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# Encyclopedia of Systems and Control

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John Baillieul • Tariq Samad  
Editors

# Encyclopedia of Systems and Control

Second Edition

With 729 Figures and 37 Tables

 Springer

*Editors*

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## Preface to the Second Edition

In preparing the first edition of the *Encyclopedia of Systems and Control*, we, the editors, were faced with the daunting task of organizing a discipline with deep roots and a wide footprint. To help with the undertaking, we were fortunate that leading experts from around the world agreed to serve as section editors. Our initial goal of about 200 articles was substantially exceeded, and the first edition featured 250 contributions in 30 parts – covering both theoretical and application-oriented topics.

In the several years since the first edition was published, we have been gratified by the recognition of the work and its usage. But systems and control is a dynamic discipline. Notable advances have occurred within the topics covered in the first edition. Moreover, new areas have emerged where synergy with control is being recognized and exploited. Indeed, as we reflect on a project that has now extended over almost a decade, we are struck by the increasingly cross-disciplinary currents that are influencing the directions of research in the field while also being guided by its mathematical underpinnings.

The vitality of systems and control as a discipline is evident in the additions to this second edition. Once again our goal, this time of about 50 new articles, was overachieved. With 366 articles in 39 parts, it would take a leap year of reading an article a day to exhaust the material in the new book! In addition to updates from the first edition, new topics include biomedical devices, building control, CPS/IoT, human-in-the-loop control, machine learning, control of micro and nano systems, quantum control, and vision-based control. As with the first edition, the current edition aims to make the vast array of topics that are now considered part of systems and control accessible to everyone who needs an introduction and also provides extensive pointers to further reading.

We continue to owe an enormous debt to major intellectual leaders in the field who agreed to serve as topical section editors (the list appears on the following pages). They have recruited teams of experts as authors and have managed extensive peer review of everything that appears in these volumes. We once again wish to express our gratitude to the many professionals at Springer who have supported the encyclopedia, notably Oliver Jackson, Andrew Spencer, and Vasowati Shome. We hope readers find this second edition of the encyclopedia a useful and valuable compendium for a discipline that is central to our technologically driven world today.

Boston, USA  
Minneapolis, USA  
April 2021

John Baillieul  
Tariq Samad

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## Preface to the First Edition

The history of Automatic Control is both ancient and modern. If we adopt the broad view that an automatic control system is any mechanism by which an input action and output action are dynamically coupled, then the origins of this encyclopedia's subject matter may be traced back more than 2,000 years to the era of primitive time-keeping and the clepsydra water clock perfected by Ctesibius of Alexandria. In more recent history, frequently cited examples of feedback control include the automatically refilling reservoirs of flush toilets (perfected in the late nineteenth century) and the celebrated flyball steam-flow governor described in J.C. Maxwell's 1868 Royal Society of London paper – "On Governors."

Although it is useful to keep the technologies of antiquity in mind, the history of systems and control as covered in the pages of this encyclopedia begins in the twentieth century. The history was profoundly influenced by work of Nyquist, Black, Bode, and others who were developing amplifier theory in response to the need to transmit wireline signals over long distances. This research provided major conceptual advances in feedback and stability that proved to be of interest in the theory of servomechanisms that was being developed at the same time. Driven by the need for fast and accurate control of weapons systems during World War II, automatic control developed quickly as a recognizable discipline.

While the developments of the first half of the twentieth century are an important backdrop for the *Encyclopedia of Systems and Control*, most of the topics directly treat developments from 1948 to the present. The year 1948 was auspicious for systems and control – and indeed for all the information sciences. Norbert Wiener's book *Cybernetics* was published by Wiley, the transistor was invented (and given its name), and Shannon's seminal paper "A Mathematical Theory of Communication" was published in the *Bell System Technical Journal*. In the years that followed, important ideas of Shannon, Wiener, Von Neumann, Turing, and many others changed the way people thought about the basic concepts of control systems. The theoretical advances have propelled industrial and societal impact as well (and vice versa). Today, advanced control is a crucial enabling technology in domains as numerous and diverse as aerospace, automotive, and marine vehicles; the process industries and manufacturing; electric power systems; homes and buildings; robotics; communication networks; economics and finance; and biology and biomedical devices.

It is this incredible broadening of the scope of the field that has motivated the editors to assemble the entries that follow. This encyclopedia aims to help students, researchers, and practitioners learn the basic elements of a vast array of topics that are now considered part of systems and control. The goal is to provide entry-level access to subject matter together with cross-references to related topics and pointers to original research and source material.

Entries in the encyclopedia are organized alphabetically by title, and extensive links to related entries are included to facilitate topical reading – these links are listed in “Cross-References” sections within entries. All crossreferenced entries are indicated by a preceding symbol: ►. In the electronic version of the encyclopedia these entries are hyperlinked for ease of access.

The creation of the *Encyclopedia of Systems and Control* has been a major undertaking that has unfolded over a 3-year period. We owe an enormous debt to major intellectual leaders in the field who agreed to serve as topical section editors. They have ensured the value of the opus by recruiting leading experts in each of the covered topics and carefully reviewing drafts. It has been a pleasure also to work with Oliver Jackson and Andrew Spencer of Springer, who have been unfailingly accommodating and responsive over this time.

As we reflect back over the course of this project, we are reminded of how it began. Gary Balas, one of the world’s experts in robust control and aerospace applications, came to one of us after a meeting with Oliver at the Springer booth at a conference and suggested this encyclopedia – but was adamant that he wasn’t the right person to lead it. The two of us took the initiative (ultimately getting Gary to agree to be the section editor for the aerospace control entries). Gary died last year after a courageous fight with cancer. Our sense of accomplishment is infused with sadness at the loss of a close friend and colleague.

We hope readers find this encyclopedia a useful and valuable compendium and we welcome your feedback.

Boston, USA  
Minneapolis, USA  
May 2015

John Baillieul  
Tariq Samad

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**Section Editor:** *Richard Hume Middleton*

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**Section Editor:** *Panagiotis Tsiotras*

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**Section Editor:** *Luigi Glielmo*

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**Section Editor:** *B. Wayne Bequette*

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**Section Editor:** *Michael Cantoni*

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**Section Editor:** *Dawn Tilbury*

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**Section Editor:** *Tariq Samad*

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