Chapter 1
Introduction to Metrology

1.1 Basic Terms

Before we talk about the various methods of dimensional metrology, it is helpful to provide a few definitions and basics.[1–5] This information is covered in more depth in other texts but is presented here for the benefit of the reader. To start with, dimensional metrology as used in this book is the art of determining distances, sizes, and shapes of objects in one, two, or three dimensions. This book will not address the measurement of color, material density, strains, or any other matter of the material state. What will be considered are the metrics of performance of measurement. To understand these metrics, it is useful to define a few terms.[6–9]

Repeatability
Repeatability is the consistency of the measurement output for a given measure, often reported at a percentage of variation based on standard deviation. A sensor can have a high precision, i.e., it outputs very small numbers or many decimal places, but if the same physical quantity gives rise to a different number each time, the output cannot be used to control the process or ensure quality. Repeatability is effectively a measure of how reliable the results are over the long haul. To repeat a number does not ensure that it is correct in the eyes of the technical community at large, but at least the number is consistent, as shown in Fig. 1.1.

Resolution
Within the terms of metrology, the *resolution is the ability of the system to distinguish two closely spaced measurement points*. In simple terms, resolution is the smallest change you can reliably measure. What prevents this measure from being reliable is typically noise. If the signal associated with a small change in the measurement is overshadowed by noise, then sometimes we will measure the change, sometimes we will not measure the change, and sometimes we will measure the noise as a change in the measurement, and therefore the measurement will not be repeatable.

Figure 1.1 Illustrative descriptions of repeatability, resolution, and uncertainty, which are different aspects of a measure.

Uncertainty (or Accuracy)

Uncertainty is the comparison of a measurement to some primary standard that is accepted by the industry and justifiable by the laws of physics. Uncertainty is the means to ensure that two different sensors provide numbers that relate to each other in a 'known' manner. When the supplier makes a part according to some dimension and tolerance, the original equipment manufacturer (OEM) needs to be able to measure that part and get the same results as the original manufacturer specifications; otherwise, the part may not fit mating parts made by other suppliers.

If a number is not repeatable or resolvable, it cannot be proven to be accurate. A popular rule of thumb is to use the "rule of ten," or what I call the "wooden ruler rule." That is, if you need to know that a dimension is within a defined tolerance, you need to measure it to 10 times better than the resolution of that number to ensure that it is accurate.

Range and speed

Two other important parameters for comparison of measurement methods that are more practical in nature include:

- *dynamic range*, which is defined in this book as the range of measurement compared to the resolution of the measurement and
- *speed*, which is how long it takes to make a measurement, which might mean measurement of a point, an area, or a displacement.

These parameters, along with other practical considerations such as size, ease of use, and cost of a particular method can vary greatly and change over time as they are less a function of theoretical limits and more a function of factors such as execution, changing support elements (like computers), and the application. Although it is difficult to be definitive or always up to date, this book discusses the current state of these parameters as well.

As the topic of this book is optical methods of measurement, we will also define a few basic optical terms that are used to define optical systems. Figure 1.2 shows these terms graphically.

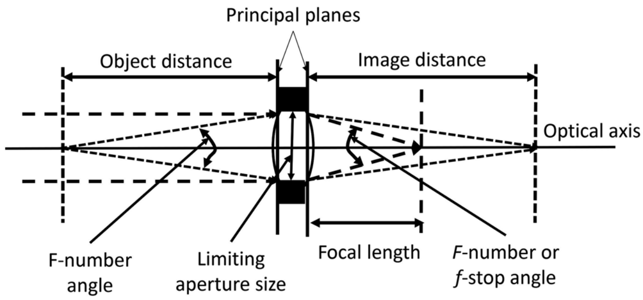

Figure 1.2 The basic parameters of a simple lens or imaging system defined relative to the principal planes of the system.

