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机器人导论（英文版）

Introduction to Robotics

（印度）S K SAHA 著

机械工业出版社
CHINA MACHINE PRESS

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序

曾几何时，机器人在人们的想象中还是一个深不可测的变形金刚。短短二十余年里，在一大批致力于机器人研究的学者和专家的共同努力下，机器人已经真实地走进了我们的生活。人们不再惧怕机器人，它作为我们的朋友，相伴在人们的左右，而这种相伴将是持续的、发展的、越来越亲密和越来越广泛的。

机器人的发展、进步以及在现实中的应用被看做是当今技术革命最伟大的进步之一，它已经成为现代生产自动化的三大支柱之一。

在工业生产中，产品的焊接、装配、搬运、喷涂、切割、研磨、检测等多种作业，已经实现了机器人替代人工操作。机器人扮演着灵巧自如、不知疲倦的“操作者”的角色，替代人工出色地完成着极其繁重、复杂、精密或者充满着危险的各种工作。在医疗卫生事业中，机器人开始替代医生，进行精细而复杂的手术，甚至可以在血管中行进，深入到人体中作业，而这种作业医生是很难完成的；在军事中，反恐及参战机器人已经能够用在实战中，显示着一个国家的国防实力；在宇宙探测中，使用登月机器人在月球、火星上完成多种科学探测；在日常生活中，服务型机器人扮演着护士、引导员、清洁工等角色，协助残疾人便利地生活，帮助人们完成繁杂的家务劳动。诸如此类，机器人已经深入到我们生活和生产的各个方面，忠实友好地帮助着人类。放眼未来，机器人的发展空间巨大，它与人类的密切程度及所能扮演的角色甚至是不可预测和想象的。

许多行业的发展离不开机器人和机器人技术的快速进步，而机器人学更是一门高度交叉的前沿学科，它包含机械学、生物学、人类学、计算机科学与工程、控制学与控制工程学、电子工程学、人工智能、社会学等。使越来越多的人对机器人发生兴趣而致力于机器人技术的研究是我的心愿。国内外许多大学开设了与机器人相关的课程。许多学者出版了不少优秀的教科书，而由 S K SAHA 教授近期出版的这本教科书，就是其中的代表之一。

本书内容包括机器人学的概况、运动学、静力分析、动力学、递推机器人动力学、控制技术、计算机、运动规划、驱动技术、传动技术及传感器技

术等，是一本全面讲述机器人学的教科书。本书内容丰富，安排巧妙，通过学生易于接受的方式解释繁杂的概念和理论，特别是通过上百个案例，理论联系实际地讨论机器人系统，由浅入深，容易激发读者的兴趣。本书插图简洁，并配有大量的练习，适合不同程度的读者选择。对于最初接触机器人的读者来说，可选择概论、传感器、执行系统、控制系统及案例等部分铺垫基础；对于较高层次的读者，其中运动学、动力学，特别是递推机器人动力学等内容具有参考价值。

我相信，本书的出版必将为我国机器人学的教育和发展，为机器人技术在我国的应用，为我国生产自动化及高技术水平的迅速提高发挥重要而有益的促进作用。

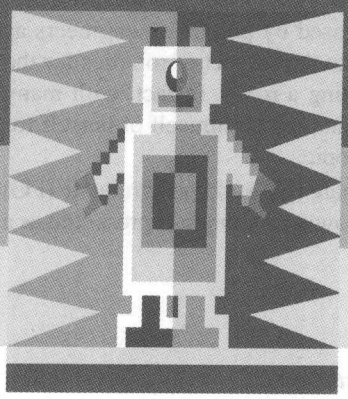
北京科技大学
郝安民

About the Author

Born in Maldaha, West Bengal (India), Prof. Subir Kumar Saha, completed most of his school studies from Vidyasagar Vidyapith, Midnapore (also in West Bengal). He completed his BE (Mech.) from RE College (now NIT), Durgapur, in 1983, followed by his Master's from IIT Kharagpur in 1985. He obtained his Ph D degree from McGill University, Canada, in 1991, and immediately joined the R&D Center of Toshiba Corporation in Japan. At Toshiba, he worked on space robot dynamics. In 1995, he returned to IIT Madras as a visiting faculty, before joining IIT Delhi in 1996 as an Assistant Professor. Since 2006, he is a Professor at IIT Delhi. Prof. Saha is a recipient of the Humboldt Fellowship and spent nine months during 1999–2000 at the University of Stuttgart, Germany. He has also been a visiting faculty to several universities abroad, e.g., McGill University, Canada; Monash University, Australia; and University of Verona, Italy.

