Precision Machine Design

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Alexander H. Slocum
Massachusetts Institute of Technology

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Preface

History has shown that precision machines are essential elements of an industrial society. Indeed, modern industry is critically dependent on precision machines ranging from those for the manufacture of integrated circuits, to machines for the manufacture of optical components, to machines for the manufacture of automobiles. There are many fine texts on the design of machine elements, and this book assumes that the reader is familiar with their concepts. However, a precision machine is an integrated system that relies on the attributes of one component to augment the weaknesses of another component. Therefore, in this book, emphasis is placed on the design of mechanical and structural precision machine components and their integration with sensor and control systems to maximize performance. In the discussion of the design of components and assemblies, emphasis is placed on how the design will affect the overall accuracy, repeatability, and resolution of the machine.

No single text can adequately cover the detailed design of mechanical, sensor, and control system components. This text is primarily concerned with the design and integration of precision mechanical components and machines. Thus with respect to sensor and control systems, basic operating principles are first discussed. Examples are then given of commercially available sensors' characteristics. Control system design is discussed in the context of how the selection of a component affects the controllability of the machine.

Design is a mixture of analysis and creative thought, and it is my intent to provide the reader with a sound theoretical background and then provide the means for the reader to experiment. When teaching design courses in the past, I always dreaded having to arrange for students to have the proper catalogs required for a hands-on design course. In addition, when working on a design, often at a client's site, I was also often frustrated when I did not have a catalog I needed in order to complete a design layout. Thus in this text, examples are given of the characteristics of commercially available components that I have found to be quite useful. I would gladly accept recommendations for additions to the examples provided.

This text also tries to address the difficult problem of how one goes from theory to practice. I have found that spreadsheets are a useful tool for helping to make this transition. In fact, spreadsheets are as far advanced over calculators as calculators are over slide rules. Thus some spreadsheets based on the design theory in the text are provided on the accompanying diskette, which is for use on a PC compatible machine with Microsoft Windows™ and Excel™ 3.0 or higher. A Macintosh disk is available from Prentice Hall. Examples of spreadsheet output are shown in Figures 1.4.4, 7.5.5, 9.2.18, and 10.8.3.

The book begins with a discussion of design philosophies for precision machines and presents in-depth case studies on the design of a machine tool and a coordinate measuring machine. Chapter 2 presents a detailed discussion on the physics of errors in machines and how such knowledge can be used to build an error budget for a machine. Chapters 3 and 4 discuss types of analog and optical sensors for use in precision machine tools.[1] Chapter 5 discusses sensor mounting methods. Chapter 6 is a detailed case study on the mapping of geometric and thermal errors in a machine tool. Chapter 7 discusses system design considerations. Chapters 8 and 9 discuss all types of linear and rotary bearings used in machine tools. Emphasis is placed on discussing fundamental properties of bearings and how the bearings behave in the machine. Chapter 10 discusses how to define actuator requirements and then discusses in detail many types of linear and rotary actuators and transmissions commonly used in precision machines.

This book is intended as a textbook for senior-level or graduate design courses and as a reference book for practicing engineers. As a textbook it assumes that the student has the level of maturity required to investigate concepts in more detail when an unfamiliar one is only briefly mentioned. Because this book in many ways is the first design book of its kind, it should be valuable to the practicing engineer as a reference and review book. In many cases detailed derivations of formulas are provided, because often the concept of the derivation helps to provide insight into the nature of the problem. The application of formulas is often illustrated with the use of spreadsheets.

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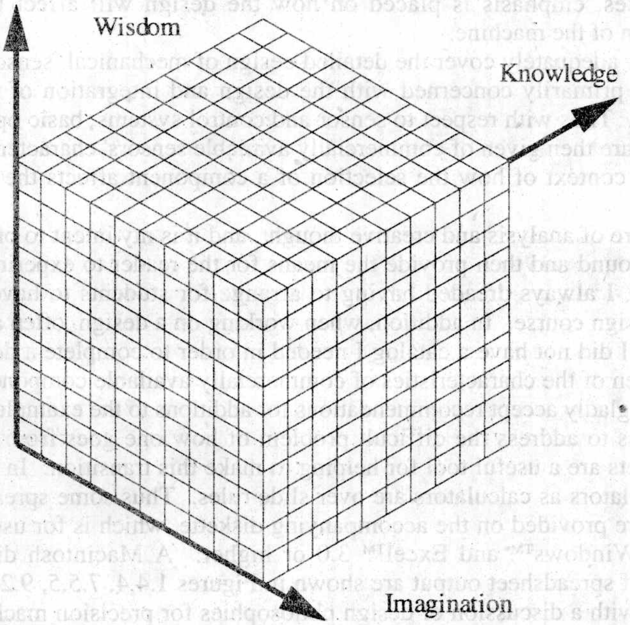
1 Chapters 3 and 4 present sensors in alphabetical order, rather than based on operating principle (e.g., inductive), because real-world engineers I queried liked the format better. In the end, the information content is the same. I welcome further comments from readers on this format.

