SYSTEM ENGINEERING HANDBOOK

EDITED BY

ROBERT E. MACHOL

Head, Department of Systems Engineering
University of Illinois in Chicago
Formerly Vice President, Systems
Conductron Corporation, Ann Arbor, Mich.

IN COLLABORATION WITH

WILSON P. TANNER, JR.

Professor of Psychology and Director of
the Sensory Intelligence Laboratory
The University of Michigan

SAMUEL N. ALEXANDER

Chief of the Information Technology Division
The National Bureau of Standards

McGRAW-HILL BOOK COMPANY

New York *San Francisco* *Toronto* *London* *Sydney*

SYSTEM ENGINEERING HANDBOOK

 Library of Congress Catalog Card Number: 64-19214

07-039371-0

56789-KPKP-7987

SYSTEM ENGINEERING HANDBOOK

McGRAW-HILL HANDBOOKS

ALJIAN · Purchasing Handbook
AMERICAN INSTITUTE OF PHYSICS · American Institute of Physics Handbook
AMERICAN SOCIETY OF MECHANICAL ENGINEERS · ASME Handbooks:
Engineering Tables
Metals Engineering—Design
Metals Engineering—Processes
Metals Properties
AMERICAN SOCIETY OF TOOL AND MANUFACTURING ENGINEERS · Die Design Handbook
AMERICAN SOCIETY OF TOOL AND MANUFACTURING ENGINEERS · Tool Engineers Handbook
BAUMEISTER AND MARKS · Standard Handbook for Mechanical Engineers
BEEMAN · Industrial Power Systems Handbook
BELL · Petroleum Transportation Handbook
BERRY, BOLLAY, AND BEERS · Handbook of Meteorology
BLATZ · Radiation Hygiene Handbook
BRADY · Materials Handbook
BURINGTON · Handbook of Mathematical Tables and Formulas
BURINGTON AND MAY · Handbook of Probability and Statistics with Tables
CARROLL · Industrial Instrument Servicing Handbook
CHOU · Handbook of Applied Hydrology
COCKRELL · Industrial Electronics Handbook
CONDON AND ODISHAW · Handbook of Physics
CONSIDINE · Process Instruments and Controls Handbook
CONSIDINE AND ROSS · Handbook of Applied Instrumentation
CROCKER AND KING · Piping Handbook
CROFT AND CARR · American Electricians' Handbook
DAVIS · Handbook of Applied Hydraulics
DUDLEY · Gear Handbook
ETHERINGTON · Nuclear Engineering Handbook
FACTORY MUTUAL ENGINEERING DIVISION · Handbook of Industrial Loss Prevention
FLÜGGE · Handbook of Engineering Mechanics
FRICK · Petroleum Production Handbook
GUTHRIE · Petroleum Products Handbook
HARRIS · Handbook of Noise Control
HARRIS AND CREDE · Shock and Vibration Handbook
HENNEY · Radio Engineering Handbook
HENNEY AND WALSH · Electronic Components Handbook
HUNTER · Handbook of Semiconductor Electronics
HUSKEY AND KORN · Computer Handbook

IRESON · Reliability Handbook
JASIK · Antenna Engineering Handbook
JURAN · Quality Control Handbook
KALLEN · Handbook of Instrumentation and Controls
KING AND BRATER · Handbook of Hydraulics
KNOWLTON · Standard Handbook for Electrical Engineers
KOELLE · Handbook of Astronautical Engineering
KORN AND KORN · Mathematical Handbook for Scientists and Engineers
KURTZ · The Lineman's Handbook
LA LONDE AND JANES · Concrete Engineering Handbook
LANDEE, DAVIS, AND ALBRECHT · Electronic Designers' Handbook
LANGE · Handbook of Chemistry
LE GRAND · The New American Machinist's Handbook
MACHOL · System Engineering Handbook
MAGILL, HOLDEN, AND ACKLEY · Air Pollution Handbook
MANAS · National Plumbing Code Handbook
MANTELL · Engineering Materials Handbook
MARKUS · Handbook of Electronic Control Circuits
MARKUS AND ZELUFF · Handbook of Industrial Electronic Circuits
MAYNARD · Industrial Engineering Handbook
MEITES · Handbook of Analytical Chemistry
MERRITT · Building Construction Handbook
MOODY · Petroleum Exploration Handbook
MORROW · Maintenance Engineering Handbook
PERRY · Chemical Engineers' Handbook
PERRY · Engineering Manual
SHAND · Glass Engineering Handbook
SHEA · Amplifier Handbook
STANIAR · Plant Engineering Handbook
STETKA AND BRANDON · NFPA Handbook of the National Electrical Code
STREETER · Handbook of Fluid Dynamics
STUBBS · Handbook of Heavy Construction
TERMAN · Radio Engineers' Handbook
TRUXAL · Control Engineers' Handbook
URQUHART · Civil Engineering Handbook
WALKER · NAB Engineering Handbook
WOODS · Highway Engineering Handbook
YODER, HENEMAN, TURNBULL, AND STONE · Handbook of Personnel Management and Labor Relations

