Computer Control of Manufacturing Systems

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To my wife, Aliza,
my father, Shlomo,
and in loving memory of my mother, Bathia

This book was set in Times Roman by Benj. H. Tyrrel.
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PREFACE

The decline in productivity has been one of the main concerns of American industry in the early 1980s. To increase productivity, industry has tried to apply more computerized automation in manufacturing. This has led to an increased number of computer-controlled machine tools, an appearance of industrial robots in the production lines, and the introduction of new technologies such as laser-beam machining.

The revolutionary change in factory production techniques and management that is predicted to take place by the end of the twentieth century will require unprecedented involvement of computer-controlled systems in the production process. Every operation in this factory of the future, from the product design, to manufacturing, assembly, and product inspection, will be monitored and controlled by computers, and performed by robots and intelligent systems. However, this trend toward computerized manufacturing is leading to a demand for appropriately trained engineers to design and maintain these systems. In response to this demand, the industry has established centers for manufacturing, productivity, and robotics at major U.S. universities, such as the University of Michigan, Carnegie-Mellon, RPI, MIT, University of Wisconsin, etc., with the objective of educating more engineers in the fields of modern manufacturing. Nevertheless, to educate students one needs appropriate textbooks as the basis for the development of a curriculum in the required areas. Such books are not currently available for modern manufacturing. In addition to supporting the above-mentioned centers, U.S. industry should encourage and support the writing of textbooks in the field of modern manufacturing.

The purpose of this book is to provide an introduction to the theory and applications of control in the manufacturing area. The book presents concepts of computer control as applied to stand-alone manufacturing systems, such as machine tools and industrial robots, and provides a useful approach to their implementations.

The book introduces the varied aspects of computer control of manufacturing systems:

Machines and mechanical hardware
Part programming languages
Algorithms for interpolation and control
Basics of digital control loops
Adaptive control and optimization
Industrial robots
Flexible manufacturing systems

It is unique in the sense that it covers all these aspects, while other existing books treat only certain limited areas of computerized systems. In addition, the coverage of interpolation, control loops, and adaptive control is more thorough than in other books.

The book has been used as a text for senior undergraduate students in mechanical and industrial engineering at the University of Michigan, and consequently is directed mainly toward this type of audience. The text, however, is written in a self-study format and can be readily used by engineers in industry who wish to adapt their knowledge to the growing importance of computerized systems.

At the University of Michigan the text is used in a single semester course with 2 h of lectures and 3 h of laboratory per week, yielding a total of 28 lectures. The laboratory is divided into two parts: (1) experiments in digital circuits, such as logic gates and counters; (2) programming and manufacturing of parts on a NC lathe and a CNC milling machine. The outline of the course at the University of Michigan is given in column A of the table below. The reading assignment and advanced material (i.e., additional reading for advanced students) in the table are related to this outline.

Chapter No.	Recitation time (hours)			Reading assignment	Advanced material
	A	B	C		
1	2	3	3	1-5	
2	1	2	2	2-5, 2-6	
3	5	7	7	3-3.2, 3-3.5	
4	3	5	3	4-1.1, 4-2.3, 4-3	
5	4	5	2	5-4	5-5
6	4	6	1		6-3.5
7	2	3	1	7-2, 7-3, 7-6	7-5
8	3	3	2	8-6	8-4, 8-5
9	3	3	3		
10	1	2	2	10-4, 10-5, 10-6	
Total	28	39	26		

Other universities might teach the course without the laboratory. For these universities I propose two outlines: column B for 3 h, and column C for 2 h of recitation per week. Since the laboratory is eliminated, more time is required to teach part programming (Chap. 3). The longer course emphasizes the hardware, interpolation, and control aspects of manufacturing systems, whereas the shorter course is more oriented to the traditional manufacturing approach, with a relatively higher percentage of the lectures devoted to machining and programming. Obviously, other approaches could be adopted depending upon the students' motivation and ability.