Prof. Saha is actively engaged in teaching, research, and technology development. He established the SAE-IIT Delhi Chapter in 1997, and the Mechatronics Laboratory at IIT Delhi in July 2001. His research, consultancy, and training activities with many private companies like Asahi India, Sona Steering, Minda-Huf, SAMTEL Colour Tubes, and public sectors like BHEL, CEPC, and government agencies like DST, MIT, CWDB are a clear indication of the industries' confidence on Prof. Saha's commitment. Prof. Saha has to his credit more than 125 research publications in reputed journals and conference proceedings.

Two of Prof. Saha's recent interests are the following: (1) Popularizing the concept of engineering education through participation in robotics competitions. For example, he has been guiding the student teams of IIT Delhi since 2003 to take part in Doordarshan–Robocon competitions. The team guided by him was the champion of 2007 and represented India in the international competition held in Hanoi, Vietnam. To strengthen the concept, Prof. Saha has launched a lecture series named as *Robotics [AT]*? during his stay in IIT Madras from Dec. 2006 to Dec. 2007. So far, he has delivered eight lectures at different engineering colleges/institutes. (2) In order to popularize engineering problems faced by the rural industries of India, e.g., the carpet industries, amongst the students of IITs and other engineering colleges, he has been formulating the rural technical problems as research problems and solving them using modern tools, be they software or theory. The concept has led to several national and international journal publications, and a PhD thesis that is expected to come out as a special book in 2009 by a reputed international publisher.



Preface

Robotics is a subject that attracts many young minds, mainly due to the exhaustive portrayal of robots in many science fiction stories and popular movies. From the sixties onwards, robots have mostly been used in industrial applications, particularly, in auto industries for the welding of car bodies. Even today, the major users of robots are the automobile giants. Robots are also finding increasing applications in medical surgeries, mining and space explorations, and even at homes to take care of elderly people.

Introduction to Robotics is a book which aims to understand the underlying concepts used in designing and building a robot, and to make it work. There are a number of books available in the market which typically cater to either researchers working mainly on the analyses aspects of robots, e.g., kinematics, dynamics, control, etc., or practicing engineers interested in the feasibility study of using robots for particular applications, procurement of robots, their programming, economics, etc. In an undergraduate curriculum of Robotics, it is important that the students are exposed to both the aspects of analyses and applications. Hence, the need was felt for a book which would cover both the aspects in a lucid manner.

The inspiration to write this kind of a book, however, came almost a decade ago (April, 1999) when Prof. Gayatri Kansal from Indira Gandhi National Open University (IGNOU), New Delhi, requested me to write some instructional materials on Robotics for their students. At the same time, I found no textbook on Robotics available in India at affordable prices. Hence, I felt the urge of writing one which should have an international quality but an Indian price. This would not only help

Indian students to own a robotics book but also others from countries of similar economic conditions.

Even though the book primarily targets the undergraduate students of Mechanical and Electrical Engineering, and Computer Science disciplines registering in a course on Robotics, it can also cater to the need for an advanced-level course on Robotics for the Master's and PhD students focusing on, say, Robot Kinematics, Dynamics, and Control. The material provided in this book can be used by practicing engineers as well who may or may not have any earlier exposure to the subject of robotics for the purposes of adopting, maintaining, and even designing a robot. In fact, with many examples and exercises provided in this book, one can prepare himself or herself for any competitive examination having Robotics as a topic.

This book is meant to cater to both the undergraduate (UG) and postgraduate (PG) level students for their courses on Robotics. The following roadmap is presented as a guide to the teachers concerned:

For UG-level course

At introductory level (preferably 2nd and 3rd year students)

For Mechanical discipline, use chapters 1–6.

For Electrical and Computer Science disciplines, use chapters 1–5, 12.

At senior level (preferably 3rd and 4th year students)

For Mechanical discipline, use chapters 2, 6–8, 11.

For Electrical and Computer Science disciplines, use chapters 2, 5–6, 8, 10–11.

For PG-level (Master's and PhD students) Course

Without any exposure to a course on Robotics

For Mechanical discipline, use chapters 1–8.

For Electrical discipline, use chapters 1–5, 10, 12.

With exposure to UG-level courses on Robotics

For Mechanical discipline, use chapters 5–11.

For Electrical and Computer Science disciplines, use chapters 5–8, 10–11.

Besides, the book is suitable for courses on Mechatronics and Multibody Dynamics. For example, chapters 3–6, 8, and 10 would constitute about 75–80% of a course on Mechatronics, whereas chapters 5–6, 8–9 can cover up to 80% of a course on Multibody Dynamics with only rigid-body treatment, and about 60% of a course on Multibody Dynamics with flexible body treatment.

Several special features are introduced in this book to make it different from any other contemporary books on Robotics:

- **Natural flow of the contents**, i.e., the topics are arranged in a way so that a student can grasp the subject logically. For example, once we hear about any new thing we are curious about how it looks or how it functions. Hence, the aspects of different robots and classifications are covered in chapters 1 and 2.