Why should students study to become design engineers? Look at the world around you where children are starving, mentally and physically. The resources needed to help these people can only be created by adding value to natural resources. This means we need ideas for new products which in turn will lead to the generation of jobs to help lift people out of poverty. Jobs are created when there is a desire for goods that need to be manufactured. To create jobs, we need people to design products that people want, and then we need people to figure out how to manufacture, distribute, sell, and service these new products. It is my goal to help people to discover how they can better use their minds so that they can use their minds to help others.



Imagine that your mind is a vast three dimensional array of cubes which are designed to hold information. With time, the number of cubes that are filled with information grows. For example, when you read about a new type of bearing, you file the information in a knowledge cube. New methods for using bearings may be filed in an imagination cube. Past experiences with the bearing may be filed in a wisdom cube. Random or systematic search patterns through the array of cubes allows you to think of solutions to problems. During the search for solutions, often you will discover that there is a collection of cubes that do not have the contents you need; thus you may discover the need for a new invention.

It is hoped that this book will help you to fill up some of your cubes, and to learn to use your array more efficiently and more imaginatively, and with greater wisdom. It is your duty as a citizen of the world to do this. If you do not work to optimize your cube, you are slapping the face of the power that gave you your potential.

It has taken four years to write this book, and numerous individuals and companies have provided support as mentioned in the acknowledgments. Care has been taken to avoid error,[2] but I would appreciate being informed of errors discovered so they may be eliminated in subsequent printings. I also welcome suggestions for modifications to the text including suggestions for new material to be added. Problems for students are bound in a separate book, and I welcome suggestions for new problems.

Alexander H. Slocum
Department of Mechanical Engineering
Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139

[2] The author, contributors, publisher, and sponsoring companies and agencies assume no liability for any damages incurred as a result of the use of information presented in this book. A good engineer will always cross check information, particularly when applied to potentially hazardous designs.

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Contents

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Chapter 1
Introduction to Precision Machine Design

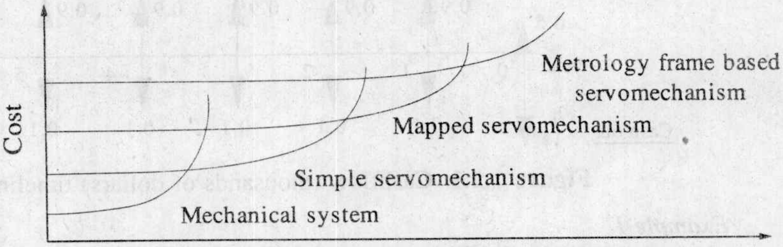
Why do you like to design machines? "It is the pitting of one's brain against bits of iron, metals, and crystals and making them do what you want them to do. When you are successful that is all the reward you want."

Albert A. Michelson

1.1 INTRODUCTION

Companies can remain competitive in world markets only if they develop new technologies and methods to keep one step ahead of the competition; maintaining the status quo is not acceptable. Hence new machines need to be designed with increased speed, accuracy, and reliability. This leads to the need for designers who have a deep understanding and love of the art and science of design.[1]

In a broad sense, the art and science of design is a potent vitamin that must be taken in balance with other mental nutrients, such as mathematics, physics, manufacturing, hands-on experience, and business skills. Most people exercise to keep physically fit so they can enhance their enjoyment of day-to-day living. Analogous to physical exercise, analysis is a form of mental pushup that trains the mind to be strong and swift. Indeed, many designs would never have even been conceived of if the design engineer did not understand the basic physics behind the process that prompted the need for a new design. Similarly, knowing how to build things can enable the design engineer to develop easily manufacturable products that are a pleasure to use. As illustrated in Figure 1.1.1, the need to integrate various disciplines means today's design engineer must be a Renaissance person. Design engineers must be more creative than their competition and more observant of the world around them. In today's tough international competitive world, if you want something, you can only obtain it with blood, sweat, tears, and design.



$$\text{Difficulty} = \frac{\text{Environment} \times \text{Load} \times \text{Range} \times \text{Speed}}{\text{Accuracy}}$$

Figure 1.1.1 Increasing difficulty often leads to the integration of engineering disciplines.

