Mechanics of Accuracy in Engineering Design of Machines and Robots

Volume I: Nominal Functioning and Geometric Accuracy

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Series Editor's Preface

Dear Reader,

The ASME Press Robotics Engineering Book Series continues to present research and engineering accomplishments in the key areas of robotics and mechanisms. This time, I am delighted to introduce a new book by Professor Vladimir T. Portman - *Mechanics of Accuracy in Engineering Design of Machines and Robots*.

Professor Portman has been a longtime collaborator of ASME Press. He is a member of the Advisory Group at the ASME Robotics Engineering Book Series. His first book on *Accuracy of Machine Tools* was published by ASME Press in 1988.

This new monograph offers a comprehensive study on accuracy as an essential problem in engineering design of machines and robots. The book presents a detailed consideration and mathematical analysis of the whole range of technical issues related to accuracy, including accuracy models and methods of assessment, form-shaping functions of various manipulators, kinematic accuracy and error analysis, and many others. The subject-matter of the book is a necessary component of mechanical engineering education.

I believe this work by Professor Portman has laid a technical foundation for advanced engineering and manufacturing of future robotic systems and machines. The book can be equally useful for researchers and graduate students, university professors teaching engineering and technological courses, and engineers and technologists in industry.

The Robotics Engineering Book Series is committed to both assisting eminent scholars in publishing their findings and introducing outstanding new researchers to the world of books in Robotics. We look forward to close collaboration with researchers and engineers around the world.

Vladimir V. Vantsevich, ScD, PhD, ASME Fellow
Founding Editor, ASME Press Robotics Engineering Book Series

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Foreword

Accuracy is one of the fundamental characteristics and one of the most important indexes of the quality of machines and robots. It significantly defines and, in turn, depends on their structure and applications. Accuracy provision, maintenance, and enhancement are permanently hot problems in modern manufacturing and manufacturing science. In the very beginning, the accuracy was considered as a purely technological problem. Both academic and engineering approaches lay with development and standardization of the metrological requirements, interchangeability, and technical measurements. In the design-related disciplines, accuracy analysis was reduced to the tolerances and fit theory [1].

As the machine structures and machine kinematics have become more and more complicated, both from structural and informativeness viewpoints, the accurate manufacture of machine parts and their dimensional chains is not sufficient for providing machine accuracy, and there is a need to consider a machine as a whole subject in its own right [2, 3]. Error propagation has to be considered from the active element AE (cutting tool, measuring probe, working instrument fitted to the end-effector, etc.) throughout all machine structure up to elements to be processed – target element (TE) – taking into account not only geometry but also kinematics errors, static and dynamic deformations, and so on. This approach is of fundamental importance for industrial robots (IR), machine tools, and coordinate measuring machines (CMM), whereat the multi-coordinate structure with complicated kinematics is accompanied by heavy demands on accuracy and productivity.

General features set off machine tools, IRs, and CMMs in a special group – the precision working machines (PWM). Interrelationships between the manipulating system and the TE and AE of the PWMs are introduced by means of an integrated object called a *form-shaping system* (FSS). The form-shaping process is dedicated to producing and/or reproducing the form and shape[1] of the TE using two types of input information: set of kinematic motions and geometry of AE. The FSS of the PWM is featured by combination of high requirement for accuracy and productivity and complicated trajectories of the AE relative to TE. Hence, the PWM simultaneously provides both the general *form* of the TE and its accurate *shape*. For example, in the machine tools, the process results in predetermined transformation of the form and shape of the blank or semi-finished item into the designed product fixed by the drawing.

The features of the machine tool FSS are methodologically formalized by means of a mathematical model called the form-shaping function (FSF) derived in the book *Accuracy of Machine Tools* [4]. Here, the FSF-based approach is extended to all PWM and applied not only to serial-kinematics machines, but also to machines with parallel and hybrid kinematics. Mathematically, the FSF presents a product of the manipulation matrix, modelling a set of the system movements, by vector of the system's AE associated with setup-related

[1]According to *Longman Dictionary of Scientific Usage* [Goldman, A., Paynem E.M.F., Longman Group, Ltd, Harlow, 1979, p. 13], "the form is the general overall character of an object." On the other hand, "the form is generalization of shape, e.g., each horse has its individual shape, but there is a large number of possible shapes that have the form of a horse. A knowledge of the form of a horse allows us to distinguish it from the other animals, and a knowledge of the shape of a horse allows us to distinguish it from the other horses".

constraints among system parameters. In this connection, the FSF models the machine hardware and bridges the real data processing done at the hardware level with virtual procedures carried out by the computerized control systems.

