SYSTEMS & CONTROL ENCYCLOPEDIA

Theory, Technology, Applications

Editor-in-Chief

Madan G Singh

UMIST, MANCHESTER, UK

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University of Manchester
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FOREWORD

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University of Pennsylvania, USA

Whenever a new field of scholarly enquiry develops, there are a number of quickly generated ideas that spread fast, and people are usually so preoccupied in the enthusiasm of the new lines of research that they fail to codify and document all the contributions. Researchers active in the field know by established information networks the oral traditions and the sometimes obscure publications in their own spheres of interest.

Systems analysis and control theory are presently developing so rapidly and across so many fields of specialization that new people coming into the subject will have a difficult time tracking down many significant contributions. The present Encyclopedia fills a void and will be of great use to the pioneer practitioners as well as to the new entrants.

For the most part, I know or can readily find papers that are useful to my lines of research if they deal with design or control of economic systems. But I will be hard put to find many relevant papers that tackle similar problems in the methodology of systems analysis or control theory, engineering, biology, health systems, environmental systems, weather and climate, medicine, manufacturing, agriculture, transportation, legal studies, data management and many other fields. In some cases, these subject areas may have findings that are directly relevant for the modelling of economic systems, my own area of investigation. In other instances, they will suggest lines of research that have worked well in other fields and, by analogy, have potential for making contributions in economics too. Having the Encyclopedia at hand will be of enormous benefit to me. This is an introspective view, but what I find as an economist will be duplicated many times in other fields. It is the multidisciplinary aspect of the systems and control analysis together with its relative youth and fast expansion that makes it a perfect fit for encyclopedic documentation.

The joint meetings of researchers from diverse fields, the systematic layout of the articles, the sifting of materials, the definitions, the cross-referencing, and, of paramount importance, the choice of contributors of the highest caliber all serve to make this venture an undertaking of great importance for the professional community of model builders and operators. The number of articles and subjects covered is veritably stupendous and could be managed only by the orchestration of people who see the field as a whole. Given the rate of expansion of the subject of systems and control, this Encyclopedia will inevitably become outdated, but it is important to initiate the effort and the project organizers are to be congratulated for their success and to be rendered professional thanks. Fortunately, they are well aware of the nature of rapid development; therefore they have designed the work so that it is not static but can grow with the expected introduction of new developments in the field. Thus the publication of regular supplementary volumes, already in preparation, will ensure that the work keeps up to date.

PREFACE

John F Coales CBE FRS

Emeritus Professor of Engineering
University of Cambridge, UK

The *Systems and Control Encyclopedia* was conceived in discussions between Pergamon Press Ltd. and a number of leading systems and control engineers. The aim of the Encyclopedia was to provide a comprehensive reference work in which anyone, whether expert or lay, could quickly find a succinct and accurate statement on any particular aspect of the design and control of physical systems (as opposed to metaphysical), be they simple or complex, mechanistic or biological, industrial, economic or social. With this end in view an Editorial Advisory Board was set up and Professor M. G. Singh was appointed Editor-in-Chief. Since it was intended that all relevant material should be included, whether theoretical or practical, the material was divided into 25 separate subject areas for each of which a Subject Editor, well-known in that particular field, was appointed. These Subject Editors were responsible for commissioning articles from suitable authors, which would give appropriate coverage of that field of activity. The Editor-in-Chief was responsible for ensuring that there was no area of significance not covered by one or other of the Subject Editors nor any avoidable significant overlap between the articles submitted.

Thanks to the enthusiasm and energy of all concerned, and particularly of the Editor-in-Chief and the Subject Editors, this comprehensive account of all aspects of systems and control is now available. I feel confident that for many years to come it will be the source to which those who seek information on any aspect of systems, large or small, or of control, whether theoretical or applied, will turn. Eight volumes containing some five million words from the pens (or word processors) of several hundred well-respected scholars is not to be lightly ignored and I believe that as systems analysis and control aspects permeate ever widening fields of human endeavor, so this Encyclopedia will be used by an ever increasing circle of scientists, engineers and teachers. They, I am sure, will then be grateful to all those who have given of their time and energy to bring this work to a successful conclusion and I wish to pay special tribute to the Editor-in-Chief and Subject Editors, without whose enthusiastic efforts it could not possibly have been completed.