A course in programming is not a prerequisite for the understanding of any portion of the book. A general background in machining and use of cutting tools is desired. The mathematical knowledge necessary for the understanding of parts of Chaps. 6 and 7 is the Laplace transformation technique which is summarized in the appendix.

A number of examples and homework problems are given for each chapter of the book. A solution manual is available from the publisher for university professors.

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The book was written while the author served as the Goebel Chair Professor of mechanical engineering and Director of Integrated Design and Manufacturing Division at the Center for Robotics and Integrated Manufacturing, University of Michigan. The manuscript has been reviewed by Professors S. Malkin (Chaps. 2 and 8), G. Ulsoy (Chaps. 4 through 6), M. Zarrugh (Chap. 9), and R. C. Wilson (Chap. 10) at the University of Michigan, as well as by two reviewers at the McGraw-Hill Book Company, and the author wishes to thank them all for their thorough review and valuable suggestions.

In acknowledging the help of others in writing the book the author would like to thank his former students O. Masory, M. Shpitalni, G. Amitay, and M. Green for their valuable research work in CNC and adaptive control systems for manufacturing. A major part of the drawings in the book was performed by Mrs. Z. Kalmar, and the manuscript was typed by Mrs. C. Cooper and Ms. L. Hagerman.

Finally, I thank my wife, Aliza, for her encouragement, day after day, and my children, Shlomik and Esther, for their patience through the year it took to complete this book.

Yoram Koren

AWARDS

The Manufacturing Engineering Education Foundation of the Society of Manufacturing Engineers has awarded Yoram Koren the M. Eugene Merchant Manufacturing Textbook Award for 1984, for the publication of this text.

LIST OF ABBREVIATIONS

ac = alternate current
AC = adaptive control
ACC = adaptive control constraint
ACO = adaptive control optimization
ADC = analog-to-digital converter
ALU = arithmetic and logic unit
APT = automatically programmed tools
ATC = automatic tool changer
BLU = basic length-unit
BRU = basic resolution-unit
BTR = behind the tape reader
CAD = computer-aided design
CAM = computer-aided manufacturing
CIM = computer-integrated manufacturing
CLU = control loops unit
CNC = computer(-ized) numerical control
CPU = central processing unit
CRT = cathode-ray tube
DAC = digital-to-analog converter
dc = direct current
DDA = digital differential analyzer
DPU = data processing unit
DRS = data reduction subsystem
EB = end of block

ECG=electrochemical grinding
ECM=electrochemical machining
EDM=electrical discharge machining
FF=flip-flop
FMS=flexible manufacturing system
FPU=floating-point unit
FRN=feedrate number
IAE=integral of absolute error
I/O=input-output
ITM=improved Tustin method
LSB=least-significant bit
LSI=large-scale integration
MCU=machine control unit
MRR=material removal rate
MSB=most-significant bit
MT=machine tool
NC=numerical control
PM=permanent magnet
pps=pulse per second
PTP=point-to-point
RAM=random-access memory
ROM=read-only memory
r=revolution
rad=radian
rpm=revolution per minute
RWS=rewind-stop
TTL=transistor-transistor logic
TWR=tool wear rate
2-D=two-dimensional

CONTENTS

CHAPTER

ONE

INTRODUCTION

The declining cost of minicomputers and microcomputers is changing the look of the factory floor. Although the application of computers to manufacturing has been somewhat slow, distinct trends can be observed. These include an increase in the use of computer-controlled machine tools, the application of new manufacturing systems such as laser-beam cutters, and the appearance of a new generation of industrial robots in the production lines.

1-1 BASIC CONCEPTS IN MANUFACTURING SYSTEMS

Modern manufacturing systems and industrial robots are advanced automation systems that utilize computers as an integral part of their control. Computers are now a vital part of automation. They control stand-alone manufacturing systems, such as various machine tools, welders, and laser-beam cutters. They run production lines and are beginning to take over control of an entire factory. Even more challenging are the new robots performing various operations in industrial plants and participating in the full automation of factories.

