System Theory:
Modeling, Analysis and Control

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System Theory: Modeling, Analysis and Control

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Preface

The word Symposium originates from the Greek word $\sigma\upsilon\mu\pi o\sigma\iota o\nu$. The literal meaning of the word is "to drink together." In ancient Greece the word was used to describe a gathering where not only drinking and eating took place but intellectual discussions as well. It is precisely for this reason that the writings of a number of notable philosophers, including Plato, bare the title: $\sigma\upsilon\mu\pi o\sigma\iota\alpha$. There is a perfect characterization of the Symposium Advances in System Theory, an event organized to celebrate Sanjoy K. Mitter's 65^{th} birthday. The timing of the Symposium comes at the end of a fifty year period during which the field of Systems and Control Theory has experienced dramatic growth. The contents of this book on the one hand reflect on past research accomplishments and on the other provide insight on future research directions.

The book *System Theory: Modeling, Analysis and Control* is a collection of papers contributed to this Symposium. There are thirty three scientific papers included in the book that fall in the following technical areas: Distributed Parameter Systems, Stochastic Control, Filtering and Estimation, Optimization and Optimal Control, Image Processing and Vision, Hierarchical Systems and Hybrid Control, Nonlinear Systems, and Linear Systems. These papers are very representative of past and current research activity in systems and control. They include three survey papers on Optimization, Nonlinear Filtering and Nonlinear Systems. Recent advances are reported on the behavioral approach to systems, the relationship between differential games and robust control, estimation of diffusion processes, Markov processes, optimal control, hybrid control, spectral estimation, noncovex quadratic programming, robust control, control algorithms and quantized linear systems. Innovative explorations are described on quantum systems from a control theory perspective, option valuation and hedging, three-dimensional medical visualization, computational structure biology, image processing, hierarchical approaches to complex systems, flow control, scheduling, and force feedback in fluid mechanics. The unifying thread that ties all these papers together is the use of mathematics for developing a keener understanding of physical phenomena and man made systems. These new tools have allowed researchers to gain more insight into the dynamic operation of these systems and to suggest methods for automatic control. Ultimately, this knowledge leads to increased productivity, promotes economic development and has a positive impact on our quality of life.

First and foremost, I would like to thank Sanjoy K. Mitter for his guidance and support. This book is dedicated to him! I am particularly grateful to all contributing authors for their timely response to our call. Without their hard work this event would not have been possible. Planning for the Symposium has been very rewarding as it gave me the opportunity to revive old friendships and make new ones. The experience also gave me a renewed appreciation of the intricacies of electronic publishing. Even though we have come far from the days of the typewriter the advances are not without cost (i.e., "No Free Lunch Theorem.")

I would like to express my sincere thanks to the Army Research Office and Dr. Linda Bushnell in particular, and to the National Science Foundation and Dr. Kishan Baheti, for providing financial support for the Symposium. The views, opinions, and/or findings contained in these papers are those of the authors and should not be construed as an official Department of the Army (or NSF) position, policy, or decision, unless so designated by other documentation. Support has also been provided by the Electrical and Computer Engineering Department at the University of Massachusetts Amherst, Professor Seshu Desu Department Head, and the Massachusetts Institute of Technology.

Special thanks go to Irvin Schick, my co-editor, for his assistance in all aspects of this event. Technical assistance with Latex was provided by Pam Williams, Vishal Misra and Steve Morin. Pat Zuzgo has assisted with finances and registration and Kathleen O'Sullivan with publicity. Their help is greatly appreciated.

