 Generations)	93
Table 4.3	Comparison of SDGA and GA based PID Controller Parameters for Pitch Control System	94
Table 4.4	Parameters of PID Controller for Different Objective Functions for DC Motor Control (for 50 Generations)	99
Table 4.5	Comparison of Step Responses of GA and SDGA for DC Motor Control	100
Table 5.1	Linguistic Variables and their Mathematical Representations	116
Table 5.2	Rule Base Matrix for Fuzzy PD Controller	117
Table 5.3	Rule Base Matrix for Inverse Fuzzy PD Controller	118
Table 6.1	Performance Index, Rise Time, Settling Time and Overshoot	151
Table 7.1	Performance of Pitch Control System with Different Controllers	158

## **CHAPTER 1**

### **INTRODUCTION**

# CONTENTS

Topic	Page No.
<b>Chapter 1: Introduction</b>	
1.1 Conventional and Intelligent Control.....	1
1.1.1 Adaptation and Learning.....	2
1.1.2 Autonomy and Intelligence.....	2
1.1.3 Structures and Hierarchies.....	3
1.2 Thesis Organization and Approach .....	5
1.3 Control Surfaces and Axes of Rotation of the Aircraft.....	6
1.3.1 Elevator.....	7
1.3.2 Aileron .....	7
1.3.3 Rudder .....	7
1.3.4 Lateral (Pitch) Axis .....	8
1.3.5 Longitudinal (Roll) Axis.....	8
1.3.6 Vertical (Yaw) Axis .....	9
1.4 Equation of Motion of a Rigid Body Aircraft .....	9
1.4.1 Rotational Motion.....	11
1.4.2 Contribution of Gravity to Equation of Motion.....	12
1.4.3 Axis Transformation.....	13
1.4.4 Linearization of Inertial and Gravitational Terms.....	14
1.4.5 Complete Liberalized Equation of Motion of the Aircraft.....	16
1.4.6 Equation of Longitudinal Motion.....	17

1.4.7 Equation of Motion in Stability Axis System.....	18
1.4.8 Short Period Approximation of the Aircraft.....	19
1.4.9 Calculation of Transfer Function for FOXTROT Aircraft (For Flight Condition-1).....	20

## **Chapter 2: Transient Response Control and Robust Stability Analysis**

2.1 Introduction.....	24
2.2 Characteristic Ratios & Generalized Time Constant .....	25
2.3 Strategy for changing the Speed of the Response.....	28
2.3.1 Generalized Time Constant Method.....	28
2.3.2 Strategy for changing the Speed of the Response (Time Scaling Method).....	30
2.4 The Characteristic Ratios with Adjustable Damping.....	33
2.5 Strategy for No Overshoot.....	36
2.6 Design of Two Parameter Controller for an Arbitrary Plant .....	40
2.7 Design of Pitch Controller for Aircraft.....	45
2.8 Kharitonov Stability Criteria .....	47
2.9 Conclusion.....	49

## **Chapter 3: Optimally Convex Controller Design**

3.1 Introduction.....	51
3.2 A General Control System.....	52
3.2.1 Classical Synthetic Open-Loop Design.....	52
3.2.2 Parameter Optimization Method.....	53
3.2.3 Algebraic Formulation of the Decomposed Plant.....	53
3.3 Design of Closed-Loop Convex Controllers.....	56

3.4 Design of Convex Controller for an Arbitrary Plant.....	56
3.5 Design of Convex Pitch Controller.....	61
3.5.1 Design of a PID Controller.....	62
3.5.2 Kharitonov's Stability Test.....	67
3.6 Model Reduction.....	68
3.6.1 A State-Space Balancing Algorithm for Model Reduction.....	68
3.7 Conclusion.....	72

## **Chapter 4: Performance Evaluation of Some Optimization Techniques**

4.1 Introduction.....	74
4.2 Steepest Descent Gradient Method .....	76
4.2.1 Convergence, Step Size and Termination.....	77
4.2.2 Direction of Steepest Descent .....	77
4.3 Characteristics of Genetic Algorithm and Genetic Operation.....	78
4.3.1 Representing the Population of Individuals.....	78
4.3.2 An Example of Coding.....	79
4.3.3 Population of Individuals.....	79
4.3.4 Selection, Reproduction and Crossover.....	80
4.3.5 Single-Point Crossover.....	82
4.3.6 Mutation.....	82
4.4 The Objective Function.....	83
4.5 SDGA Simulation of Pitch Control System.....	84
4.6 Design of GA optimized PID Controller for Pitch Control System .....	87
4.6.1 Choice of Objective Function .....	88