Next, one would be interested to know the components of a robot. Hence, actuators and sensors are explained in chapters 3–4. Having learnt about the robot structure and its components, it is natural to be curious about how a robot moves and what are the forces causing it. Here comes the necessity of transformation, kinematics, statics, and dynamics. They are covered in chapters 5–9, respectively. This is followed by the control laws in Chapter 10. Now, the robot is ready for practical use, and a user has to decide how to move it for a particular task. Motion planning of Chapter 11 is the one which explains robot movement. Finally, it is the hardware and the software that drives the robot, which are taken up in Chapter 12.

- **Textboxes** are given to highlight historical, contemporary, and other interesting information that would help the reader to complement his or her theoretical knowledge gained from the contents of the chapters.
- **Web-/MATLAB-based exercises** are given at the end of each chapter. These exercises will help a student to keep him or her abreast with what is happening on Robotics around the world, and to get practically acquainted with how to implement the mathematical concepts for real applications.

The complete organization of the book is as follows:

Chapter 1: Introduction In this chapter, different types of robots are introduced with their application areas, population, etc.

Chapter 2: Serial Robots In this chapter, different methodologies used for robot classification of serial robots are presented.

Chapter 3: Actuators Several types of actuators, namely, pneumatic, hydraulic and electric types are explained in this chapter, along with how to select them.

Chapter 4: Sensors Sensors, the important components of a robot system, are explained here.

Chapter 5: Transformations Architectures of a robot are defined in this chapter . Mathematical description of the robot's pose, i.e., the position and orientation of its end-effector, is presented, along with the definition of Denavit and Hartenberg (DH) parameters.

Chapter 6: Kinematics This chapter forms the fundamental basis for the design and control of a robot. Equations relating the joint coordinates with the Cartesian coordinates of the end-effector are derived.

Chapter 7: Statics When the robots move slowly, it is sufficient to consider the forces acting on the robots irrespective of what motion is caused due to them. This is called statics.

Chapter 8: Dynamics Dynamics is useful for control and virtual representation of a robot system. Different methodologies like Euler–Lagrange and Newton–Euler equations of motion are derived here.

Chapter 9: Recursive Robot Dynamics* Recursive robot dynamics, a set of modern and advance algorithms, are presented here. The star (*) mark next to the title indicates that this chapter can be skipped for a course in the UG- and preliminary PG-levels. It should be taken up only in the advanced level PG course meant for Master's

and PhD students or by those who want to take up a Master's project or PhD research in the area of robot dynamics.

Chapter 10: Control Linear control, P, PD, PID control laws, stability, etc., are covered in this chapter.

Chapter 11: Motion Planning Several motion-planning aspects are discussed. Joint and Cartesian-space-based trajectory planning equations are derived in this chapter.

Chapter 12: Computers for Robots Once the algorithms are developed, it is important to implement those in electronics hardware. Hence, different robot programs like ACL, etc. , are described.

References This section contains the list of books, papers, and other sources from where different materials are taken for the use in this book.

Appendix A: Mathematical Fundamentals In this appendix, many basic concepts from linear algebra, control theory, and others are introduced which will help the readers to understand the expressions used in different chapters, namely, chapters 5–10.

Appendix B: Use of MATLAB and RIDIM Software How to use the two software applications, namely, MATLAB, and the in-house developed RIDIM, is explained here.

Appendix C: Case Studies—Student Projects Several case studies, namely, the robots developed by the students for robotic competitions, and for their UG/PG projects are explained.

The book is accompanied by the following website where the RIDIM software will be available for the uses of this book. It will also contain the solution manual for the teachers. For the benefits of the students and teachers, the website will be updated at regular intervals.

`http:// www.mhhe.com/saha/robotics`

At the end, it is my duty to acknowledge the people without whose support the book would not have seen the light of day. It has been a long journey since April 1999. But I am happy that it is finally done, and it was surely a 'slow but steady' endeavour by me. After Prof. Gayatri Kansal, as mentioned earlier, I want to remember my PG students, Mr Mahesh Sharma, Mr Subhashis Pati, Mr T Gopala Rao, Mr Tamogna Das, Mr Naveen Sukumar, for typing some part of the chapters and drawing several diagrams for this book. I am grateful to Mr S S Petkar, Mr Arvind Patle, MTech students, and Mr Pankaj Marothiya and Mr Amit, BTech students, for generating the C++ code for the in-house developed RIDIM (Recursive Inverse Dynamics for Industrial Manipulator) software which is used to solve many examples of this book and also available through this book's website. I am indebted to two of my ex-PhD students, Dr Prasad Bhangale and Dr Himanshu Chaudhary, for their use of RIDIM during their research work and testifying it as a reliable one. I want to acknowledge many students of IIT Delhi, particularly those who have been participating in the ROBOCON competitions under my supervision and showed great enthusiasm in large numbers to build the many working robots that appeared in

Appendix C. Thanks are also due to Dr I N Kar, Associate Professor in the Department of Electrical Engineering at IIT Delhi, for readily agreeing to read Chapter 10 on Control and giving me timely comments on it. My special thanks to Mr Suril V Shah, a student currently doing his PhD, who painstakingly read the chapters and helped me to prepare the solutions of the problems given in the exercises of this book. I would like to thank the many reviewers for their valuable comments which have truly raised the standard of this book.

