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Fundamentals of Dimensional Metrology

FOURTH EDITION

Connie Dotson · Roger Harlow · Richard L. Thompson

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PREFACE

In the fourth edition of *Fundamentals of Dimensional Metrology,* we have attempted to improve the pedagological flow of the text and to incorporate metric measurement devices and concepts. You should use this text as a Dimensional Metrology course textbook or as a reference if you are working in the field of Dimensional Metrology. It is also intended that, as an instructor, you can apply the procedures and concepts to any educational level and across disciplines: Machine Shop, Tool and Die, and Quality Control courses and programs should find equal application of this text.

As the Preface to the second edition stated, ". . . the principles have not changed, ignorance of these principles and the cost of this ignorance increasingly impact modern industry." This statement is even truer now with the reduction in Quality Control inspection efforts and an increase in placing the responsibility for Quality Control on the shoulders of the individual worker. The individual *must* have complete familiarity with the basics, techniques, and devices within the Dimensional Metrology field.

Industry is currently struggling with many concepts: Total Quality Management (TQM), Computer Integrated Manufacturing (CIM), Statistical Process Control (SPC), Just-In-TIME (JIT), and Shop Floor Metrology Systems, which we have addressed as necessary. In addition, because industry is working to adapt the metric system to all measurements, we have emphasized metric measurements in many examples.

FEATURES OF THE FOURTH EDITION

The features of the third edition remain with improvements, including many suggested from peer reviews.

- The chapter on measurement language has been moved to Chapter 2, so that current metrology terms are introduced early in the text.
- Many of the drawings and illustrations have been updated and corrected.
- Portions of theoretical material have been reduced and replaced by practical application examples to improve clarity and relevance for students.
- Chapter 3 has updated references for geometric dimensioning and tolerancing practices.
- Chapters 13 and 16 have been updated to include use of laser measurement technology.

- Chapter 17 has been extensively updated to include more information on current technologies employed in coordinate measuring machines, including the use of CMMs on the shop floor.
- Chapter 18 has been updated to include current applications and the use of multisensor systems.

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The content of this text has been extensively influenced by the comments and input from those who have used and reviewed the text. We would sincerely appreciate continuing to receive comments from the users of the text.

The author would also like to express gratitude for the guidance and editorial expertise of John Fisher, Juanita Brown, and Araceli Popen. Their suggestions contributed extensively to the improvement of this edition.

ABOUT THE AUTHOR

Connie Dotson is a professional trainer, with strong technical and metrology experience.

Connie is a Journeyman Tool and Die Maker, and holds a Master of Business Administration degree with emphasis on Adult Learning. Over the past 15 years, Connie has taught technical, apprentice, software, and metrology courses in colleges and private industry. These courses include Blueprint Reading, Drafting, Tool and Die Design, Fixturing, Machinery's Handbook, Geometric Dimensioning and Tolerancing, Coordinate Measuring Machine operating software, and Vision metrology softwares. She has been a speaker at national conferences, including the American Society for Training and Development, providing workshops on Train-the-Trainer, and interactive teaching skills. Connie also volunteers with the junior achievement program and high school and trade school career workshops.

CONTENTS

CHAPTER

1 MEASUREMENT AND METROLOGY

OBJECTIVES

When you, as the learner, have carefully read and studied each section, answered the chapter questions, and thought about the material presented, you should be able to:

- ❑ Explain why measurement is similar to a language and essential for communication in industry.
- ❑ Describe how measurement is essential at many levels, such as skilled craftsmanship, production manufacturing, and scientific research.
- ❑ Explain why the principles of measurement are stressed in this text rather than the care of instruments.
- ❑ State why metrology is essential to most career development.
- ❑ Explain the role of metrology in national and international trade.
- ❑ Define the application of measurement acts to inspection techniques.

OVERVIEW

We can trace measurement to the early Phoenicians when they were trading around the Mediterranean Sea. They had to develop methods of equating a quantity of a product to an amount of currency. All measurements are relative in that they are comparisons of some standard to the item being measured.

