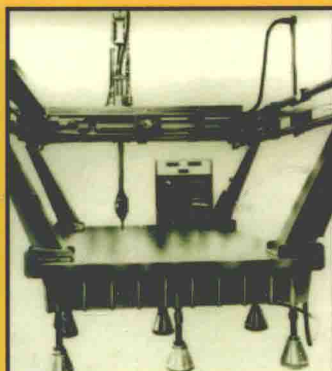
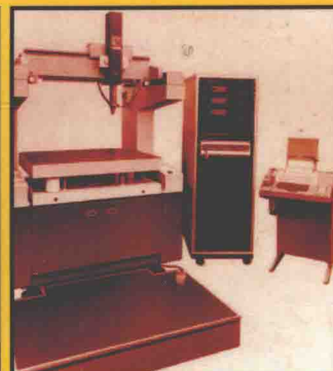
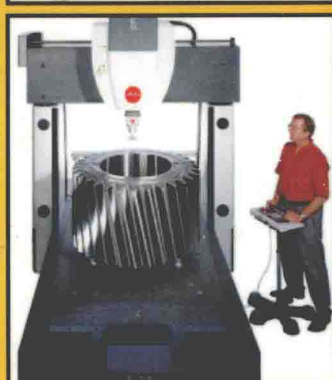
Coordinate Measuring Machines and Systems

Second Edition




Edited by
Robert J. Hocken
& Paulo H. Pereira

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Second Edition

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Dedication

To our beloved wives, Dene and Roseli,
for their unconditional support and
encouragement. Bob and Paulo

Preface

Since John Bosch edited and published the first version of this book in 1995, the world of manufacturing and coordinate measuring machines (CMMs) and coordinate measuring systems (CMSs) has changed considerably. Perhaps most significantly, we have seen a large volume of manufacturing move to Asia, particularly the People's Republic of China. We have also seen enormous growth in the capability of what were once called microcomputers and the incredible strides in communication through the multifaceted ever-changing marvel, the World Wide Web. In addition to that the proliferation and miniaturization of the cell phone, personal digital assistants of all sorts, digital books, etc. and much of the work we do and the tools we do it with would have seemed quite alien a decade and a half ago.

So, what has changed in *Coordinate Measuring Machines and Systems*? First and foremost, it is helpful to remind ourselves that the basic physics of the machines has not changed at all. A good deal of this book, therefore, deals with topics that have not changed in essence but have just become more deeply understood. In other areas, software as an example, the expectations of the user for operator interfaces, ease of use, algorithms, speed, communications, and computational capabilities have expanded remarkably. Further, some types of machines, particularly the non-Cartesian CMMs, have expanded in market share and increased in accuracy and utility. We have also seen big changes in probing systems, called accessory elements in this text, and the number of points they can deliver to ever more sophisticated software. New applications have multiplied and pressures to improve machine performance have continued to increase. The concept of uncertainty has been better defined and is now widely used. It has been an interesting and exciting 16 years.

In addition to two new editors, one from academia and one from a metrology-intensive user industry, this book has many new authors and a known cadre of experts who have grown with the field since the last version. Many of them the reader will recognize from the literature on metrology, machine, and software standards development, and their activities in technical societies. We, the editors, are confident that we have assembled a first-rate team and believe that this book will be a valuable resource for students, practitioners, and researchers. Our authors come from around the world, and we intend that this book will play an important part in the global economy of manufacturing.

Contributors

Dean E. Beutel has responsibility for global manufacturing process execution for Caterpillar Inc. His organization supports development, maintenance, and improvement of manufacturing processes internationally. Dean joined Caterpillar in 1978 as a sweeper, and has performed a variety of manufacturing and quality engineering functions for over 33 years. He obtained his certification as a journeyman machinist in 1984, as well as his bachelor's degree from Bradley University in production operations the same year. He was certified as a quality engineer by the ASQ in 1987 and maintains this certification.