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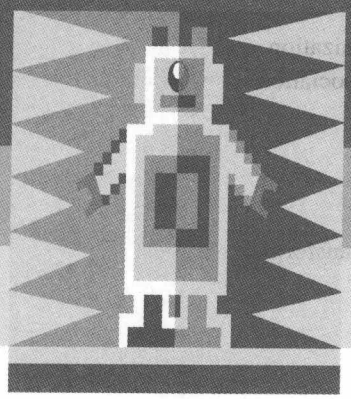
My thanks will remain incomplete if I do not mention Tata-McGraw Hill for readily agreeing to publish this book, and their executives, Ms Vibha Mahajan, Ms Shukti Mukherjee, Ms Surabhi Shukla, Ms Sohini Mukherjee, Mr Baldev Raj, Ms Anjali Razdan and many others in the background, for their persuasion and help without whom the book would not have been a reality. Finally, it is my family—wife, Bulu and daughter, Esha—who have been waiting for long to get more attention from me, and to be able to spend some quality family time with me. I am grateful for their patience, understanding, support and cooperation.

I am confident that the readers will find this book truly valuable in terms of its quality and lucid presentation so that they can easily acquire the required knowledge. However, being the first edition, it may contain some inadvertent mistakes and typos, which I urge the readers to point out to me directly (saha@mech.iitd.ac.in) or write to the book's website the address of which has been mentioned earlier. Happy Reading!

IIT Delhi
February 14, 2008

SUBIR KUMAR SAHA



List of Abbreviations

ABU	Asian Broadcasting Union
AC	Alternating Current
ADC	Analog-to-Digital converter
AGV	Automatic Guided Vehicle
BRA	British Robot Association
CCD	Charged Coupled Device
CID	Charge Injection Device
CNC	Computer Numerical Controlled
CP	Continuous Path
CPL	Computer Programming Language
CPU	Central Processing Unit
CSG	Constructive Solid Geometry
D	Derivative
DAC	Digital-to-Analog converter
DAE	Differential Algebraic Equations
DC	Direct Current
DeNOC	Decoupled Natural Orthogonal Complement
det.	Determinant
DH	Denavit and Hartenberg
DOF	Degrees of freedom

DSP	Digital Signal Processing
EL	Euler–Lagrange
EMF	Electromotive Force
GIM	Generalized Inertia Matrix
HaPRA	Hanging Planar Robotic Arm
I	Integral
ISO	International Standard of Organization
JIRA	The Japan Industrial Robot Association
JV	Joint Variable
KE	Kinetic Energy
LED	Light-Emitting Diode
LSI	Large Scale Integrations
LVDT	Linear Variable Differential Transformer
MCI	Matrix of Convective Inertia
MIMO	Multi-Input Multi-Output
MOS	Metal Oxide Semiconductor
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
NASA	National Aeronautic Society of America
NC	Normally Closed
NE	Newton–Euler
NO	Normally Open
NOC	Natural Orthogonal Compliment
ODE	Ordinary Differential Equations
P	Proportional
PD	Proportional Derivative
PE	Potential Energy
PI	Proportional Integral
PID	Proportional Integral Derivative
PLC	Programmable Logic Controller
PM	Permanent Magnet
PO	Percentage Overshoot
PR	Prismatic Revolute
PSD	Position-Sensitive Detector
PTP	Point to Point
PUMA	Programmable Universal Manipulator for Assembly
RAM	Random Access Memory
RIA	Robotics Institute of America
RIDIM	Recursive Inverse Dynamics for Industrial Manipulators
RNE	Recursive Newton–Euler
RP	Revolute—Prismatic
RPL	Robot-Programming Language

RUR	Rossum's Universal Robots
RVDT	Rotary Variable Differential Transformer
SCARA	Selective Compliance Assembly Robot Arm
SBED	Shoulder-Back/Elbow-Down
SBEU	Shoulder-Back/Elbow-Up
SFED	Shoulder-Front/Elbow-Down
SFEU	Shoulder-Front/Elbow-Up
SISO	Single-Input Single-Output
TF	Transfer Function
WMR	Wheeled Mobile Robot
VCI	Vector of Convective Inertia
VLSI	Very Large Scale Integrations
5P	Proper Planning Prevents Poor Performance