CONTRIBUTORS

ISAAC L. AUERBACH, *President, Auerbach Corporation.* (*Digital Computer-system Characteristics*)

GEORGE A. BEKEY, *Electrical Engineering Department, University of Southern California.* (*Simulation*)

RICHARD BELLMAN, *The RAND Corporation.* (*Dynamic Programming—Theory and Application*)

EUGENE W. BIERLY, *U.S. Atomic Energy Commission.* (*The Lower Atmosphere*)

ROBERT H. BODEN, *Rocketdyne Division of North American Aviation, Inc.* (*Propulsion*)

KENNETH E. BOULDING, *The University of Michigan.* (*Economics*)

LUDWIG BRAUN, *Associate Professor of Electrical Engineering, Polytechnic Institute of Brooklyn.* (*Feedback Theory*)

ARTHUR W. BURKS, *Professor of Philosophy, The University of Michigan.* (*The Propositional Calculus*)

NORMAN L. CANFIELD, *U.S. Weather Bureau.* (*The Lower Atmosphere*)

A. CHARNES, *Northwestern University.* (*Elements of a Strategy for Making Models in Linear Programming*)

J. F. CLAYTON, *Bendix Systems Division, Bendix Corporation.* (*Management*)

GEORGE R. COOPER, *School of Electrical Engineering, Purdue University, Lafayette, Indiana.* (*Decision Theory*)

W. W. COOPER, *Carnegie Institute of Technology.* (*Elements of a Strategy for Making Models in Linear Programming*)

L. J. CUTRONA, *Vice President for Applied Research, Conductron Corporation; Professor of Electrical Engineering, The University of Michigan.* (*Communications Equipments*)

GEORGE B. DANTZIG, *Chairman, Operations Research Center, University of California, Berkeley, California.* (*The Simplex Method*)

A. NELSON DINGLE, *Department of Meteorology and Oceanography, The University of Michigan.* (*The Lower Atmosphere*)

CHARLES L. DOLPH, *Professor of Mathematics, The University of Michigan.* (*Properties of the Laplace and Related Transforms*)

W. G. DOW, *Professor and Chairman, Department of Electrical Engineering, The University of Michigan.* (*Selected Energy-conversion Subsystems*)

RAYMOND L. DUSSAULT, *Itek Corporation.* (*Optical Sensors*)

LESLIE C. EDIE, *Port of New York Authority.* (*Urban Areas*)

JEROME FREEDMAN, *Lincoln Laboratory, Massachusetts Institute of Technology.* (*Radar*)

D. L. GERLOUGH, *Planning Research Corporation.* (*Simulation*)

JOHN E. GIBSON, *Director, Control and Information Systems Laboratory, School of Electrical Engineering, Purdue University.* (*Adaptive and Learning Control Systems*)

JOHN A. GOSDEN, *Program Manager, Auerbach Corporation.* (*Digital Computer-system Characteristics*)

CARL D. GRAVES, *TRW Space Technology Laboratories.* (*Space and Astronomy*)

ARTHUR D. HALL, *Head, Television Engineering Department, Bell Telephone Laboratories.* (*Communications Systems*)

WALTER HELLY, *Port of New York Authority.* (*Urban Areas*)

E. WENDELL HEWSON, *Department of Meteorology and Oceanography, The University of Michigan.* (*The Lower Atmosphere*)

CONRAD H. HOEPPNER, *President, Industrial Electronetics Corporation.* (*Radio-telemetry Systems*)