The effective tool for machine motion modeling is the matrix technique for multistage coordinate transformations from the AE to TE, and vice versa. The technique allows unification of a large body of data relating to errors of different physical natures aimed at their summation and further comparison with allowable values of the performance indexes formulated at all stages of machine design. As a native widening, the same matrix technique is applied to studying infinitesimal displacements, and the fact of their smallness allows significant simplification of the PWM accuracy-related problems [4–6].

Despite the fact that the matrix technique was successfully long used for a wide spectrum of industrial problems in the theory of gearing [7], mechanism and machine theory [8–10], machine tools and manufacturing technology [4–5], and robotics [11–14], in the last few decades great progress has been made by commercialization of powerful computer instruments – general software systems for mathematical and other applications – carrying out both traditional calculations and non-trivial intellectual procedures such as symbolic computations, graphical presentation of results, etc. In this book, the Mathematica® software system [15] is systematically applied to overcome mathematical and technical difficulties in the considered problems.

In terms of Mathematica, the synthesis of the FSF is reduced to ordered multiplication of a set of matrices selected (with possible repetitions) from six elementary matrices modelling elementary motions of rigid bodies. As applied to the FSF of real machines and robots, the set is combined according to coordinate codes of the machine fixing the number, nomenclature, and order of kinematic motions. For accuracy-related problems, a standard matrix of geometric and kinematic errors is added to six abovementioned matrices. The final step of the machine functioning – a setup for a specified operation – is formalized through simultaneous equations of different complexity connecting system parameters. This approach is successfully applied to the synthesis of both linear and non-linear models for serial-, parallel-, and hybrid-kinematics machines.

The book comprises the Introduction and four parts including 19 chapters with consecutive numbering, and three appendices. Each part combines a theoretical chapter with applications to machines and robots with different kinematic types. The formalized consideration is accompanied with application examples, which, as a rule, are explained with numerical solutions using realistic initial values.

In the *Introduction* (Chapters 1 and 2), the general approach to accuracy problems in manufacturing, especially to the PWM (IRs, machine tools, CMMs, etc.) accuracy is described, and basic definitions in the field are entered.

In *Part I* "Model of Nominal Functioning" (Chapters 3–7), geometric and kinematic problems relating to nominal, i.e., without external and internal disturbances, performance of the PWM are considered. After general FSS and FSF definitions, they are applied to the PWM of different kinematics types. The consideration is finished by setup problems, in which the theoretical approach is illustrated by various examples: industrial robots for welding and painting, lathes, milling machines, grinding machines, gear- and thread-cutting machines, CMMs, etc.

Part II "Geometric and Kinematic Accuracy" (Chapters 8–12) describes geometric problems and mathematical models related to actual (with disturbances) performance of PWMs with serial- and parallel-type kinematics. In Chapters 8–11, the linearized mathematical model – a budget of geometric and kinematic errors – is formulated using variation of nominal FSF and the standard form of error matrices. The developed approach is illustrated by some practical examples: error budgets of robots, machine tools, and CMMs. In Chapter 12, non-linear problems are considered by definition of two FSFs describing a pair of geometrically-closed surfaces, and some real-life examples are solved.

Part III "Stiffness-Related Accuracy Problems" (Chapters 13–16) consists of formulation of the static problems and synthesis of the stiffness-compliance matrices. The synthesis uses the Jacobian matrix obtained through transformation of the error budget expression from *Part II*. To overcome the difficulties caused by heterogeneous units of measurement of the stiffness matrix entries, a convenient performance index – the collinear stiffness value (CSV) – is applied. The CSV is used for natural stiffness evaluation in both regular and singular configurations, and the minimum CSV is applied to construct a machine workspace satisfying preliminary given stiffness limits. In particular, the CSV allows computation of a virtual protective barrier, keeping the machine from approaching the vicinity of singular configurations of the parallel-kinematics mechanisms. As examples, the CSV-based local and global stiffness features of the machines are simulated, investigated, and visualized. An approach to synthesis of the stiffness matrices for the closed chains and net of links is considered.

Part IV "Deterministic Metrology of Machines and Robots" consists of material relating to assessments and enhancement of the PWM accuracy. An approach of engineering metrology developed in the ISO and ASME standards based on coordinate methods is applied to enhance the PWM accuracy.

Appendices consist of the basic information about application of the Mathematica® software system for solution of typical analytical and numerical problems on accuracy of the PWM.

Generally, the book is built using the form-shaping function as a basic model allowing a unified approach for synthesis of the calculating model of the precision machine mechanics.

The book is issued in two volumes. Volume 1 includes Introduction, Parts I and II (Chapters 1–12), and hence, embraces the general accuracy definitions, nominal machine functioning models, and geometrical accuracy problems

The book is intended for machine and robot designers and researchers, university graduate and senior undergraduate students, and may be also useful for instructors in the mechanical engineering field for teaching processes.

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