INTRODUCTION

Madan G Singh

Professor of Control Engineering
University of Manchester Institute of Science and Technology, UK

Systems and control constitutes a metadiscipline which has applications to virtually all areas of human activity. Although control systems can be traced back to Ancient China, the various strands of systems thinking only began to come together during and after the Second World War. Since that time, the nature and scope of the discipline have been clarified and an extensive body of knowledge has been acquired. It has also assumed institutional and professional characteristics.

This Encyclopedia is the first comprehensive work that covers the entire field of systems and control in a unified manner. The subject matter ranges from basic theory through technology to the various application domains. The Encyclopedia also covers the socio-economic and humanistic aspects of the field including its history.

General encyclopedias have both a reference and an educational function. They have also at times influenced intellectual history. In addition to serving reference and educational needs, a specialized encyclopedia in a new and rapidly evolving field such as systems and control is expected to contribute to its development and acceptance.

1. Systems and Control

Systems and control, as it is understood today, is still relatively new as compared to other metadisciplines like mathematics and physics. Furthermore, systems and control is not yet widely understood by scientists, engineers and decision makers, and even workers in the field may not have a full grasp of its scope, extent and history. A basic discussion of systems and control, therefore, is appropriate in order to adequately introduce the Encyclopedia.

1.1 Nature, Scope and Broad Organization of the Encyclopedia

Systems and Control is a multidisciplinary field which extends in a continuous spectrum from scientific fundamentals through technology to various applications. In the broadest sense, a system can be regarded as a well-defined group of related elements organized to satisfy some purpose. The satisfaction of the purpose brings us to the control aspects. Traditionally, the field of systems and control has covered the spectrum ranging from the "soft" side (relating to systems descriptions and general systems theory at the one extreme) and then going through systems analysis and operations research aspects (the art of analyzing methods of doing things and designing and implementing new and better methods) to the "hard" side of control engineering (controlling or regulating processes, be they physical, biological, environmental or social). This wide range of knowledge impinges upon virtually all areas of human activity. However, because of this very breadth of coverage of the field, work on systems aspects of areas like engineering (chemical, electrical, mechanical, etc.), biology, economics, management and others, tends to appear in specialist journals and books in these diverse fields. One result is that the unifying thread which the systems concepts provide is often lost. The main motivations of the editors, authors and the publisher of the *Systems and Control Encyclopedia* in bringing together this comprehensive eight-volume work was to provide a coherent source of up-to-date knowledge in a convenient and easily accessible form to educators, decision makers, scientists and the informed public. The present Encyclopedia brings together in one set of volumes a concise summary of virtually all aspects of systems and control as it is practised and viewed in different parts of the world.

Although every effort has been made to ensure that this Encyclopedia proves to be "user friendly" and a guide has been provided such that the user can get the most out of the Encyclopedia, the original organization of this work was done on the basis of subjects. The first cut split up the field of systems and control into *Theory*, *Technology* and *Applications*.

The *Theory* was itself split into a number of major themes in order to reflect the principal aspects of systems and control. The themes are as follows.

(*a*) *Modelling and Simulation*
This broad area was further split up into:

Physical Systems Modelling
Identification
Estimation Theory
Signal Processing
Simulation Techniques
Model Simplification

(*b*) *Systems and Control Theory*
This was split up into the areas of:

Fuzzy Systems
Pattern Recognition

General Systems Theory
Stability Theory
Realization Theory for Linear and Nonlinear Systems
Classical Control
Computer-Aided Design of Control Systems
Multivariable Control
Distributed Parameter Systems
Discrete Systems
Self-Tuning Regulators and Adaptive Control

(*c*) *Optimization and Operations Research*
This was further decomposed into:

Static Optimization
Dynamic Optimization
Optimal Control
Game Theory
Stochastic Systems
Robustness and Sensitivity

(*d*) *Complex Systems Theory*
This was further subdivided into:

Hierarchical Optimization and Control
Decentralized Control
Model Simplification for Complex Systems
Singular Perturbations
Stability of Interconnected Systems
Team Theory

There is obviously a fair amount of interaction and overlap between the four major theoretical themes outlined above and this is fully reflected within the Encyclopedia.

