



Downloaded from <http://hnm.sciencelibrary.com/asmigitalcollection/asm>

Metrology and Instrumentation

Practical Applications for Engineering and Manufacturing

Samir Mekid

ASME
PRESS

WILEY

October 2022

Metrology and Instrumentation

Wiley-ASME Press Series

Fabrication of Process Equipment
Owen Greulich, Maan H. Jawad

Engineering Practice with Oilfield and Drilling Applications
Donald W. Daring

Flow-Induced Vibration Handbook for Nuclear and Process Equipment
Michel J. Pettigrew, Colette E. Taylor, Nigel J. Fisher

Vibrations of Linear Piezostructures
Andrew J. Kurdila, Pablo A. Tarazaga

Bearing Dynamic Coefficients in Rotordynamics: Computation Methods and Practical Applications
Lukasz Brenkacz

Advanced Multifunctional Lightweight Aerostructures: Design, Development, and Implementation
Kamran Behdinan, Rasool Moradi-Dastjerdi

Vibration Assisted Machining: Theory, Modelling and Applications
Li-Rong Zheng, Dr. Wanqun Chen, Dehong Huo

Two-Phase Heat Transfer
Mirza Mohammed Shah

Computer Vision for Structural Dynamics and Health Monitoring
Dongming Feng, Maria Q Feng

Theory of Solid-Propellant Nonsteady Combustion
Vasily B. Novozhilov, Boris V. Novozhilov

Introduction to Plastics Engineering
Vijay K. Stokes

Fundamentals of Heat Engines: Reciprocating and Gas Turbine Internal Combustion Engines
Jamil Ghojel

Offshore Compliant Platforms: Analysis, Design, and Experimental Studies
Srinivasan Chandrasekaran, R. Nagavinothini

Computer Aided Design and Manufacturing
Zhuming Bi, Xiaoqin Wang

Pumps and Compressors
Marc Borremans

Corrosion and Materials in Hydrocarbon Production: A Compendium of Operational and Engineering Aspects
Bijan Kermani and Don Harrop

Design and Analysis of Centrifugal Compressors
Rene Van den Braembussche

Case Studies in Fluid Mechanics with Sensitivities to Governing Variables
M. Kemal Atesmen

The Monte Carlo Ray-Trace Method in Radiation Heat Transfer and Applied Optics
J. Robert Mahan

Dynamics of Particles and Rigid Bodies: A Self-Learning Approach
Mohammed F. Daqaq

Primer on Engineering Standards, Expanded Textbook Edition
Maan H. Jawad and Owen R. Greulich

Engineering Optimization: Applications, Methods and Analysis
R. Russell Rhinehart

Compact Heat Exchangers: Analysis, Design and Optimization using FEM and CFD Approach
C. Ranganayakulu and Kankanhalli N. Seetharamu

Robust Adaptive Control for Fractional-Order Systems with Disturbance and Saturation
Mou Chen, Shuyi Shao, and Peng Shi

Robot Manipulator Redundancy Resolution
Yunong Zhang and Long Jin

Stress in ASME Pressure Vessels, Boilers, and Nuclear Components
Maan H. Jawad

Combined Cooling, Heating, and Power Systems: Modeling, Optimization, and Operation
Yang Shi, Mingxi Liu, and Fang Fang

Applications of Mathematical Heat Transfer and Fluid Flow Models in Engineering and Medicine
Abram S. Dorfman

Bioprocessing Piping and Equipment Design: A Companion Guide for the ASME BPE Standard
William M. (Bill) Huitt

Nonlinear Regression Modeling for Engineering Applications: Modeling, Model Validation, and Enabling Design of Experiments
R. Russell Rhinehart

Geothermal Heat Pump and Heat Engine Systems: Theory and Practice
Andrew D. Chiasson

Fundamentals of Mechanical Vibrations
Liang-Wu Cai

Introduction to Dynamics and Control in Mechanical Engineering Systems
Cho W.S. To

Metrology and Instrumentation

Practical Applications for Engineering and Manufacturing

Samir Mekid

King Fahd University of Petroleum & Minerals
Dhahran, Saudi Arabia



WILEY

This edition first published 2022

© 2022 John Wiley & Sons, Inc.

This Work is a co-publication between John Wiley & Sons, Inc. and ASME Press.

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, except as permitted by law. Advice on how to obtain permission to reuse material from this title is available at <http://www.wiley.com/go/permissions>.

The right of Samir Mekid to be identified as the author of this work has been asserted in accordance with law.