It is well to keep in mind that the automatically controlled factory is nothing more than the latest development in the industrial revolution that began in Europe two centuries ago and progressed through the following stages:

1. Construction of simple production machines and mechanization started in 1770, at the beginning of this revolution.
2. Fixed automatic mechanisms and transfer lines for mass production came along at the turn of this century. The transfer line is an organization of manufacturing

facilities for faster output and shorter production time. The cycle of operations is simple and fixed and is designed to produce a certain product.

3. Next came machine tools with simple automatic control, such as plugboard controllers to perform a fixed sequence of operations and copying machines in which a stylus moves on a master copy and simultaneously transmits command signals to servodrives.
4. The introduction of numerical control (NC) in 1952 opened a new era in automation. NC is based on digital computer principles, which was a new technology at that time.
5. The logical extension of NC was computerized numerical control (CNC) for machine tools, in which a minicomputer is included as an integral part of the control cabinet.
6. Industrial robots were developed simultaneously with CNC systems. The first commercial robot was manufactured in 1961, but they did not play a major role in manufacturing until the late 1970s.
7. A fully automatic factory which employs a flexible manufacturing system (FMS) and computer-aided design/computer-aided manufacturing (CAD/CAM) techniques is the next logical extension. FMS means a facility that includes manufacturing cells, each cell containing a robot serving several CNC machines, and an automatic material-handling system interfaced with a central computer.

The new era of automation, which started with the introduction of NC machine tools, was undoubtedly stimulated by the digital computer. Digital technology and computers enabled the design of more flexible automation systems, namely systems which can be adapted by programming to produce a new product in a short time. Actually, "flexibility" is the key word which characterizes the new era in automation of manufacturing systems. Today manufacturing systems are becoming more and more flexible with progress in computer technology and programming techniques.

Manufacturing systems can be divided into small stand-alone equipment, like robots and CNC machine tools, and comprehensive systems with manufacturing cells and FMSs which contain many stand-alone systems. Both types of systems are controlled either by a computer, or by a controller based on digital technology. They can accept data in the form of programs and are able to process it and provide command signals to actuators which drive slides, rotary axes, or material-handling conveyors. In stand-alone systems and simple manufacturing cells, the input data defines the position of moving slides, velocities, type of motion, etc. In more sophisticated manufacturing cells, in which a robot equipped with a vision-aid or tactile feedback device is serving a few CNC machine tools, the system makes decisions based upon the feedback signals. In FMSs the level of decisions performed by the computer is the most sophisticated in manufacturing. Parts moving on the handling conveyor are routed to the appropriate manufacturing cell by the supervisory computer. If a particular cell is busy, the computer routes the parts to another cell which is able to perform the required operations. Decisions requiring such changes in routing are accomplished in real time by the FMS computer.

The simplest manufacturing system is the NC of machine tools, such as lathes, drilling and milling machines, grinders, etc.

1-2 FUNDAMENTALS OF NUMERICAL CONTROL

Controlling a machine tool by means of a prepared program is known as numerical control, or NC. NC equipment has been defined by the Electronic Industries Association (EIA) as "A system in which actions are controlled by the direct insertion of numerical data at some point. The system must automatically interpret at least some portion of this data."

In a typical NC system the numerical data which is required for producing a part is maintained on a punched tape and is called the *part program*. The part program is arranged in the form of blocks of information, where each block contains the numerical data required to produce one segment of the workpiece. The punched tape is moved forward by one block each time the cutting of a segment is completed. The block contains, in coded form, all the information needed for processing a segment of the workpiece: the segment length, its cutting speed, feed, etc. Dimensional information (length, width, and radii of circles) and the contour form (linear, circular, or other) are taken from an engineering drawing. Dimensions are given separately for each axis of motion (X, Y, etc.). Cutting speed, feedrate, and auxiliary functions (coolant on and off, spindle direction, clamp, gear changes, etc.) are programmed according to surface finish and tolerance requirements.