On the *Technology* side, the major technologies which were specifically examined were those of measurement and control as they applied to various industries. Thus the major themes here were:

Technology of Actuators
Special Actuators required in Communications, Power Generation, Nuclear Industry, etc.
Measurements in the Control Area
Intelligent Instrumentation
Measurements in the Biological Area
Environmental Measurements
Measurements in Chemistry
Database Management
Distributed Control

In all the above areas, the changes that have been taking place in computers and microelectronic technology were fully reflected.

In the way of *Applications*, the first cut was to examine domains where human beings enter into the system or control process and where they do not. Thus the application areas were split up into the following themes.

(*a*) *Technological Applications*
Here, the human being does not usually enter into the closed-loop and the major areas were:

Process Control in Chemical Industries (Paper, Cement, Sugar, etc.)
Control of Power Generation and Distribution
Control in Aeronautics and Space
Robotics

(*b*) *Semitechnological Applications*
Here, the human being interacts with the system and the major areas considered were:

Road Traffic Control
Air Traffic Control
Other Transportation Systems
Manufacturing Systems
Building Systems
Utility Systems (Gas, Electricity, Water)
Communication Systems
Management Systems
Health Care Systems
Social Effects of Automation

(*c*) *Nontechnological Applications*
Here, the main areas considered were:

Modelling and Control of Biological Systems
Biomedical Engineering
Environmental Systems
Agricultural Systems

The Systematic Outline of the Encyclopedia in Volume 8 provides the above breakdown in greater detail (article by article).

1.2 Evolution

The emergence of systems and control as a coherent discipline is the result of several converging developments that have occurred over a number of years. The most significant amongst these developments have been:

(a) the broad intellectual trends in mathematics, physics, electrical sciences and mechanical sciences over the last few centuries;

(b) scientific and technical innovations;

(c) organizational developments in industry, government and the universities.

This section very briefly traces the evolution of systems and control with emphasis on the substance of these developments and their contribution to the nature and scope of the discipline.

The intellectual advances providing the background for the development of systems and control were made in mathematics over a period of about three centuries, particularly in the area of description and analysis of dynamic phenomena.

Another strand comes from the development of control systems for the machines and engines which powered the industrial revolution and which were invented or designed without a clear understanding of the underlying theory. For example, the flyball governor of James Watt was only analyzed much later and a theoretical justification was eventually provided by

James Clerk Maxwell. In the nineteenth century and the early part of the twentieth century, the need to control electrical current, voltage and arcs (for lighting) led to significant advances in the development of electrical control systems.

The invention of valves and their use in radio (amplifier design) led to significant advances in the area of control sciences with the pioneering work of Bode, Black, and others, on the analysis and design of single-input/single-output systems using feedback control.

The Second World War saw the bringing together of the various strands of systems and control in order to tackle a series of specific problems and needs. The disciplines of *Operational Research*, *Systems Analysis* and *Control Engineering* emerged during this period as the warring nations sought to apply the scientific method to problems of logistics, location and control of anti-aircraft guns, search procedures for submarines, etc., by bringing together interdisciplinary teams of scientists.

The post-war period saw significant technological advances (e.g., the invention of the transistor, integrated circuits, large-scale integration, microprocessors, etc.) and also significant theoretical advances. These trends came together in the 1960s and early 1970s as the USA launched their Space Program, and immense resources became available to study the problems of control, estimation, measurement, actuation, etc., in order to put a man on the moon. The advances in aerospace technology in this period were underpinned by theoretical advances in the optimization of multivariable dynamical systems, estimation, filtering, smoothing, observation, etc., through the pioneering work of Bellman, Kalman, Luenberger, Rosenbrock, Pontryagin, and others.