Registered Office

John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA

Editorial Office

111 River Street, Hoboken, NJ 07030, USA

For details of our global editorial offices, customer services, and more information about Wiley products visit us at www.wiley.com.

Wiley also publishes its books in a variety of electronic formats and by print-on-demand. Some content that appears in standard print versions of this book may not be available in other formats.

Limit of Liability/Disclaimer of Warranty

The contents of this work are intended to further general scientific research, understanding, and discussion only and are not intended and should not be relied upon as recommending or promoting scientific method, diagnosis, or treatment by physicians for any particular patient. In view of ongoing research, equipment modifications, changes in governmental regulations, and the constant flow of information relating to the use of medicines, equipment, and devices, the reader is urged to review and evaluate the information provided in the package insert or instructions for each medicine, equipment, or device for, among other things, any changes in the instructions or indication of usage and for added warnings and precautions. While the publisher and authors have used their best efforts in preparing this work, they make no representations or warranties with respect to the accuracy or completeness of the contents of this work and specifically disclaim all warranties, including without limitation any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives, written sales materials or promotional statements for this work. The fact that an organization, website, or product is referred to in this work as a citation and/or potential source of further information does not mean that the publisher and authors endorse the information or services the organization, website, or product may provide or recommendations it may make. This work is sold with the understanding that the publisher is not engaged in rendering professional services. The advice and strategies contained herein may not be suitable for your situation. You should consult with a specialist where appropriate. Further, readers should be aware that websites listed in this work may have changed or disappeared between when this work was written and when it is read. Neither the publisher nor authors shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

Library of Congress Cataloging-in-Publication Data

Names: Mekid, Samir, author.

Title: Metrology and instrumentation : practical applications for engineering and manufacturing / Samir Mekid.

Description: Hoboken, NJ : Wiley, 2021. | Series: Wiley-ASME Press series | Includes index.

Identifiers: LCCN 2021034345 (print) | LCCN 2021034346 (ebook) | ISBN 9781119721734 (hardback) | ISBN 9781119721727 (adobe pdf) | ISBN 9781119721710 (epub)

Subjects: LCSH: Metrology. | Measuring instruments.

Classification: LCC QC88 .M38 2021 (print) | LCC QC88 (ebook) | DDC 620.0028/4—dc23

LC record available at <https://lcn.loc.gov/2021034345>

LC ebook record available at <https://lcn.loc.gov/2021034346>

Cover image: Courtesy of Abderrahman Mekid

Cover design: Wiley

Set in 9.5/12.5pt STIXTwoText by Straive, Chennai, India

Contents

Preface	<i>xiii</i>
Acknowledgments	<i>xv</i>
About the Author	<i>xvii</i>
1	Fundamental Units and Constants in Metrology 1
1.1	Introduction 1
1.2	Current Definitions of the Main SI Units 6
1.3	New Definition of Seven Base Units of the SI 6
1.4	Derived International System (SI) Units 7
1.5	SI Conversion 7
1.6	Fundamental Constants 8
1.7	Common Measurements 9
1.8	Principles and Practices of Traceability 10
1.8.1	Definition of Traceability 10
1.8.2	Accreditation and Conformity Assessment 11
	Multiple Choice Questions of this Chapter 12
	References 12
2	Scales of Metrology 13
2.1	Introduction to Practical Metrology across All Scales 13
2.2	Nanometrology 14
2.2.1	Introduction and Need in Industry 14
2.2.2	Definition of Nanometrology 15
2.2.3	Importance of Nanometrology in Science and Technology 15
2.3	Standards 18
2.4	Micrometrology 22
2.4.1	Introduction and Need in Industry 22
2.4.2	Definition of Micrometrology 22
2.4.3	Examples of Micrometrology of Microparts 22
2.5	Macroscale Metrology 23
2.5.1	Standards 25
2.6	Large-Scale Metrology and Large-Volume Metrology 29
2.6.1	Introduction and Need in Industry 29
2.6.2	Definition 30
2.6.3	Verification Standards 32