THEODORE E. DJAFERIS

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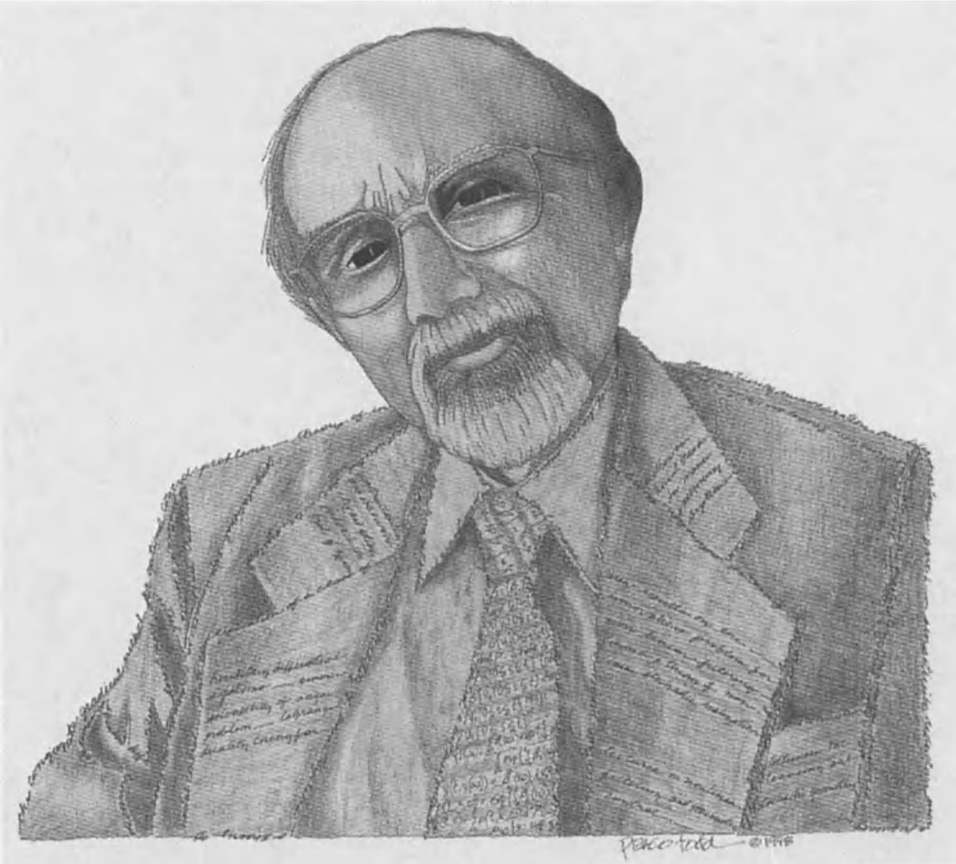
that we dedicate this volume to a
magnificent friend, scholar, teacher and mentor



Sanjoy K. Mitter

1 SANJOY K. MITTER: A SCHOLAR, A GENTLEMAN, AND A FRIEND

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Sanjoy Kumar Mitter was born on 9 December 1933 in Calcutta, India. His father, Subodh Chunder Mitter—son of Sir B.C. Mitter, the first Indian member of the Privy Council of Britain—was an electrical engineer educated at University College, London, and the founder of Mitter Industries. His mother, Protiva Mitter, was the daughter of Sir C.C. Ghose, justice of the Calcutta High Court.

Sanjoy received his early education at Ballygunj Government High School and St. Paul's School. He then attended Presidency College and St. Xavier's College, Calcutta, from which he graduated with Honours in Mathematics. His, as they say, was a good year: his classmates included Sukhamoy Chakravarty, a distinguished economist and member of the Indian Planning Commission; Amartya Sen, now Master of Trinity College, Cambridge, and the winner of the 1998 Nobel Prize in Economics; Partha Sarathi Gupta, a distinguished historian; and Andre Beteille, a well-known anthropologist.

After receiving a B.S. degree in Mathematics from Calcutta University in 1954, Sanjoy obtained a B.Sc. in Engineering, ACGI, in 1957 and a Ph.D. in

*Affectionately Compiled, from Sources both Written and Oral

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Electrical Engineering in 1965, both from Imperial College of Science and Technology (London). His doctoral thesis was entitled "Function Space Methods in Optimal Control with Applications to Power Systems."

From 1957 to 1961, he was a Development Engineer with Brown Boveri and Co., Ltd., in Baden, Switzerland. After spending a year at the Battelle Memorial Institute in Geneva, he joined Imperial College, where he served as Fellow in the Central Electricity Research Board from 1962 to 1965.