In the future, expert systems may evolve to replace mundane engineering tasks. However, it is unlikely that computers will ever be able to do creative design. If a computer program can be designed to do creative design, a computer program can also be designed to design new computer programs. Thus there will always be jobs for creative design engineers. However, high-paying engineering jobs will soon no longer be available for students who lack good creative and/or analytic skills.[2] On the other hand, the future for bright, creative, hard-working design engineers is very promising. How can new design engineers be taught to think and be creative? Integrating theory and application with real-world considerations seems to be a good method and is stressed in following chapters. The remainder of this chapter addresses broad issues including:

- Basic economics
- Basic project management skills
- Design philosophies
- The design process in the real world

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1 *"Enthusiasm is one of the most powerful engines of success. When you do a thing, do it with all your might. Put your whole soul into it. Stamp it with your own personality. Be active, be energetic, be enthusiastic and faithful and you will accomplish your object. Nothing great was ever achieved without enthusiasm."* Ralph Waldo Emerson

2 *"The hero of my tale, whom I love with all the power of my soul, whom I have tried to portray in all his beauty, who has been, is, and will be beautiful, is Truth."* Leo Tolstoi

1.2 FUNDAMENTALS OF ECONOMIC ANALYSIS[3]

The initial specifications for a machine are often generated by a company's salespeople, who are responding to requests from customers; however, it often seems as if the customer wants infinite performance for zero cost. When presented with customer requirements, it is the duty of the design engineer to sketch out realistic options and cost estimates for a family of possible designs that could meet the customer's specifications. This initial step is usually done by senior design and manufacturing engineers with experience in determining just how long and how much it will cost to design and build a new product.

The underlying principle of economic analysis is that money has different values depending upon when it is actually received or spent. The simplest example of this is a traditional passbook savings account; $1000 deposited today at 6% interest will be worth approximately $1349 five years from now. The amount of $1000 today or $1349 in 5 years is equivalent, assuming that 6% is the highest interest rate you could obtain. Because money received or paid out at some future time has a different value when considered at "what it is worth today," economic analysis is vital to decisions on machinery purchases and hence can greatly influence a machine's design. It should be stressed that there are many ways to evaluate an investment decision; the necessary brevity of this section precludes a more detailed discussion, and it is recommended that all engineers complete an engineering economics course at some point in their career.

1.2.1 Cashflow Timelines

The first step in evaluating an investment is to identify the applicable cashflows, as well as when they are expected to occur. One convenient method for visualizing cashflows is to mark them on a timeline.

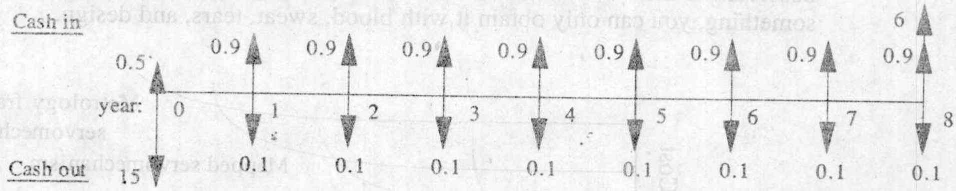

Figure 1.2.1 Cashflow (thousands of dollars) timeline for Example 1.

Example 1

An automated drill press is under consideration for purchase for $15,000. It is estimated that by replacing the old drill press with a new one, the company will save $900 per year in labor costs, but there will be an added maintenance cost of about $100 per year. The old press can be sold for $500 today, and the estimated salvage value of the new press in 8 years is $6000. Figure 1.2.1 shows the applicable cashflows as a function of time. Subtracting the "cash out" amounts from the "cash in" amounts for each given year, the result is the net cashflow timeline shown in Figure 1.2.2. The timeline demonstrates that in the beginning of the first year ($t = 0$), the company has a net negative cashflow of $14,500. In years 1 to 7 there is a net positive cashflow of $800, and in year 8 there is a $6800 positive cashflow from the sale of the machine and that year's profits. To answer the question "Should the company buy the new drill press?", it is necessary to evaluate the predicted cashflows; doing so requires an understanding of compound interest factors.

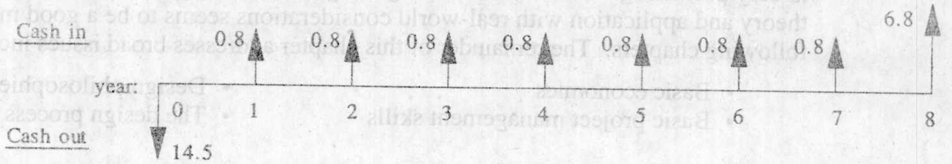

Figure 1.2.2 Net cashflow (thousands of dollars) timeline for Example 1.