2.7	Instruments Techniques	34
2.7.1	Large Coordinate Measuring Machines	35
2.7.2	Laser Trackers	35
2.7.3	Theodolite	35
	Multiple Choice Questions of this Chapter	37
	References	37
3	Applied Math and Statistics	39
3.1	Introduction	39
3.2	Scientific and Engineering Notation	39
3.3	Imperial/Metric Conversions	40
3.4	Ratio	41
3.5	Linear Interpolation	42
3.6	Number Bases	42
3.7	Significant Figures, Rounding, and Truncation	43
3.8	Geometry and Volumes	44
3.8.1	Perimeter	44
3.8.2	Volume and Area	44
3.9	Angular Conversions	44
3.10	Graphs and Plots	45
3.11	Statistical Analysis and Common Distributions	47
3.11.1	Definition of Measurement Data	47
3.11.2	Statistical Measurements	47
3.11.3	Statistical Analysis of Measurements	47
3.11.4	Probability	48
3.11.5	Sample and Population	49
3.11.6	Formulation of Mean and Variance for Direct Measurements	49
3.11.7	Mean and Variance Based on Samples	50
3.11.8	The Standard Deviation of the Mean	51
3.12	Formulation of the Standard Uncertainty and Average of Indirect Measurements	52
3.12.1	How to Determine the Measured Value and Random Error?	52
3.12.2	Repeated Measurements of One Single Quantity	52
3.12.3	Normal Distribution	53
3.12.4	Student's <i>t</i> -distribution	55
	Multiple Choice Questions of this Chapter	60
4	Errors and their Sources	61
	Introduction	61
4.1	Definition of the Error and Their Types	61
4.1.1	Systematic Errors	62
4.1.2	Random Errors	63
4.1.3	Components of Motion Error Assessment	63
4.2	Measurement Characteristics	63
4.2.1	Characterization of the Measurement	63
4.2.2	Resolution, Error Uncertainty, and Repeatability	64
4.2.3	Model of Measurement	67

4.3	Propagation of Errors	69
4.4	Sources of Errors	73
4.4.1	Static Errors and Dynamic Errors	73
4.5	Error Budget	77
4.5.1	Components of the Error Budget	77
4.5.2	Example of Error-Budget Table	78
4.6	Error Elimination Techniques	79
4.6.1	Methods	79
4.7	Model of Errors in CNC Using HTM	81
4.8	Case Study of Errors Budget	87
4.8.1	Description of the Designed System	87
4.8.2	Error Modeling and Experimental Testing	88
4.9	Solved Problems	96
	Multiple Choice Questions of this Chapter	97
	References	97
5	Measurement and Measurement Systems	99
5.1	Introduction	99
5.2	What Can Be Standard in a Measurement?	101
5.3	Definitions of Key Measurement Components	102
5.3.1	Measurement System	102
5.3.2	Measurement System Analysis	103
5.3.3	Measurement Process	103
5.4	Physical Measurement Process (PMP)	103
5.5	Difference between Number and an Analysis Model	104
5.6	Measurement Methods	105
5.6.1	Metrology and Measurement	105
5.6.2	Metrological Characteristics of Measuring Instruments	108
5.7	Instrumentation for Measurement	109
5.7.1	Background	109
5.7.2	Measurement Instrumentations	109
5.7.3	Digital Measuring Device Fundamentals	109
5.8	Non-Portable Dimensional Measuring Devices	110
5.8.1	Laser Interferometry, Application to CNC Machines	110
5.8.2	Coordinate Measuring Machine (CMM)	118
5.9	Metrology Laboratory Test for Students	140
	Multiple Choice Questions of this Chapter	146
	References	146
6	Tolerance Stack-Up Analysis	149
6.1	Introduction	149
6.1.1	Importance of Tolerance Stack-Up Analysis	149
6.1.2	Need for Tolerance Stack-Up Analysis in Assemblies	151
6.1.3	Manufacturing Considerations in Engineering Design	151
6.1.4	Technical Drawing	152
6.1.5	Definitions, Format, and Workflow of Tolerance Stack-Up	153