John A. Bosch is the chairman and CEO of Commander Aero, Inc. Mr. Bosch joined the U.S. Air Force as an aircraft maintenance officer immediately after graduating from Penn State with an engineering degree in 1951 and then spent 28 years at General Electric with assignments in engineering and general management before joining Sheffield as president, a position he held from 1982 to 1993. Mr. Bosch was a research associate at the National Institute of Standards and Technology (NIST) and consultant, advance measurement technology for Giddings & Lewis. Mr. Bosch has authored a number of technical and business publications and served on the board of directors of Leland Electrosystems and Shaw Aero Devices, Inc.

James B. Bryan is an independent consultant in precision engineering. Mr. Bryan retired in 1985 from the Lawrence Livermore National Laboratory after 30 years of service in metrology. He is the recipient of the 1977 Society of Manufacturing Engineers International Medal for Research in Manufacturing, an honorary member of the American Society of Precision Engineering, a member of CIRP since 1964, a charter member of ANSI/ASME Committee B89 on Dimensional Metrology, and the first chairman of B89.6.2 Temperature and Humidity Environment for Dimensional Measurement. Mr. Bryan was selected by *Fortune* magazine as one of its heroes of the year in 2000, received a Lifetime Achievement Award also in 2000 from EUSPEN, was selected by SME's *Manufacturing Engineering* magazine as a 2007 Master of Manufacturing, and received the M. Eugene Merchant Manufacturing Medal of ASME/SME in 2008.

Ralf Christoph studied precision mechanics at the Friedrich Schiller University in Jena, Germany. In 1985, he received his PhD in the field of application of image sensors in optical coordinate measuring machines. He earned his postdoctoral thesis qualification in the field of optical sensors for geometric measurement in 1989. Since 1990, Dr. Christoph has been employed at Werth Messtechnik GmbH in Giessen, Germany, first as engineering and development manager and since 1993 as owner and managing director. For more than 10 years, he has participated in the preparation of guidelines and standards for VDI, DIN, and ISO in the field of coordinate measuring technology.

Ted Doiron is the leader of and a physicist in the Engineering Metrology Group of the Precision Engineering Division, one of five divisions of the Manufacturing Engineering Laboratory at NIST. He is the author or the coauthor of many technical papers and is considered one of the U.S. experts on gage blocks and gage block metrology. He is also responsible for complex dimensional standards at NIST.

Marion B. (Bill) Grant is a technical steward for metrology and advanced manufacturing for Caterpillar Inc. in Peoria, Illinois. He received his PhD in physics from the University of Illinois in 1985. Dr. Grant is active in ASME serving on the B46 and B89 committees, is the U.S. representative on the ISO TC213 Committee on coordinate metrology, and has several publications to his credit.

Robert J. Hocken is the Norvin Kennedy Dickerson, Jr., Distinguished Professor of Precision Engineering and Director of the Center for Precision Metrology at the University of North Carolina, Charlotte. Before 1988, Dr. Hocken worked at the National Bureau of Standard—NBS (now NIST) as chief, Precision Engineering Division. Dr. Hocken received his PhD in physics from the State University of New York at Stony Brook in 1969 and is an author or a coauthor of 60 articles and research reports. Dr. Hocken is a key contributor to many national and international standards organizations. He has received many awards including the Presidential Executive Award.

Jörg Hoffmann is a research assistant at the Chair Quality Management and Manufacturing Metrology of University Erlangen-Nuremberg (Germany), active member of VDI-GMA Section 3.44 "Dimensional Measurands" and is nominated for CIRP Research Affiliates. Dipl.-Ing. Hoffmann is doing research in the field of probing systems for the measurement of microparts and multisensor coordinate metrology. He is the author or the coauthor of 21 scientific papers, lecturer at the VDI seminar "Multisensor Coordinate Metrology" and developed an STM-based probing system for nanometer resolving CMMs (patent pending).

Wolfgang Knapp is the head of metrology at the Institute of Machine Tools and Manufacturing (IWF) at the Swiss Federal Institute of Technology (ETH) and a consultant in precision manufacturing, with his office located in Schleitheim, Switzerland. Dr. Knapp received his PhD from the Swiss Federal Institute of Technology in 1984. The theme of Dr. Knapp's thesis was a proposed method for testing CMMs. He has authored several technical papers and is currently the Swiss expert on international standards committees pertaining to machine tools.