While these developments were taking place in the area of aeronautics and space, control and systems concepts were continuing to pervade many other areas of human activity. Significant advances were being made across the whole range of systems activities from general systems theory to applications in biology, medicine, societal systems, process control, manufacturing systems, etc.

The 1970s and early 1980s saw further advances which were fuelled to a significant extent by the continuous process of subminiaturization of electronic circuitry which led eventually to the development of cheap and powerful microprocessors. The near-exponential decrease in the cost of computing power in the last three decades has made a very significant impact on systems and control, both at the level of applications in diverse areas where cheap computing power made systems and control feasible and at the level of development of the underlying theory.

The major recent theoretical advances which have been motivated by the microelectronics revolution have been in the area of analysis and synthesis of complex systems. Here the *need* (to analyze, design and control improved manufacturing systems, chemical and other processes, societal systems, aircraft, missiles, spacecraft, transportation systems, utilities systems, etc.) has combined with the *technological possibilities* opened up by the cheapness of computing power (through advances in parallel and distributed computing, robotics, etc.) and this in turn has led to the development of *new tools and concepts* for analyzing complexity in static and dynamical systems.

The major new tools which have been developed are concerned with the decomposition of complex problems into simpler ones which may be coordinated in different ways. Significant advances were made in the fields of hierarchical and decentralized control, singular perturbation analysis and decomposition theory in order to tackle the complexity of systems like manufacturing plants, communication networks, road, rail, water and air transportation, utility networks, management systems, etc.

While advances were being made in getting a better understanding of the design process for complex systems, progress was also being made at the level of the basic regulator (through self-tuning and adaptive control) as well as for multivariable control where the implementation of digital control using microprocessors threw up a number of important issues of robustness and sensitivity.

The most important recent trend which is likely to have a continuing impact in the future is the bringing together of the advances in computer science, changes in technology and the advances in the theory of complex systems which are in the process of revolutionizing many new areas of application of systems and control. In particular, recent advances in artificial intelligence (especially in knowledge based and other expert systems) and in computer architectures is beginning to have a profound effect not only on the design process in the control area but more broadly in the applications of systems and control to manufacturing, management, command, communication and control systems, biology and medicine, etc.

2. *Institutional and Professional Aspects*

Soon after the Second World War, as the discipline of systems and control began to take up a coherent form, a number of professional societies and organizations emerged to allow for the dissemination of knowledge through the organization of conferences. These professional societies also provided a forum for the exchange of ideas and opinions by different professionals, particularly for teaching curriculum development.

One of the societies attempted to cover virtually the whole of the systems and control area (the International Federation of Automatic Control) whereas others covered more specialized aspects (e.g., International Federation of Systems Research, International Federation of Operations Research Societies, International Federation of Information Processing, IMACS, etc.). In the past few years, there has been increasing cooperation between these different societies as technological changes have

increased or decreased areas of overlap amongst the societies.

3. Acknowledgments

This Encyclopedia is the result of the farsighted vision of Mr Robert Maxwell who was willing to furnish the substantial financial resources necessary to bring together the contribution of about 1500 leading experts in the various areas which constitute systems and control from around the world. In a very real sense, people like Mr Maxwell are playing today the role that the Medicis played during the Renaissance in allowing scientific and artistic activity to come together outside the strict commercial criteria which govern the modern world, and I am most grateful to him for having provided the resources which have enabled this enterprise to be conceived, developed and brought to fruition. I am sure that I speak here not only for myself but for a substantial section of the systems and control community which will benefit from his generosity and vision.