6.2	Brief Introduction to Geometric Dimensioning and Tolerancing (GD&T)	156
6.2.1	Notation and Problem Formulation	156
6.2.2	Dimension Types	157
6.2.3	Coordinate Dimensioning	158
6.2.4	Tolerance Types	160
6.2.5	Characteristics of Features and Their Tolerances	162
6.3	Tolerance Format and Decimal Places	164
6.4	Converting Plus/Minus Dimensions and Tolerances into Equal-Bilaterally Toleranced Dimensions	165
6.5	Tolerance Stack Analysis	167
6.5.1	Worst-Case Tolerance Analysis	169
6.5.2	Rules for Assembly Shift	169
6.5.3	Worst-Case Tolerance Stack-Up in Symmetric Dimensional Tolerance	171
6.5.4	Worst-Case Tolerance Stack-Up in Asymmetric Dimensional Tolerance	173
6.6	Statistical Tolerance Analysis	173
6.6.1	Definition of Statistical Tolerance Analysis	173
6.6.2	Worst-Case Analysis vs RSS (Root-Sum Squared) Statistical Analysis	175
6.6.3	Second-Order Tolerance Analysis	176
6.6.4	Cases Discussions	176
6.6.5	Understanding Material Condition Modifiers	178
	Appendix A from ISO and ASME Y14 Symbols	188
	Multiple Choice Questions of this Chapter	189
	References	189
7	Instrument Calibration Methods	191
7.1	Introduction	191
7.2	Definition of Calibration	191
7.3	Need for Calibration	192
7.4	Characteristics of Calibration	193
7.5	Calibration Overall Requirements and Procedures	195
7.5.1	Calibration Methods/Procedures	195
7.6	Calibration Laboratory Requirements	197
7.7	Industry Practices and Regulations	198
7.8	Calibration and Limitations of a Digital System	199
7.9	Verification and Calibration of CNC Machine Tool	201
7.10	Inspection of the Positioning Accuracy of CNC Machine Tools	202
7.11	CNC Machine Error Assessment and Calibration	207
7.12	Assessment of the Contouring in the CNC Machine Using a Kinematic Ballbar System	219
7.13	Calibration of 3-axis CNC Machine Tool	221
7.14	Calibration of a Coordinate Measuring Machine (CMM)	225
7.14.1	CMM Performance Verification	225
7.14.2	Accreditation of Calibration Laboratories	226
	Section 1: Scope and Description	231
	Section 2: Calibration Requirements	232
	Section 3: Preliminary Operations	232
	Section 4: Calibration Process	233

Section 5: Data Analysis	234
Section 6: Calibration Report	234
Multiple Choice Questions of this Chapter	235
References	235
8	Uncertainty in Measurements 237
8.1	Introduction and Background 237
8.2	Uncertainty of Measurement 238
8.3	Measurement Error 238
8.4	Why Is Uncertainty of Measurement Important? 239
8.5	Components and Sources of Uncertainty 239
8.5.1	What Causes Uncertainty? 239
8.5.2	Uncertainty Budget Components 240
8.5.3	The Errors Affecting Accuracy 240
8.6	Static Errors and Dynamic Errors 241
8.7	Types of Uncertainty 241
8.8	Uncertainty Evaluations and Analysis 242
8.9	Uncertainty Reporting 243
8.10	How to Report Uncertainty 245
8.11	Fractional Uncertainty Revisited 247
8.12	Propagation of Uncertainty 247
	Multiple Choice Questions of this Chapter 252
	References 252
9	Dimensional Measurements and Calibration 255
9.1	Length Measurement 255
9.2	Displacement Measurement 255
9.3	Manual Instruments 260
9.3.1	Caliper 260
9.3.2	Vernier Caliper 261
9.3.3	Micrometer 262
9.3.4	Feeler Gauge 262
9.3.5	Liner Measurement Tool 263
9.3.6	American Wire Gauge 263
9.3.7	Bore Gauge 263
9.3.8	Telescopic Feeler Gauge 264
9.3.9	Depth Gauge 265
9.3.10	Angle Plate or Tool 265
9.3.11	Flat Plate 266
9.3.12	Dial Gauge 266
9.3.13	Oil Gauging Tapes 267
9.3.14	Thread Measurement 267
9.3.15	Planimeter 267
9.4	Diameter and Roundness 269
9.4.1	How to Measure a Diameter? 269
9.4.2	Roundness 270
9.5	Angular Measurements 276