Edward Morse has more than 20 years of experience with both coordinate measuring machines and geometric tolerancing. He was first interested in tolerancing and metrology while in the master of engineering program at Cornell University in the late 1980s. After earning his ME, he worked at the Brown & Sharpe Manufacturing Company—first as an applications engineer and then as a project leader in the advanced systems group, linking industrial shop floor controls to measuring equipment. He returned to Cornell to earn his MS and PhD in mechanical engineering.

The focus of his doctoral dissertation was a theoretical investigation of the "Physics of Mechanical Assembly," namely, how tolerances can be analyzed to determine if the assembly of intolerance components can be guaranteed. Since completing his graduate studies in 1999, Dr. Morse has been a member of the faculty in the Mechanical Engineering and Engineering Science Department at the University of North Carolina, Charlotte, home of a world-renown graduate program in dimensional metrology. His research interests include tolerancing for assembly, CMM testing and standards, estimation and evaluation of task-specific measuring uncertainty, and large-scale metrology systems and standardization. Dr. Morse holds Senior Level Certification as an ASME Geometric Dimensioning and Tolerancing Professional. He is a member of the ASME Y14 subcommittee 5.1 (Mathematical definition of Y14.5 dimensioning and tolerancing principles). He is also a member of ASME B89 Committee (Dimensional Metrology), B89.4 (Coordinate Measuring Technology), and B89.7 (Measurement Uncertainty), in addition to several project teams within the B89.4 group. In the area of international standards, Dr. Morse serves as a subject matter expert for the United States in ISO Technical Committee 213 for Working Group 10 (Coordinate Measuring Machines), Working Group 4 (Uncertainty), and Advisory Group 12 (Mathematical support group for GPS).

Hans Joachim Neumann studied radio engineering at the Mittweida High School of Engineering in Saxony, Germany. After two years of development in optoelectronic engineering at the Carl Zeiss Company in Jena, he transferred to Carl Zeiss in Oberkochen, Germany, in 1957. There, he first worked in managerial roles in the fields of electronic engineering for telescopes and precision measuring equipment, then in software and applications engineering, and finally as manager of marketing communication in the industrial measuring technology division. Until 2001, he was in charge of standardization and technical information as a consultant for the corporation and a member of the ISO committee for coordinate measuring technology. For 11 years, he was the chairman of the VDI/DIN joint committee for coordinate measuring technology, for which he was awarded an honorary badge by VDI. He currently works as a technical author and instructor.

Jun Ni is the Shien-Ming (Sam) Wu Collegiate Professor of Manufacturing Science and professor of mechanical engineering at the University of Michigan, U.S. He is as the founding Dean of the University of Michigan–Shanghai Jiao Tong University Joint Institute located in Shanghai, China (2006–2014). He also serves as the director of the S. M. Wu Manufacturing Research Center and as the co-director of a National Science Foundation sponsored Industry/University Cooperative Research Center for Intelligent Maintenance Systems. Professor Ni's research and teaching interests are in the areas of manufacturing science and engineering, the design of optimal maintenance operations, and statistical quality control and improvement. He has received many honors and awards, including ASME's William T. Ennor Manufacturing Technology Award, the Presidential Faculty Fellows Award from the National Science Foundation, and the elected Fellow of ASME and SME.

Paulo H. Pereira has over 28 years of experience in manufacturing and is currently part of the Global Quality Processes team at Caterpillar Inc. in Peoria, IL responsible for the corporate quality management system. Before that, he was the chief metrologist for five years at the Integrated Manufacturing Operations Division—East Peoria facility of Caterpillar Inc., where he was in charge of metrology planning and implementation. Before that, he was an internal consultant in metrology for Caterpillar for about five years. Dr. Pereira received his PhD in mechanical engineering (metrology) from the University of North Carolina, Charlotte, in 2001. Dr. Pereira has been a certified quality engineer by ASQ since 2006 and holds both his bachelor's and master's degrees in mechanical engineering from the University of São Paulo–São Carlos, Brazil. Dr. Pereira is a member of the ASME B89 committee (Dimensional Metrology) and also serves as a subject matter expert for the United States in the ISO Technical Committee 213 for Working Group 10 (Coordinate Measuring Machines).