In putting together the Encyclopedia I was greatly helped by the Editorial Advisory Board under the chairmanship of my former teacher, Professor John F. Coales FRS, who contributed to the division of the subject into 25 subject areas and who advised me on the choice of appropriate Subject Editors for the various areas. In this respect, I received useful advice not only from my distinguished colleagues, who were the members of the Editorial Advisory Board (J. F. Coales, A. Bensoussan, P. Eykhoff, C. Holling, L. Klein, G. Klir, M. Mansour, M. Thoma and T. Vámos), but also from the members of the Honorary Editorial Advisory Board who are listed at the beginning of this volume. I am most grateful to all these colleagues for so generously giving me their time, expertise and experience without which this work would not have been of the quality that we have managed to achieve.

Of course, my most significant debt of gratitude must go to the Subject Editors whose dedication and expertise made this work at all possible.

I am deeply indebted to the editorial staff at Pergamon Press and Pergamon Books Ltd., and in particular Mr. Alan Steel, who as the Director of Publishing of Pergamon Press was responsible for the conception of this project and who, as the Joint Managing Director of Pergamon Books Ltd., finally brought it to fruition. I have also benefitted from the dedicated contributions of Mr Michael Mabe and the rest of the editorial and production team, without whose efficient and painstaking help this Encyclopedia would never have been published.

I have been very fortunate in having had not only the opportunity of working with so many gifted colleagues from around the world in bringing this major enterprise to completion, but also the competent and friendly help of colleagues here at UMIST who contributed immeasurably. I would like to thank in particular Mrs Pamela Glass who has been the Editorial Assistant responsible for the Encyclopedia in my office in Manchester and who has put in long hours over the years to ensure that the liaison between my office and the Subject Editors and others on the one hand and the publisher on the other remained efficient and free of friction. I would also like to thank my secretary, Mrs E. Tongue, who has helped in this liaison.

Finally, I would like to acknowledge the contribution of my wife, Dr Anne Marie Singh, and the children who have uncomplainingly accepted that I devote such a large part of my time and energy to bringing this work to fruition.

4. The Future

This work has of course been in planning for many years. In order to ensure that it is as up-to-date as possible, authors have made every effort to update their bibliographies. We are also in the process of producing supplementary volumes which will provide updated material in the light of changes that are taking place within the subject.

GUIDE TO USE OF THE ENCYCLOPEDIA

This Encyclopedia is a comprehensive reference work covering all aspects of systems and control. Information is presented in a series of alphabetically arranged articles which deal concisely with individual topics in a self-contained manner. At the same time, each article is part of the larger, systematic, work. This Guide outlines the main features and organization of the Encyclopedia, and is intended to help the reader locate the maximum amount of information on a given topic.

Accessibility of material is of vital importance in a reference work of this kind and article titles have therefore been selected, not only on the basis of article content, but also with the most probable needs of the reader in mind. In general, article titles have been formulated so that the key concept precedes any qualifying or subsidiary phrase. In addition, the following conventions have been largely adopted: "aspects" or "methods" follow "systems and control" concepts, for example

Linear Systems: Control Theory
Linear Systems: General Aspects
Linear Systems: Robustness
Linear Systems: Stability
Realization Theory: Hankel Matrix Approach
Unconstrained Optimization: Conjugate Gradient Methods

and "applications" precede "systems and control" concepts

Food Industry: Process Control
Ship Positioning: Adaptive Control

In cases where the main concept is modified by a single adjectival word or short phrase, the inverted form of the title has been used.

Aggregation, Chained
Air Conditioning, Variable Air Volume

In longer titles where such an inversion would result in awkward or unwieldy phrasing, "inverted" titles have been avoided in favor of more natural-sounding titles.

In the titles of articles dealing with measurements, applications of measurement or techniques used in measurement, the measurement aspect was regarded as the key concept when the technique or application applied to only one field of measurement, for example

Biological Measurement: Blood Mechanical Properties
Biological Measurement: Blood Gas Analysis

For other articles dealing with measurements, the technique or application was regarded as the key concept when it applied to *more* than one field of measurement, for example

Nuclear Magnetic Resonance Imaging in Biology

In some cases this approach has led to key concepts being "buried" in the title. Therefore, where a particular topic cannot be found by an initial search through the Encyclopedia, the reader should consult either the Systematic Outline of the Encyclopedia or the Subject Index (both of these are described in more detail below).