9.5.1	Line Standard Angular Measuring Devices	277
9.5.2	Face Standard Angular Measuring Devices	277
9.5.3	Measurement of Inclines	279
9.5.4	Optical Instruments for Angular Measurement	280
9.6	Metrology for Complex Geometric Features	282
9.6.1	Edge Detection Techniques Using a CCD Camera	282
9.6.2	Full Laser Scanning for Reverse Engineering	283
9.7	Measurement Surface Texture	285
9.7.1	Geometry of Surface	285
9.7.2	Surface Integrity	286
9.7.3	Specification of Surfaces	286
9.7.4	Sampling Length	287
9.7.5	Instruments and Measurement of Roughness	290
	Multiple Choice Questions of this Chapter	291
	References	291
10	Mechanical Measurements and Calibration	293
10.1	Importance of Mechanical Measurements	293
10.2	Mechanical Measurements and Calibration	293
10.3	Description of Mechanical Instruments	294
10.3.1	Mass Measurements	294
10.3.2	Force Measurements	295
10.3.3	Vibration Measurements	295
10.3.4	Volume and Density	296
10.3.5	Hydrometers	298
10.3.6	Acoustic Measurements	298
10.4	Calibration of Mechanical Instruments	300
10.4.1	When Is Equipment Calibration Needed?	300
10.4.2	When Is There No Need for Calibration?	301
10.4.3	Process of Equipment Calibration	301
10.5	Equipment Validation for Measurement	301
10.5.1	Is There a Need of Equipment Validation?	302
10.5.2	Features and Benefits of Validation	302
10.5.3	Process of Validation of Equipment	302
10.6	Difference between Calibration and Validation of Equipment	303
10.7	Difference between Calibration and Verification	303
10.8	Calibration of Each Instrument	304
10.8.1	Mass Calibration	304
10.8.2	Force Calibration	304
10.8.3	Pressure Calibration	304
10.8.4	Vibration Measurements	306
10.8.5	Volume and Density	307
10.8.6	Hydrometers	308
10.8.7	Acoustic Measurements	308
	Multiple Choice Questions of this Chapter	308
	References	308

11	Thermodynamic Measurements	309
11.1	Background	309
11.2	Scale of Temperature	309
11.2.1	Ideal Gas Law	310
11.2.2	Vacuum	310
11.2.3	Gas Constants	310
11.3	Power	312
11.4	Enthalpy	312
11.5	Humidity Measurements	312
11.6	Methods of Measuring Temperature	313
11.7	Temperature Measured through Thermal Expansion Materials	314
11.7.1	Liquid-in-Glass Thermometer	314
11.7.2	Bimetallic Thermometer	314
11.7.3	Electrical Resistance Thermometry	315
11.7.4	Resistance Temperature Detectors	316
11.7.5	Examples for Discussion	318
11.7.6	Thermistors	320
11.8	Thermoelectric Temperature Measurement or Thermocouples	321
11.8.1	Basic Thermocouples	321
11.8.2	Fundamental Thermocouple Laws	322
11.9	Thermocouple Materials	323
11.9.1	Advantages and Disadvantages of Thermocouple Materials	324
11.9.2	Thermocouple Voltage Measurement	325
11.10	Multi-Junction Thermocouple Circuits	326
11.11	Thermopiles	327
11.12	Radiative Temperature Measurement	327
	Multiple Choice Questions of this Chapter	329
	References	329
12	Quality Systems and Standards	331
12.1	Introduction to Quality Management	331
12.2	Quality Management	332
12.2.1	Total Quality Management (TQM)	332
12.2.2	Quality Management System (QMS)	333
12.2.3	TQM Is Essential to Complete TQS	333
12.2.4	ISO-Based QMS Certification	333
12.3	Components of Quality Management	334
12.3.1	Quality System (QS)	334
12.3.2	Quality Assurance (QA)	335
12.3.3	Quality Control (QC)	335
12.3.4	Quality Assessment	335
12.4	System Components	336
12.4.1	Quality Audits	336
12.4.2	Preventive and Corrective Action	336
12.4.3	Occupational Safety Requirements	337
12.4.4	Housekeeping Practices	338

12.5	Quality Standards and Guides	338
	Multiple Choice Questions of this Chapter	339
	References	340
13	Digital Metrology Setups and Industry Revolution I4.0	341
13.1	Introduction	341
13.1.1	What Is a Digital Measurement?	341
13.1.2	Metrology and Digitalization	341
13.1.3	Implementation Strategy	343
13.2	Data Acquisition	343
13.3	Setup Fundamentals for Measurement and Data Acquisition	344
13.3.1	Length Measurement in Open Loop	344
13.3.2	Thermal Measurement and Data-Acquisition Considerations	345
13.3.3	Data Transfer to Cloud	349
13.3.4	Internet of Things (IoT) Metrology	349
13.3.5	Closed-Loop Data Analysis- (In-Process Inspection)	350
13.4	Digital Twin Metrology Inspection	352
	Multiple Choice Questions of this Chapter	354
	References	354
	Index	357

Preface

This book is conceived for engineers and technicians operating in various industrial fields. It is also for students of mechanical, production, and other related disciplines in engineering to facilitate understanding of fundamentals of measurements, instruments and governing rules followed by learning various shop-floor required measurement techniques.