Steven D. Phillips is the group leader of the Large Scale Coordinate Metrology Group at NIST and serves as the vice chair of the ASME B89 committee for dimensional metrology. He holds three U.S. patents and received the Department of Commerce's Gold and Silver Medals for work in coordinate metrology. Dr. Phillips is the author of 25 archival research publications in diverse fields such as chemistry, physics, applied optics, and precision engineering. Dr. Phillips holds a MS and PhD in physics from the University of California at Santa Barbara, a BS in mathematics and an MBA. He is also the SME-1 U.S. representative to TC213WG10 and TC213WG4 responsible for developing international standards for coordinate metrology applications and dimensional measurement uncertainty.

Craig M. Shakarji heads NIST's Algorithm Testing and Evaluation Program for Coordinate Measuring Systems. Dr. Shakarji chairs the ASME B89 project team on CMM software and serves as a subject matter expert and editor of several standards in the ISO 213 standards committee on CMMs. He was awarded the Department of Commerce Gold Medal for his achievements in CMM standards harmonization. Dr. Shakarji, a mathematician, received his PhD from the University of California, Los Angeles and his master's degree from Caltech, and in 1996 joined NIST, where he has done extensive research in the computational metrology field.

Dennis A. Swyt received his PhD in physics from Case Western Reserve University in 1971. After joining NIST in 1972, he had a number of assignments with increasing responsibilities. Dr. Swyt is the author of 50 technical papers, has a U.S. patent, and serves on several advisory panels. In 1980, he received the NIST Silver Medal Award for his development of a photomask linewidth standard. Dr. Swyt retired from NIST as chief of the Precision Engineering Division.

Albert Weckenmann is professor at and head of the Chair Quality Management and Manufacturing Metrology of University of Erlangen-Nuremberg (Germany), fellow of CIRP and vice-chairman of CIRP STC P. Dr.-Ing. Weckenmann has been doing research in coordinate metrology for more than 32 years and is the coauthor of a number of VDI/VDE and DIN standards, as well as books on coordinate metrology and geometrical product specification. He is chairman of IMEKO TC 14 (Measurement of Geometrical Quantities), chairman of the German VDI-GMA Section 3.40 "Micro- and Nanometrology" and member of the advisory board of DIN-Section NATG (Fundamentals in Engineering). Dr.-Ing. Weckenmann is the author or coauthor of more than 300 scientific papers and 5 books and editor or coeditor of 19 books. He is the inventor or coinventor of 17 patented inventions.

Guoxiong Zhang was conferred a degree of Honorary Doctor by Moscow State University of Technology (Stankin) in 1996. He has been honored with the titles of All-China Model Teacher, Model Worker of Tianjin City, Honorary Expert in Measuring and Testing Technologies and Instruments of Tianjin City for his outstanding contributions in teaching and research work. He was the chairman of the Department of Precision Instrument Engineering, Tianjin University, China, 1986–1995; and dean of the College of Precision Instrument and Opto-Electronics Engineering, Tianjin University, 1995–1997. He was elected as the chairman of the Scientific and Technical Committee on Precision Engineering of the International Academy for Production Engineering (CIRP), 1991–1994; president of the Chinese Production Engineering Institution, 1995–1999; chairman of the All-China Teaching Guiding Committee on Instruments and Gauges, 1996–2001. He worked as a visiting scholar at the U.S. National Bureau of Standards, 1981–1984; visiting professor at the University of North Carolina at Charlotte in 1991, 1998, 2003, and 2007. He has completed more than 60 projects including 12 international cooperative programs and three United Nation Development Programs. He has published 13 books and more than 500 academic papers. Among them, more than 50 papers were indexed by the Science Citation Index (SCI) and 180 by the Engineering Index (EI). He received a China National Invention Award and six awards for Advancement for Science and Technology conferred by The Ministry of Education of China, Tianjin City and other provinces of China. One of the projects completed by him and his American colleagues when he worked at the U.S. National Bureau of Standards received a U.S. government award.

Contents

1 Evolution of Measurement

Robert J. Hocken and John A. Bosch

CONTENTS

Measurement is an integral part of our everyday lives. It is something that most people take for granted. In looking back at the evolution of measurement, one finds that it relates directly to the progress of mankind. This chapter provides a brief historical summary of this evolution from the perspective of industrial metrology.