3 Section 1.2 was written by Richard W. Slocum III.

1.2.2 Compound Interest Factors

The *time value of money* concept is also referred to as *interest* and *interest compounding*. The value of various types of cashflows at different times along the timeline can be calculated, using the following mathematical factors/formulas, in which *i* is the interest rate per period (e.g., *i* = 0.1 for 10% interest) and *n* is the number of periods.

• *Single-Payment Future Worth Factor*: This gives the value of a cashflow now (t = 0) at some time n periods in the future:

$$(F/P,\ i,\ n) = (1+i)^n \qquad (1.2.1)$$

• *Single-Payment Present Worth Factor*: This gives the present value (t = 0) of a cashflow that will occur n periods in the future:

$$(P/F,\ i,\ n) = \frac{1}{(1+i)^n} \qquad (1.2.2)$$

• *Uniform Series Future Worth Factor*: This gives the value (at some time n periods in the future) of a uniform series of cashflows occurring once per period:

$$(F/A,\ i,\ n) = \frac{(1+i)^n - 1}{i} \qquad (1.2.3)$$

• *Uniform Series Present Worth Factor*: This gives the present value (t = 0) of a uniform series of cashflows occurring once per period:

$$(P/A,\ i,\ n) = \frac{(1+i)^n - 1}{i(1+i)^n} \qquad (1.2.4)$$

• *Capital Recovery Factor*: This gives the uniform series of cashflows over n future periods that are equivalent to one cashflow at the present (t = 0):

$$(A/P,\ i,\ n) = \frac{i(1+i)^n}{(1+i)^n - 1} \qquad (1.2.5)$$

The product of the principal and the CRF is the payment due each period. This is the factor used to calculate the payment required to repay a car loan or a home mortgage.

• *Sinking Fund Factor*: This gives the uniform series of cashflows over n future periods that are equivalent to one large cashflow in period n:

$$(A/F,\ i,\ n) = \frac{i}{(1+i)^n - 1} \qquad (1.2.6)$$

It used to be that these formulas were too cumbersome to use, so they were tabulated for various interest rates and time periods; however, modern programmable and financial calculators and PC-based spreadsheet programs eliminate this problem.

Example 2

Fred wishes to borrow $12,000 to apply toward purchase of a new car. If the bank is offering 5-year loans at 12%, what will Fred's monthly payment be? The *Capital Recovery Factor* is used here. The period is 1 month, there are 60 periods in 5 years, and the interest rate per period is 12%/12 months per year, or 1%: Monthly car payment = (A/P ,1%,60) × $12,000. The A/P factor is 0.02224, so Fred's payment is $266.88 per month.

Example 3

Mary is presently a sophomore in college and she wishes to begin a monthly savings program that will accumulate enough money so that by graduation she will be able to make a down payment on a home. She has 29 months until graduation and estimates that \$11,000 will be required for a down payment. If interest rates on deposits remain constant at about 6%, how much should she save each month? The *Sinking Fund Factor* is used here. There are 29 periods and the interest rate per period is 6%/12 months per year, or 0.5%/period: Required monthly savings = (A/F,0.5%,29) × \$11,000. The A/F factor is 0.0321, so Mary must save \$353.10 per month.

1.2.3 Economic Analysis of Projects

Economic evaluation of projects involves a determination of whether a series of cashflows over time, as shown in the timeline of Example 1, meet a company's investment criteria. Usually, a company's management establishes a minimum interest rate that investments must provide in order to be considered worthwhile.[4] It is generally safe to say that this minimum rate is somewhere near the rate for long-term government Treasury bonds (which are virtually risk-free), plus a factor for estimated risk. For example, if Treasury bonds yield a risk-free 9%, why should the company invest in a high-risk project unless that project will yield at least the T-bill rate plus, say, 3% to cover the increased risk? In this instance, management would thus set the minimum interest rate at 12%. The minimum interest rate is referred to by a number of terms including:

- Desired (minimum) rate of return
- Discount rate
- Hurdle rate
- Desired (minimum) yield

All refer to the same interest *i* as discussed above.

There are two principal methods for determining if a series of cashflows meet an established minimum rate of return:

1. Calculate the rate of return that results from the cashflows, and compare it to the minimum rate of return. Calculation of rate of return is a matter of setting up the applicable cash flows with the appropriate factors (P/A, A/F, and so on), and then solving for the interest i in the expression for the sum total of all cashflows (in and out): $PW_i = 0$ = sum of cash flows discounted at some interest rate i.