The book introduces basic needs from math, statistics, and measurement principles. It discusses errors and their sources in manufacturing while describing the various measurement instruments. Simple physical parameters such as force, torque, strain, temperature, and pressure are explained. The subsequent chapters cover tolerance stack-ups, GD&T, calibration principles in various aspects of manufacturing, and quality standards. ASME and ISO are cited according to needs and to corresponding knowledge throughout the book. Each chapter ends with a set of MCQs with answer tables to help prepare technicians and engineers for various qualification diplomas and certificates. The book adopts an illustrative approach to explain the concepts with solved examples to support understanding.

Chapter 1 of the book introduces the fundamental units and constants needed in metrology supported by the international vocabulary of metrology and international standards.

Chapter 2 emphasizes metrology that covers all scales, starting from nanoscale to large scale. Differences and relationships between scales are introduced to understand the differences and possible complementarity, while Chapter 3 introduces basic math and science background mainly to refresh memories and be a reference in case there is a need to check information. Math and science are of great importance when dealing with measurement since the inception of humanity.

Chapter 4 defines the error and its various possible sources: how error propagates in measurement, errors associated with motion, error classification, and error elimination. An estimation of error, or uncertainty analysis, is a tool for determining the performance capability of machine tools and highlighting potential areas for performance and cost improvement.

In Chapter 5, the measurement and quantification are the fundamental concepts of metrology, including the measurement system characteristics. This considers explicit and internationally accepted definitions, principles, and standards. The purpose of any measurement system is to provide the user with a numerical value corresponding to the variable being measured by the system. What are the international related standards? Examples of length measurement, parts, and machine inspection with reverse engineering are provided.

One of the most significant chapters is Chapter 6 as it introduces the tolerance stacks analysis methods. This chapter establishes uniform practices for stating and interpreting dimensioning, tolerancing, and related requirements for use on engineering drawings and in related documents under ASME Y14.5.1. A brief introduction to geometric dimension and tolerancing is followed by

Acknowledgments

This book is like a vessel of time and knowledge since much of it has been dedicated to compiling information and data, verifying and checking numerous experiments, and ensuring that knowledge is delivered in a simple manner that can be easily captured by readers.

Several specialist companies in the area of metrology and manufacturing have contributed directly or indirectly to this book; hence, I am very thankful to all of them.

I acknowledge the courtesy of Fotofab (Chicago, USA), Leica (UK), and Renishaw (UK) to use some of their materials.

I am thankful to Otila Prian and Nina Fernandez from CREAFORM (AMETEK) for their reverse engineering samples; Ross Snyder, Application Engineer from Sigmatrix (Michigan, USA) for his stack-up analysis contribution. I would also like to thank Mr. Nicolaus Spinner from SPINNER Werkzeugmaschinenfabrik GmbH in Sauerlach (Germany) for providing me with the calibration results of his machines.

My thanks are extended to my Managing Editors: Gabriella Robles and Sarah Lemore from John Wiley & Sons, Inc.

I would also like to acknowledge my MSc student Usman Khan and our departmental secretary Mino Thankachan for the hard work of formatting the chapters. Not to forget Abderrahman Mekid and Khawla Mekid for their editing and revisions.

The author would like to acknowledge the support of King Fahd University of Petroleum and Minerals (KFUPM) through the Deanship of Research Oversight and Coordination (DROC) for their support in research and resources made available to this book under BW#191006.

October 1, 2021

Professor Samir Mekid

About the Author

Samir Mekid is professor of mechanical engineering at KFUPM and chartered engineer registered with IMechE (UK) and ASME member. Prior to joining KFUPM, he was assistant professor at UMIST (UK) and The University of Manchester (UK). He has worked with Caterpillar in the design department and has been an expert EU evaluator for various countries to several European Framework Projects Programs, e.g., FP6, FP7. He was member of the Scientific Advisory Board of the Centre of Excellence in Metrology for Micro and Nanotechnology (CEMMNT) in the UK. His area of research includes machine design, manufacturing instrumentation, metrology, mechatronics, smart materials, and sensors design. He has published over 180 publications in professional journals and international conference proceedings and edited three books. He holds more than 30 patents.

During his ongoing career, he taught several courses for undergraduate and graduate students including: metrology, sensors and actuators, together with machine design. He has trained approximately one hundred engineers through short courses on tolerance stack-ups, GD&T, manufacturing systems, and materials selection. He is currently the Founding Director of the Interdisciplinary Research Center for Intelligent Manufacturing and Robotics at KFUPM.