Between 1965 and 1967, he was Assistant Professor at the Case Institute of Technology, and between 1967 and 1969, Associate Professor at Case Western Reserve University. He was also a member of the Systems Research Center of Case Western Reserve University from 1965 to 1969.

In 1969, he joined the Massachusetts Institute of Technology, where he served first as Visiting Assistant Professor of Electrical Engineering (1969–1970), then as Associate Professor (1970–1973). In 1973, he became Professor of Electrical Engineering at M.I.T., a position he continues to hold today. He has also served as Director (1981–1986), then co-Director (1986–1999) of the Laboratory for Information and Decision Systems, as well as founding co-Director (from 1986 onward) of the Center for Intelligent Control Systems, a research consortium of Brown University, Harvard University, and M.I.T.

Sanjoy has held visiting appointments at the Science Research Council, Imperial College of Science and Technology (London, England), Technische Universität (Berlin, Germany), Rijksuniversiteit Groningen (Groningen, Holland), Scuola Normale Superiore (Pisa, Italy), University of Florence (Florence, Italy), Washington University (St. Louis, Missouri), University of Maryland (Baltimore, Maryland), Institut National de Recherche en Informatique et en Automatique (Versailles, France), and Tata Institute of Fundamental Research (Bombay, India).

He has served on several advisory committees and editorial boards for the Institute of Electrical and Electronics Engineers (IEEE), the Society for Industrial and Applied Mathematics (SIAM), the Americal Mathematical Society (AMS), the National Science Foundation (NSF), and and the Army Research Office (ARO). He is currently associate editor of a number of professional journals including *Journal of Applied Mathematics and Optimization*, *Random and Computational Dynamics*, and *Ulam Quarterly*. He was elected Fellow of the Institute of Electrical and Electronics Engineers in 1979, and Member of the National Academy of Engineering in 1988. Most recently, he has received the 2000 IEEE Control Systems Award "for contributions to optimization, optimal control, and nonlinear filtering, and for interdisciplinary research that has expanded the boundaries of control theory."

Sanjoy and his wife Adriana Mitter (formerly Fachini, of Milan, Italy) maintain homes in Cambridge, Massachusetts and Florence; their whereabouts at any given time, much like the precise location of subatomic particles, can only be stated probabilistically.

1.1 PRINCIPAL CONTRIBUTIONS

Sanjoy has contributed widely and influentially to many important areas in systems and control science and engineering, notably optimization, optimal control, linear systems theory, non-linear filtering and, most recently, image analysis, vision, and learning.

Sanjoy's earliest work includes "A Theory of Modal Control" (with J.D. Simon, 1968), in which he provided a proof of the pole assignment theorem that forms the cornerstone of the pole-placement method for synthesizing linear feedback control. (This subject was independently researched by W.M. Wonham.) He also investigated computational methods for optimal control and was the first to show, in "Successive Approximation Methods for the Solution of Optimal Control Problems" (1966), how algorithms such as Newton's method and the conjugate gradient technique could be generalized to yield effective methods for trajectory optimization, generation of optimal open loop controls, and neighboring-optimal feedback control laws. These algorithms have been widely used in aerospace problems and have influenced much further work.

In "A Descent Numerical Method for Optimization Problems with Non-Differentiable Cost Functionals" (with Dimitri P. Bertsekas, 1973) Sanjoy presented a convergent algorithm for optimization using ε-subgradients; all subsequent work on non-differentiable optimization has used this work as a starting point. "Recursive Stochastic Algorithms for Global Optimization in $\mathbf{R}^d$" (with Saul B. Gelfand, 1991) presented for the first time a convergence analysis for algorithms of the simulated annealing type for global optimization. This research has implications in diverse areas such as maximum likelihood identification, learning in neural networks, and signal processing applications such as MAP estimation of noisy images.