We have all heard the old saying "Measure it twice and cut it once." From an economic standpoint this comment makes a great deal of sense. The measurements we make with accuracy and precision will reduce the waste of materials, and will further contribute to the production of high-quality items. Costs affect the way companies compete for sales and customers. The competition is both global and keen. Thus, a simple error in measurement when setting up a machining center could cost a company a contract, loss of work and, if sufficient, loss of jobs and closure of the company.

BACKGROUND

In our modern industrial society we need to be able to produce manufactured goods that are made to exacting standards, able to be repaired with interchangeable parts, and be consistent in their production so that costs can be reduced.

1–1 MEASUREMENT AS THE LANGUAGE OF SCIENCE

Metrology is the science of measurement, and measurement is the language of science. It is the language we use to communicate about size, quantity, position, condition, and time, Figure 1–1.

A language consists of grammar and composition. Grammar is a science; composition, an art. This book unfolds the grammar of measurement, but only experi-

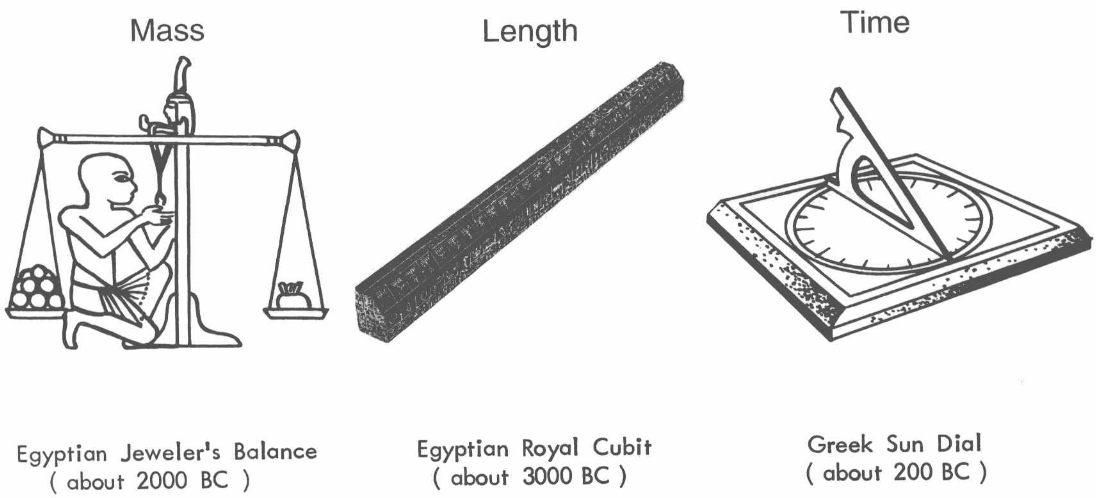


Figure 1–1 Without metrology there is no science. This principle has been recognized since the early years of human history as these examples of fundamental quantities show. Each era produced its equivalents.

ence will develop the art. The language of measurement is much easier than French or Russian, because we already have considerable skill in it. Properly applied, this skill can decrease the effort and improve the results from work, hobbies, or continued studies.

Not all persons are equal in measurement skill. It is not difficult to imagine a person with a Ph.D. handling a micrometer like a C-clamp, nor the director of quality assurance warming gage blocks by rubbing them prior to use. Their ability to use data may exceed their ability to gather data. It is for this reason that the ability to measure reliably is very important. It is also for this reason that the ability to apply the language of measurement is important for personal development.

There are three reasons why we all need measurements. First, we need measurements to make things, whether the things we make are of our own designs or somebody else's. This applies to all skilled workers and artisans. Second, we need measurements to control the way other people make things. This applies to ordering an engagement ring, fencing a yard, or producing a million spark plugs. Third, we need measurements for scientific description. It would be impossible to give definite information to someone else about aircraft design, electron mobility, or the plans for a birthday party without measurements.