RONALD A. HOWARD, *Associate Professor of Electrical Engineering and Associate Professor of Industrial Engineering, Massachusetts Institute of Technology.* (*Probability*)

R. M. HOWE, *Department of Aeronautical Engineering, The University of Michigan.* (*Guidance*)

LESLIE M. JONES, *High Altitude Engineering Laboratory, Department of Aeronautical and Astronautical Engineering, The University of Michigan.* (*The Upper Atmosphere*)

WALTER J. KARPLUS, *Department of Engineering, University of California, Los Angeles.* (*Analog Elements*)

GRANINO A. KORN, *Professor of Electrical Engineering, University of Arizona.* (*Electronic Analog/Hybrid Computers and Their Use in System Engineering*)

RICHARD A. LAING, *Logic of Computers Group, The University of Michigan.* (*The Propositional Calculus*)

VERNON D. LANDON, *Radio Corporation of America, Defense Electronic Products, Astro-Electronics Division, Princeton, New Jersey.* (*Satellite Systems*)

GERARD A. La ROCCA, *Head of Scientific Space Projects, Space and Information Systems Division, North American Aviation.* (*System Testing*)

GEORGE K. LEWIS, *Department of Geography, Boston University.* (*Land Masses*)

WILLIAM A. LYNCH, *Head, Mechanical Engineering Department, Polytechnic Institute of Brooklyn.* (*Feedback Theory*)

DUNCAN E. MACDONALD, *Itek Corporation.* (*Optical Sensors*)

ROBERT E. MACHOL, *Head, Department of Systems Engineering, University of Illinois in Chicago; formerly Vice President, Systems, Conductron Corporation, Ann Arbor, Michigan.* (*Methodology of System Engineering*)

MAURICE A. MEYER, *Vice President, Adcole Corporation.* (*Logical Circuits*)

PHILIP M. MORSE, *Director, Operations Research Center, Massachusetts Institute of Technology.* (*Queues and Markov Processes—the Response of Operating Systems to Fluctuating Demand and Supply*)

LLOYD G. MUNDIE, *Lockheed-California Company, Burbank, California.* (*Infrared*)

JACK N. NIELSEN, *Director of Research and Development, Vidya Division, Itek Corporation.* (*Aerodynamic Systems*)

R. D. O'NEAL, *Vice President, Aerospace Systems, The Bendix Corporation, Detroit, Michigan.* (*Management*)

CLAY L. PERRY, *Director, Computer Center, University of California, San Diego, La Jolla, California.* (*Numerical Analysis*)

RICHARD W. PEW, *Human Performance Center, Department of Psychology, The University of Michigan.* (*Human Information-processing Concepts for System Engineers*)

DONALD J. PORTMAN, *Department of Meteorology and Oceanography, The University of Michigan.* (*The Lower Atmosphere*)

AUBREY W. PRYCE, *Acoustics Programs, Office of Naval Research, Washington, D.C.* (*The Ocean*)

FAZLOLLAH M. REZA, *Syracuse University, Syracuse, New York.* (*Information Theory*)

HAROLD D. ROSS, JR., *Director of Research Relations, IBM Corporation, Data Systems Division, Poughkeepsie, New York.* (*Reliability*)

MANUEL ROTENBERG, *University of California, San Diego, La Jolla, California.* (*Numerical Analysis*)

EDWARD RYZNAR, *Department of Meteorology and Oceanography, The University of Michigan.* (*The Lower Atmosphere*)

MORRIS SCHULKIN, *Westinghouse Electric Corporation, Baltimore, Maryland.* (*The Ocean*)

SIDNEY STERNBERG, *Vice President and General Manager, Electro-Optical Systems Inc., Pasadena, California.* (*Satellite Systems*)

ROBERT M. THRALL, *Professor of Mathematics and Operations Analysis, The University of Michigan.* (*Game Theory*)

JOHN G. TRUXAL, *Vice President for Educational Development, Polytechnic Institute of Brooklyn.* (*Feedback Theory*)

FOREWORD

In late 1960 Professor Harry H. Goode of The University of Michigan agreed to prepare a System Engineering Handbook for the McGraw-Hill Book Company. He apparently prepared a brief outline and indicated a few of the individuals from whom he intended to request articles. After his untimely death on October 30 of that year, Tanner, who was his literary executor, discovered these papers in his files and conceived the idea of completing this work as a memorial to Professor Goode. At his suggestion, Machol and Alexander agreed to join him in this effort. Completion of the original outline was done by the three of us in 1961.