4.7 Comparative Analysis of SDGA and GA of Pitch Control System.....	94
4.8 Speed Control of a DC Motor.....	95
4.8.1 Problem Formulation.....	95
4.9 GA Simulation of DC Motor Speed Control.....	97
4.10 Comparative Analysis of GA and SDGA of DC Motor.....	99
4.11 Obstacle Avoidance using Multiobjective Optimization Technique.....	100
4.11.1 Path planning Strategy.....	102
4.11.2 Plan Generation and Selection.....	104
4.11.3 Algorithm for Automatic Vehicle Guidance.....	106
4.11.4 Results of Guidance Strategy.....	106
4.12 Conclusion.....	108

## **Chapter 5: Fuzzy Model Reference Learning Controller (FMRLC)**

5.1 Introduction.....	110
5.2 Fuzzy Model Reference Learning Controller (FMRLC).....	111
5.2.1 Plant.....	113
5.2.2 Reference Model.....	113
5.2.3 The Fuzzy Controller.....	114
5.2.4 Rule Base.....	116
5.2.5 Fuzzy Inverse Model .....	117
5.2.6 Knowledge-Base Modifier.....	118
5.3 Simulation of Nonlinear System.....	119
5.3.1 Euler Method.....	119
5.3.2 Runge-Kutta Method .....	120

5.4 Simulation of Pitch Control System .....	121
5.5 Simulation of Aircraft Under Various Conditions.....	122
5.6 Control Surface of FMRLC .....	129
5.7 Results and Analysis.....	130

## **Chapter 6: Radial Basis Function Neural Controller (RBFNC)**

6.1. Introduction.....	132
6.2. Radial Basis Function Neural Network (RBFNN).....	133
6.3. Problem Formulation.....	135
6.4. Design of RBFNC.....	135
6.4.1 Reference Model.....	140
6.5 Simulation of Aircraft under Various Conditions.....	141
6.6. Control Surface and Contour Map.....	146
6.7 Comparative Analysis of FMRLC and RBFNC.....	150
6.8. Conclusion.....	151

## **Chapter 7: Conclusion and Future Scope of the Work**

7.1 Contribution of this Work.....	154
7.2 Scope of Future work.....	158

## **REFERENCES.....161**

## **Publications Related to the Present Research Work.....170**



## 1.1 Conventional and Intelligent Control

The control of highly complex, nonlinear and distributed time varying systems although approached through conventional methods may give desired performances, but in the absence of a detailed accurate model, the trend is towards intelligent control. Conventional control methods have evolved as early as around 3<sup>rd</sup> century B.C. when Greek Ktesibios in Alexandria Egypt invented water clock, the first feedback device. James Watt introduced fly ball governor in 1769 to regulate the speed of the steam engine vehicles [1]. The first mathematical model and its usefulness to describe plant behavior is attributed to J. C. Maxwell in 1868. Since then state space analysis, frequency domain method, Laplace Transform and several other techniques assisting control theory came into active use followed by establishment of optimal control, robust control, stochastic control, hierarchical control, adaptive control and intelligent control methodologies.

Conventional control systems are designed and developed using mathematical models described by discrete event system models and/ or differential/difference equations. These models are usually valid under several assumptions and may not be accurate to describe many important aspects of the behavior of dynamic systems. Increasing the complexity of the mathematical model adversely affects the performance of the control algorithms. Fixed robust feedback controllers can only approximate the plant behavior in the neighborhood of an operating point. Wider operating range with higher degree of autonomy is possible with adaptive controllers. With the requirement of a still greater degree of autonomy the focus shifts naturally towards intelligent controllers under the validity of situations like:

There are problems when the plant can not be described by mathematical frameworks.

1. There is a need to sense the environment and to deal with significant uncertainties, unmodeled and unanticipated changes in the plant or surroundings.
2. Use of strategic decision making with high degree of autonomy and intelligence
3. Need to generate control action for a complex system over an extended period of time without external intervention and in the face of drastic changes of operating conditions.
4. The controller has to cope with large amount of data, fault diagnosis, alarm systems and control reconfiguration.