Figure 1–2 Whenever you make a measurement, its accuracy, or lack of it, may be traced to the International Bureau of Weights and Measures in Sevres, France.

A course in strength of materials will not make a person a bridge designer, but full grasp of the course could make a bridge designer exceptional. So is it in measurement. The principles in this text are, at their best, generalizations. They are useful only when related to specific measurement situations. These are as diversified as the needs of mankind.

1-2 THE USES OF MEASUREMENT

MEASUREMENT TO MAKE THINGS

In the late 1700s, Scotsman, James Watt (1736–1819), was jubilant that Englishman, John Wilkinson (1728–1808), had perfected the horizontal boring machine with such great precision, that it could bore the cylinders for Watt's steam engine to a tolerance of "one thin shilling." Wilkinson's machine could bore a 144.78 cm diameter (57 in.) cylinder to an accuracy of about 1.59 mm (1/16 in.). This unheard-of accuracy made Watt's dream of the steam engine a reality. This same accuracy in today's automobile cylinders would make it an intolerable oil burner, if it would run at all, or a simple picture frame out of square even to the eye.

Apart from the need for measurement in mass production, measurement is necessary whenever we make anything. The Native American Indian making a flint arrow had an approximate idea of the size needed dependent on his target. This is true in all the crafts and skilled trades, Figure 1–2.

Unless numerical values are established, things that must fit together can be made only by trial and error. Even today, some fitting is expected on one-of-a-kind jobs such as making a complex die, outfitting an ocean liner, or rebuilding an automobile engine. Measurement skill reduces hand fitting. The better the ability to measure, the faster skilled jobs are completed. Of course, the measurements required in one field may be very different from those required in another. However, no craftspeople can be higher skilled than their ability to measure.

The International System of Units has seven base units and two supplementary units. From these base units, several derived units with special names are extracted. The seven base units are listed in Table 1–1.

Quantity	Symbol	Name
Length	l	Meter (m)
Mass	m	Kilogram (kg)
Time	t	Second (s)
Electric Current	I	Ampere (A)
Temperature	T	Kelvin (K)
Luminous Intensity	I	Candria (cd)
Amount of Substance	m	Mole (mol)
Plane Angle		Radian (rad)
Solid Angle		Staradian (sr)

TABLE 1–1 Base Units

Plane angle and solid angle are additional units. The meter was defined in 1983 by the International Committee on Weights and Measures as the "distance light travels in a vacuum during a period of 1/299,792,458 m/s." This is the same as saying light travels at 299,792,458 meters per second.

Strictly speaking, *metrology* is the measurement of mass, length, and time. From these primary quantities are derived all of the quantities involved in mechanics, electronics, chemistry, and hydraulics. This text is restricted to *mensuration*. Mensuration is the branch of applied geometry that is concerned with finding the length of lines, areas of surfaces, and volumes of solids from certain simple data of lines and angles. This includes those measurements that are required to use tools and instruments for designing, building, operating, and maintaining material objects, whether they are refrigerators or cyclotrons. This is the reason for the term *dimensional metrology*.

The basic principles of dimensional metrology are fascinating as well as practical. They epitomize the scientific method that characterizes this modern age of manufacturing more than anything else. These principles rely on logic and reflect philosophy. They spring into life whenever we produce goods or search for scientific knowledge.

It is most unfortunate that it is difficult for anyone to achieve experience in all of the special roles of measurement. The resulting parochialism has held back progress. As an example science struggles along with antiquated reliance on vernier calipers while becoming superbly proficient with optical instruments. Industry, on the other hand, long ago made the vernier instruments obsolete for critical work, and is increasing its dependence on optical and laser instruments. There are three general areas to which the basic principles may be applied: communications about measurement, acts and applications of measurement, and codification of measurement.

MEASUREMENT TO CONTROL MANUFACTURE

An extension of an individual making things is the control of the manufacturing process by others. This is the role of manufacturing, including inspectors and quality control personnel.

There always has been an inspection department in industry, although it was the machine operator at one time. In today's industrial environment the concepts of Total Quality Management (TQM) are resurrecting the fact that the production worker will also be the inspector.