The large amount of clerical work involved in this undertaking required that our efforts be concentrated in a single city and a single office. The efforts involved, during 1961 and 1962, in convincing outstanding scholars to devote their time to the preparation of articles for this handbook were performed primarily by Machol and Tanner, who were both in Ann Arbor. The editorial efforts in 1962 and 1963, the proofreading and indexing in 1964, and the heavy load of administrative and clerical responsibilities for putting this handbook together in 1962–1964 were Machol's.

In addition to being a memorial to Professor Goode, for whom we still grieve, this handbook has been an eleemosynary effort to benefit the Goode Educational Fund. Most of the authors, as well as the three editors, have waived their honoraria and other financial rights in this work, and the editors wish to express their very deep appreciation to the authors who have contributed so freely of their time to this worthy purpose.

Robert E. Machol
Wilson P. Tanner, Jr.
Samuel N. Alexander

PREFACE

Gratitude having been expressed in the Foreword and the organization of this book briefly outlined at the beginning of Chapter 1, it remains to explain to the reader what I have attempted to do in this handbook and how I have attempted to do it.

The words "system" and "system engineering" mean many things to many people; what I mean by them is explained in Sec. 1-1, and this definition has influenced the choice of subjects, of authors, and of material included. Thus, for the topic of urban environment I chose operations research experts who wrote a chapter (4) of very different flavor than might have been prepared by a sociologist or city planner; and the chapter (31) on human engineering is written from an information-theoretic viewpoint which I believe to be peculiarly pertinent to system engineering.

In the level of mathematical sophistication of the presentation, one runs always between the Scylla of laborious, inefficient, dull presentation on too elementary a level and the Charybdis of passing completely over the reader's head by use of advanced mathematics. It is recognized not only that the mathematical preparation of readers varies greatly, but also that there may be quite a difference between the mathematics to which the reader has been formally exposed and that with which he is facile. In most chapters, familiarity with elementary calculus (such as may be learned in the first year or two of most undergraduate engineering curricula) is assumed; in addition, familiarity with elementary matrix operations (at least to the extent of notation) is assumed in a number of chapters. More advanced techniques such as variational methods and function theory are rarely used. However, this rule is not followed slavishly, and in certain chapters such as Dynamic Programming (27) and Laplace Transform (39), a considerable degree of sophistication is expected of the reader, though still not at the level of the professional mathematician (except perhaps in the appendix to Chapter 39).

Probability theory is a special case. About a dozen chapters require an understanding of this theory; for those who are not familiar with it, Chapter 38 presents it in a very elementary and, in my opinion, extraordinarily lucid fashion.

Length and coverage of this handbook are necessarily compromises, and have been subjects of much consideration. Inevitably some readers

will find here things they consider superfluous and fail to find others which they seek. Certainly Part II (Chapters 2 through 7) on environments is unusual in a handbook of this type, but I think it will be exceptionally interesting and useful to many system engineers.

I have endeavored to make the handbook efficient by minimizing overlap and repetition. I have carefully scrutinized and coordinated the outlines, and subsequently the texts, of each chapter, and exchanged many of these among authors (as will be obvious, for example, to anyone who reads Chapters 20 and 21, or 25 and 26, which had considerable possibility of overlap). I have inserted numerous cross references from one chapter to another for this reason. However, this approach was also not followed slavishly; the reader does not wish to turn continually from one chapter to another, and each chapter was therefore made self-contained, within reasonable limits of duplication.

So much time is required to produce a work of this magnitude that, inevitably, some material appeared to lose its freshness. A special effort was therefore made to review the sections and bring them up to date through 1964 by changes either in manuscript or in proof.

Finally, in a book of this magnitude, in spite of editing and proofreading efforts, there will inevitably be errors. I would greatly appreciate having them called to my attention.

Robert E. Machol

CONTENTS

PART IV. SYSTEM THEORY

PART V. SYSTEM TECHNIQUES

PART VI. USEFUL MATHEMATICS ASSOCIATED WITH SYSTEM ENGINEERING

Index follows Chapter 41.

Part I

INTRODUCTION