Sanjoy has been a pioneer in the study of infinite-dimensional systems, extending H^∞ theory to delay systems in "H^∞ Sensitivity Minimization for Delay Systems" (with David S. Flamm, 1987). His paper "Controllability, Observability and Optimal Feedback Control for Affine Hereditary Differential Systems" (with Michel C. Delfour, 1972) was the first to develop a complete theory that permitted the solution of the quadratic cost problem for linear hereditary systems over both finite and infinite time intervals. The recent *Representation and Control of Infinite Dimensional Systems* (with Alain Bensoussan, Giuseppe Da Prato, and Michel C. Delfour, 1992–1993) presents for the first time a comprehensive theory of linear feedback control for a large class of distributed-parameter systems and systems with memory, including the theory of exact controllability and the theory of boundary control. This book provides the rigorous basis for structuring control systems for large space structures and aero-elastic problems.

Some of Sanjoy's most significant contributions have been in the area of stochastic systems, and in particular in non-linear filtering and its applications to stochastic control. After the initial work on non-linear filtering and stochastic control by H.J. Kushner, R.L. Stratonovich, W.M. Wonham, M. Zakai, T. Kailath and others in the 1960s, a number of important issues remained open—such as the innovations problem, the duality between filtering and control, and the construction of finite-dimensional filters. In a series of papers, Sanjoy and his collaborators proceeded to give definitive answers to these questions.

In "New Results on the Innovation Problem for Non-Linear Filtering" (with Deborah F. Allinger, 1981), Sanjoy solved the long-standing open problem on the causal equivalence between the observation and innovation σ-algebras. First conjectured by T. Kailath and P.A. Frost in the late 1960s, the extension of this property to the non-Gaussian case had eluded numerous well-known probabilists during the decade that followed. Proving it rigorously for the case of independent signal and noise, Sanjoy's result has helped generalize the Bode-Shannon view of Wiener filtering to the non-linear case. More recently, in his contribution to the Thomas Kailath *Festschrift*, "LQG Control with Communication Constraints" (with Vivek S. Borkar, 1997) he showed that when the alphabet of codewords transmitted to the controller is finite and subject to delays and distortion, encoding the innovation rather than the observation process leads to an optimal control signal that is linear in the state estimate.

Bringing in ideas from quantum physics—Feynman's functional integral point of view and group representation theory—Sanjoy breathed new life into the stalled field of non-linear filtering. In his paper "On the Analogy between Mathematical Problems of Non-Linear Filtering and Quantum Physics" (1979), he investigated the close relationship between non-linear filtering and statistical and quantum physics, with a view towards obtaining finite-dimensional solutions using algebraic and path-integral methods. In particular he suggested studying the Lie algebra of operators associated with the Zakai equation, and investigating its relation to the question of existence of finite-dimensional filters. (Some of the results related to finite-dimensional filters were independently obtained by R.W. Brockett.) This work inspired a great deal of research in non-linear filtering—e.g. the work of J.S. Baras, S.I. Marcus, S. Yau, W.S. Wong, M. Hazewinkel, and others—and pinpointed in a precise way the complexity of obtaining finite-dimensional filters in many non-linear situations (e.g. "Finite Dimensional Nonlinear Estimation for a Class of Continuous and Discrete Time Systems," with S.I. Marcus and D. Ocone, 1980.) This research has had a significant influence in the subsequent work of system theorists and even physicists.

Sanjoy's "Optimal Control and Pathwise Nonlinear Filtering for Nondegenerate Diffusions" (with Wendell H. Fleming, 1982) solved the problem of the duality between filtering and stochastic control for the general non-linear case. By showing that the filtering equation may be transformed into the dynamic programming equation for stochastic control, this result makes precise and generalizes in a far-reaching way the suggested duality between linear filtering and LQ control. In "Robust Recursive Estimation in the Presence of Heavy-Tailed Observation Noise" (with Irvin C. Schick, 1994), Sanjoy investigated robust Kalman filtering in a rigorous way for the first time, developing a methodology for extending the Kalman filter to cases where the noise is non-Gaussian.