Because of pride in their work and ambition to get ahead, the workers of today set a pace and quality in keeping with the end use. This approach works for one article as well as high-quality, high-quantity production runs.

In order to mass produce, tasks have become specialized over the years, requiring skilled people who perform only a portion of the job, but who do it well and fast. This led to the "piece-part" system of manufacturing in which the worker's pay was determined by the number of parts completed. The worker was paid only for the satisfactory parts and it became necessary to determine what was satisfactory. Therefore, gages were required, as were the services of an arbiter who would pass on what was acceptable and what was not. Thus, the role of the inspector was created.

In today's workforce we see groups of people producing a product or providing a service where determined acceptability is based on customer desires and requirements. Each team member is, to some extent, a specialist as well as a generalist and capable of contributing to the overall result.

Interchangeable manufacture does not stop at the factory walls. Parts are made in widely scattered plants and even in different countries. The result is a refinement of the language of measurement. Not only is the ability to measure to very small dimensions required, but the measurements must be based on an accepted standard or the parts will not interchange. *Standard of length is as important as the means of measuring.*

With today's technology, "good enough" has been pushed beyond the borders of belief. Yesterday's standards and instruments can fulfill their new functions only through the imagination and ingenuity of the team members. Working with statistics and computers, they regulate every phase of modern life that requires mass-produced products.

However, no matter how capable their computers are or how specifically their calculations can predict production, everything the team does depends on the information they receive. These data are the accurate measurements provided by previous operations. The team inspector is crucial to the entire arrangement. Each team member depends on the other, and we all depend on the expertise of the entire team. Their responsible employment is needed at every level, from production inspection to comparing master standards to the wavelengths of light. Those who specialize in measurement lead adventurous lives, because they are present at both the births and deaths of new products and new scientific achievements. Few decisions are made without their valued counsel.

MEASUREMENT FOR PROGRESS

Human progress has been paced by the ability to measure. This is even truer today than in antiquity. Measurement is truly a universal language. Where every other communication must be translated, all industrial people today recognize the same standards of length, and convert in and out of each other's systems of measurement.

This has been due largely to industrial progress, but it is needed as much in pure science as it is in applied science. There is no way one research worker can repeat the work of another without specific measurements, Figure 1–3. This is quite true throughout all branches of science, from astronomy to biology. (In fact, the micrometer was invented for use in astronomy, not shop work.) For many years, progress was slowed and goods were more expensive by the "zero of ignorance." This refers to the

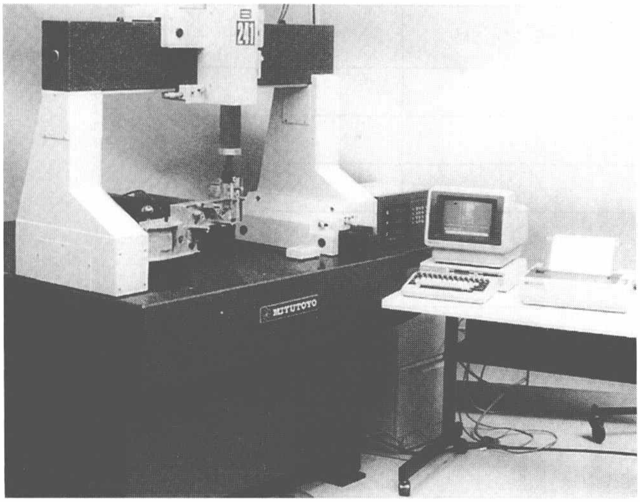


Figure 1–3 The computer has vastly extended the potential for metrology, but the results are no better than the data fed into it. Multiple axis machines such as this coordinate measuring machine benefit in particular from the computer's ability to manipulate metrological data. *(Courtesy of Mitutoyo Manufacturing Co., Ltd.)*

extra decimal place added to the tolerance of a part because the designer was not sure how accurate the dimension really had to be. In few fields is that old luxury still possible. In most products today the quality control instruments are already at their limits—there is no zero of ignorance left.