Compared with a conventional machine tool, the NC system replaces the manual actions of the operator. In conventional machining a part is produced by moving a cutting tool along a workpiece by means of handwheels, which are guided by an operator. Contour cuttings are performed by an expert operator by sight. On the other hand, operators of NC machine tools need not be skilled machinists. They only have to monitor the operation of the machine, operate the tape reader, and usually replace the workpiece. All thinking operations that were formerly done by the operator are now contained in the part program. However, since the operator works with a sophisticated and expensive system, intelligence, clear thinking, and especially good judgment are essential qualifications of a good NC operator.

Preparing the part program for a NC machine tool requires a *part programmer*. The part programmer must possess knowledge and experience in mechanical engineering fields. Knowledge of tools, cutting fluids, fixture design techniques, use of machinability data, and process engineering are all of considerable importance. Part programmers must be familiar with the function of NC machine tools and machining processes and have to decide on the optimal sequence of operations. They write the part program manually or by using a computer-assisted language, such as APT. Their program is punched on a tape by means of a perforating device, e.g., a Teletype, or with the aid of the computer.

The part dimensions are expressed in part programs by integers. Each unit corresponds to the position resolution of the axes of motion and will be referred to as the *basic length-unit (BLU)*. The BLU is also known as the "increment size" or "bit weight," and in practice it corresponds approximately to the accuracy of the NC system. To calculate the position command in NC, the actual length is divided by the BLU value. For example, to move 0.7 in in the positive X direction in a NC system with BLU = 0.001 in, the position command is X + 700.

In NC machine tools each axis of motion is equipped with a separate driving device which replaces the handwheel of the conventional machine. The driving device may be a dc motor, a hydraulic actuator, or a stepping motor. The type selected is determined mainly by the power requirements of the machine.

By *axis of motion* we mean an axis in which the cutting tool moves relative to the workpiece. This movement is achieved by the motion of the machine tool slides. The main three axes of motion will be referred to as the X, Y, and Z axes. The Z axis is perpendicular to both X and Y in order to create a right-hand coordinate system, such as shown in Fig. 1-1. A positive motion in the Z direction moves the cutting tool away

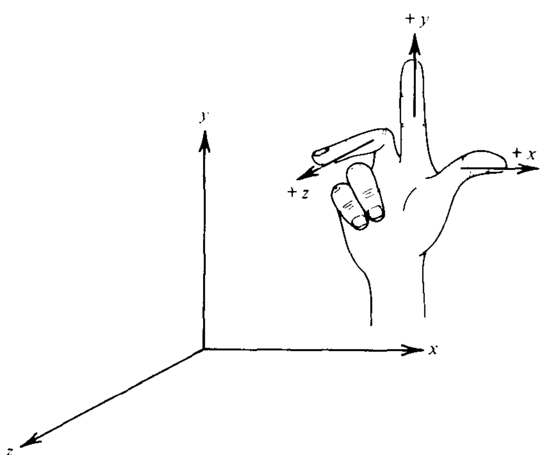

Figure 1-1 A right-hand coordinate system.

from the workpiece. The location of the origin ($X = Y = Z = 0$) may be fixed or adjustable.

Figure 1-2 shows the coordinate system of a drilling machine, a milling machine, and a lathe. In the drilling machine the X and Y axes are horizontal. A positive motion command in the drill moves the X axis from left to right, the Y axis from front to back, and the Z axis toward the top. In the milling machine shown in Fig. 1-2b the directions are as marked. In the lathe only two axes are required to command the motions of the tool. Since the spindle is horizontal, the Z axis is horizontal as well. The cross axis is denoted by X. A positive position command moves the Z axis from left to right and the X axis from back to front in order to create the right-hand coordinate system.