Articles are linked by an extensive and comprehensive cross-referencing system. Cross-references to other articles in the Encyclopedia are of two types: in-text and end-of-text. Those in the body of the text are designed to refer the reader to articles that present in greater detail material on the specific topic under discussion. They generally take one of the following forms:

> ... positive systems and Lyapunov stability are further discussed in *Adaptive Systems: Hyperstability and Positivity*.

> We shall now extract such a basic recursion (see *Adaptive Controllers: Convergence Analysis*)

The cross-references listed at the end of an article were chosen by the relevant Subject Editors to identify broad background reading, and to direct the reader to articles that cover different aspects of the same topic. These cross-references can lead the reader to articles that are not obviously related to the article in question. For example, the article *Adaptive Controllers: Supervision Level* has the following end-of-text cross-references:

> *See also:* Parameter-Adaptive Controllers: Applications; Sampled-Data Systems: History; Self-Tuning Controller Implementation

An important feature of the Encyclopedia is the group of short definition articles interspersed alphabetically throughout the Encyclopedia. They provide a concise explanation of the terms used in all branches of systems and control, some aspects of which are dealt with at greater length in full articles elsewhere in the Encyclopedia. Where appropriate, definition articles have cross-references and bibliographies.

The pattern set by the definition articles is followed in the organization of individual articles. Each article begins with a brief introductory statement which aims to present a concise and self-contained definition of the subject covered in the article. The main body of the article is divided into sections and subsections, provided with headings as an aid to selective reading. The main body of the article is then followed by the cross-references and the bibliography.

The nature of an encyclopedia demands a higher degree of uniformity in terminology and notation than many other scientific works. The widespread use of the International System of Units in most scientific disciplines has determined that such units be used in this Encyclopedia. It has been recognized, however, that in some fields English units are more generally used. Where this is the case, English units are given with their SI

equivalent quantity and unit following in parentheses. Where possible, the symbols defined in *Quantities, Symbols and Units*, published by the Royal Society of London, have been used. Where this has not been possible, notation has been standardized throughout a particular field. In all cases, symbols are defined at their first appearance in the text of an article.

Most articles in the Encyclopedia include a bibliography giving sources of further information. Each bibliography consists of general items for further reading and/or references which cover specific aspects of text. Where appropriate, authors are cited in the text using a name/date system as follows:

> ... as was recently reported (Smith 1984).
> Jones (1985) reports ...

All authors cited in the Encyclopedia are listed in the Author Citation Index in Volume 8. This gives details of the text page on which the author is cited and also the page on which full bibliographic details can be found. It can therefore be used to look up the name of an author known to have published material relevant to the subject of interest.

The contributor's name appears in full at the end of an article. All contributors can be found in the alphabetical List of Contributors in Volume 8, along with the organization with which they are affiliated and the titles of the articles of which they are authors or co-authors.

A device for identifying articles on a specific subject and a possible starting point for general study is the Systematic Outline of the Encyclopedia, which can be found in Volume 8. This reflects the basic structure and hierarchy used in commissioning articles for the Encyclopedia. The outline provides a schematic overview of the articles contained in the Encyclopedia and lists all articles under general subject headings.

The most important information source for locating a particular topic in the Encyclopedia is the multilevel Subject Index. This is a comprehensive and detailed index in which approximately 20000 entries are listed. It has been the aim of the publisher to make this index as complete and fully self-consistent as possible. A detailed thesaurus was consulted throughout compilation of the index to ensure consistency of terms and to obtain related and higher-level terms for greater completeness.

Lastly, article bibliographies have been supplemented by the inclusion of a general section on Information Sources in Systems and Control in Volume 8 which also provides a List of Acronyms used in the field of systems and control.

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