As never before, the ability of an engineer, a chemist, a biologist, or a physicist and the technicians who support them to test ideas hinges on an understanding of measurement.

1-3 ■ COMMUNICATIONS ABOUT MEASUREMENT

Measurement depends on communication. It utilizes completely arbitrary units and terms. Furthermore, it is a social activity because unless there is a need to communicate, there is no need for measurement. The only legitimacy that measurement units have, whether inches, meters, or archines (a Russian standard length equal to 28 in. or 71 cm), lies in their acceptance and usefulness. This acceptance requires the cooperation of other people; hence, the social aspect.

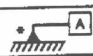
Communication requires language. Thus, we must first determine that all parties understand the meanings of certain terms. Two terms are central to final understanding: *precision* and *accuracy.* Roughly, precision pertains to the degree of fineness, whereas accuracy pertains to conformity with an accepted *standard.*

It is generally agreed that people are more efficient when they understand what they are doing. Therefore, the basic language of measurement is always expanding to meet new requirements. In the twentieth century an entire vocabulary for expressing *dimensions* and *tolerances* has come into use. Along with it have come the symbols that represent the terms, Figure 1–4. These have become very important to the practitioners of metrology.

Communications are subject to many serious distortions. Personal as well as cultural biases add to the propaganda and what is called "disinformation." In measurement we know these as errors. For data to be useful we must recognize the errors and quantify them.

A study of such errors is beneficial beyond the gathering of data for production or research, because we are bombarded with similar errors in all areas of our daily lives. As in measurement, some are easily recognized, but others are so accepted that it takes a strong will to admit their possibility. The bald-faced lie is expected from the high-pressure salesman, but how hard is it to question the university professor, doctor, or statesman—particularly on points with which we agree? Similarly, we know that visible and invisible dirt or loose clamps will impair measurements, but it requires conscious effort to keep in mind the equally damaging effect of parallax, temperature fluctuations, cosine error, and hysteresis to name a few. *Error always exists.* The only questions are: *How much? Where? To what effect?* and, *What can be done about it?*

The precision of measurements often may be checked by *repeatability.* The accuracy can only be checked by comparison with a higher standard. Because of the importance of the convertibility and interchangeability of measured data, the methods of traceability to the international standard have been

SYMBOL FOR:	ASME Y14.5M	ISO
STRAIGHTNESS	⏤	⏤
FLATNESS	⏥	⏥
CIRCULARITY	○	○
CYLINDRICITY	⌭	⌭
PROFILE OF A LINE	⌒	⌒
PROFILE OF A SURFACE	⌓	⌓
ALL AROUND		 (proposed)
ANGULARITY	∠	∠
PERPENDICULARITY	⊥	⊥
PARALLELISM	//	//
POSITION	⌖	⌖
CONCENTRICITY (concentricity and coaxiality in ISO)	◎	◎
SYMMETRY	⌯	⌯
CIRCULAR RUNOUT	•↗	↗
TOTAL RUNOUT	•⌰	⌰
AT MAXIMUM MATERIAL CONDITION	Ⓜ	Ⓜ
AT LEAST MATERIAL CONDITION	Ⓛ	Ⓛ
REGARDLESS OF FEATURE SIZE	NONE	NONE
PROJECTED TOLERANCE ZONE	Ⓟ	Ⓟ
TANGENT PLANE	Ⓣ	Ⓣ (proposed)
FREE STATE	Ⓕ	Ⓕ
DIAMETER	Ø	Ø
BASIC DIMENSION (theoretically exact dimension in ISO)	[50]	[50]
REFERENCE DIMENSION (auxiliary dimension in ISO)	(50)	(50)
DATUM FEATURE		 or 

• MAY BE FILLED OR NOT FILLED

Figure 1–4 Revisions to the American Society of Mechanical Engineers Dimensioning and Tolerancing Standard (ASME Y14.5M-1994) are intended to improve national and international standardization.