- The optical system *principal planes* can be defined as the locations where the light ray path of incoming and outgoing light intersect or "appear" to bend. Any optical system imaging system can be defined with the use of an initial principal plane, a final principal plane, and the distance between the two planes. These planes are perpendicular to the optical or central axis of the optical system.
- The *focal length* of a lens or lens system is defined as the distance from the final principal plane along the optical axis where light rays coming to the optical element from infinity intersect at what is called the focus of the lens.
- If light rays come from some location closer than infinity at some *object focal distance* measured from the initial principal plane, an image is formed at the *image focal distance* measured from the final principal plane.
- The *f*-number (or *f*/#) of the lens is the focal distance, whether from infinity or some finite source, divided by the *limiting aperture* of the imaging system. This *f*-number is a measure of the cone of light collected from the source or focused at the image. If the measure is to the focal length distance, the *f*-number is often called the *f*-stop of the lens, as is marked on photographic lenses. This cone angle of light can also be defined by the sine of the half-angle of the light, called the numerical aperture. For small angles, the *f*-number is approximately the inverse of two times the numerical aperture.

1.2 Methods of Optical Metrology

The use of light to obtain dimensional information has seen significant growth in the past 30 years.[3,4] Using light to measure optical components has been around for over a hundred years but is just recently seeing potential in manufacturing. This change for optical metrology has been driven by two primary factors. First, computing power improvements have moved the analysis of optical metrology data from long, painstaking hours of skilled interpreters looking at patterns that only a select few understood, to near instantaneous interpretations ready for use by the manufacturer. An example is the interpretation of interferometric data. For many years, skilled opticians would use templates to look at the strips seen in an interferometer to attempt to estimate errors. Today, simple computer programs can make detailed maps and generate aberration numbers in a few seconds. The other factor driving the change in optical metrology is the requirements imposed by parts being manufactured at speeds much faster than at any other time in history.

Industries such as primary metals, automotive, textiles, and even plastic extrusion have found that simply being 'functional' just isn't enough. Every part needs to fit properly, experience the right type of wear, provide the right aerodynamics, and provide the best lifetime. The expanded use of digital models has driven lower cost by avoiding overdesign, but also has left less margin of error. Computers and the Internet have provided the tools to deal with large amounts of information very quickly within the concepts embodied by the popular industry term "Internet of things." But for all this information to be useful, the measurements must be complete, fast, and correct.

Manufacturing has employed contact probes and gages in regular use since the turn of the 20th century.[1] Coordinate measurement machines (CMMs) have advanced from slow, laboratory systems to automated factory floor systems. But even with those improvements, 100% inspection is rarely feasible with CMMs alone. Many fixed gages have now become computerized as well, providing a dedicated part gage, with computer output at the speeds needed.[7,9,10] In some cases, this has led to rooms full of gages and billions of dollars in expenses each year. At these costs, the small-batch run envisioned as the main tool of flexible manufacturing systems just is not economically feasible.

Even with these computerized advances, the high speed and high tolerances of new parts have pushed past the limits of these more traditional sensors. The flexibility of optical metrology methods to check hundreds of points on one part and then a different set of points on the next part all in a matter of seconds has provided a capability not previously available with traditional fixed gages.[11]

So, just what is this field of optical metrology?[12] Optical metrology takes on many forms. The optical component may be a laser, a white-light source, and fast sensor, or a camera. In each case, some change in the way light reflects or otherwise interacts is used to make the measurement. The basic mechanisms of optical metrology include a change in:

1. the amount of light that is reflected or transmitted;
2. the direction or location of the light;
3. the nature of light such as phase, coherence, or polarization; and
4. the distribution of the returned light (such as focus).

These simple mechanisms are shown in Fig. 1.3 and provide a wide range of optical tools that allow the measurement of a wide range of subjects—from

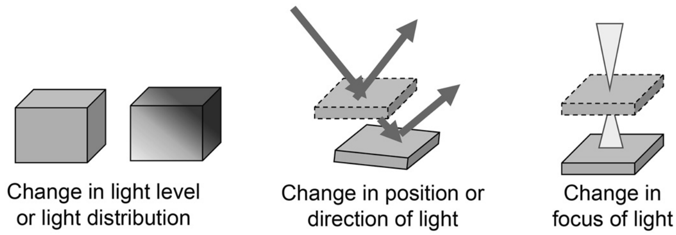

Figure 1.3 Simple illustrations of the basic mechanisms of changes in light characteristics in response to dimensional measurement.

liquids to mountains. The following chapters discuss the methods that make use of these basic mechanisms in order to measure dimensions.

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