2. Calculate the present worth of the cashflows using the minimum rate of return to discount (or bring back) to the present cashflows that occur in future time periods. This analysis calculates the present worth of the investment, expressed as PW_x where x is the percent minimum rate of return, or discount rate. If the PW_x is positive, it is known that the proposed investment's rate of return is greater than the established minimum. If the PW_x is negative, it is known that the proposed investment's rate of return is below the established minimum.

Because calculation of the rate of return is an iterative process, it is time consuming for all but the simplest cashflows. Calculation of the PW_x is relatively straightforward and returns a quick go or no-go decision on the proposed investment.

Example 4

The management of the company in Example 1 has established a minimum rate of return of 12% for all projects. Should the new drill press be purchased? First, set up the equation as shown in Figure 1.2.3. Note that cashflows out of the company are, by convention, expressed as negative numbers, and cashflows into the company are expressed as positive numbers. Since the PW_{12} of -\$8102 is negative, the proposed new drill press does not meet the company's required investment criteria, and the press should not be purchased. Many investment decisions are analogous to the preceding example; the key to accurate investment analysis is to correctly identify the applicable cashflows that will result from a proposed investment.

$$PW_{12} = -\$14{,}500 + \$800(P/A,12\%,7) + \$6{,}800(P/F,12\%,8)$$

No multiplier since t = 0.	P/A gives present worth of the cashflow for years 1-7.	P/F gives present worth of the cashflow in year 8.

Figure 1.2.3 Present worth calculation for Example 4.

4 The danger in this method is that it is sometimes applied without including such effects as quality and employee and customer satisfaction.

1.2.4 Machine Cost Determination

There have been countless machines designed to perform tasks in a technically elegant manner. However, only those machines that can operate in a cost-effective manner will become commercial successes.[5] There are two components to the cost of any machine: the fixed cost component and the variable cost component. Fixed costs are defined as those costs that are continually present because the machine is there; thus they occur irrespective of whether the machine is producing products. Examples of fixed costs include: cost of required spare parts inventories, certain maintenance costs, and cost of floor space. Variable costs are costs incurred that are directly related to the amounts of product produced. Examples of variable costs include: material, labor, most maintenance costs, and utilities (i.e., power) used by the machine. The task of comparing various alternative machines is mathematically simple, consisting generally of addition, subtraction, and multiplication of the various cost components. The difficult part of the problem is identifying which cost components are relevant to a given situation and developing realistic estimates of production rates, wages, interest rates, taxation rules, and so on.

Initial Capital Expenditure

Initial capital expenditures are the up-front costs associated with placing a given piece of machinery into service. There are numerous expenses to consider, many of which are easily overlooked by engineers in the early stages of design. Nonetheless, they are real costs that will be included in evaluations by potential purchasers. Examples of initial capital expenditures include:

- Cost of the machine itself.
- Cost of freight and rigging; machines that are oversized to the point of not being truckable on a standard-size truck may incur significant extra shipping costs.
- Cost of spare parts inventory.
- Cost of training employees to operate and maintain the machine.
- Cost of physical plant modifications, such as power sources, structural changes to accommodate weight, size, vibration, noise, and so on.

Awareness of these factors can help a design engineer to minimize a machine's associated costs. In many cases this can be done without changing the machine's basic design or increasing its cost. For example, if one is designing a large electric-powered press that utilizes an innovative method of high-speed operation, the design engineer can:

- Make the machine so that it comes apart into major subassemblies for ease of shipping and installation.
- Utilize gearboxes, motors, and other general components that are also used on other machines of this type. This reduces the purchaser's need to develop another entire supply of spare parts for the machine, and may simplify the purchaser's training expenses for repair technicians. For instance, if research shows that 75% of presses use "Brand X" motors with "Brand D" speed controllers, there is some merit in this machine also doing so, unless there is a sound technical or economic reason to do otherwise.
- Utilize control logic systems similar to other machines of this type, unless there is a sound technical or economic reason to do otherwise. This will reduce operator training expenses associated with the machine.
- Design the component parts' layout for serviceability and operator comfort and safety.

For this example, the cost of implementing these suggestions would probably be small, yet they may result in a more economical machine design than, for instance, a press that requires double-wide trucks for transport, has many hard-to-find motors and gearboxes, and has an operator control system unlike most other machines of its type.

Fixed Maintenance Costs

Fixed maintenance costs are costs to maintain the machine that are not dependent upon the volume of production. For example, if the lubrication oil must be changed "every month or 250 hours of operation," the cost to do so is a fixed maintenance cost, assuming that the machine is used on a 5-day-per-week, single-shift production schedule. In general, fixed maintenance costs are not as significant as variable maintenance costs for machines that are in relatively constant use.

5 *"A hen is only an egg's way of making another egg."* Samuel Butler

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