1

Optical Metrology Overview

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1.1 Introduction

Modern tools of manufacturing add new flexibility to how parts can be made. Multiple axes of motion, multi-pass operations, fine control in some areas, and fast sweeps in others are all means to improve the speed, quality, and flexibility of manufacturing. A key set of tools that is needed to work within this new multidimensional environment is metrology, and this metrology tool set must be up to the task of providing the type of information needed to control manufacturing systems.

FIGURE 1.1
Mechanical gages are traditionally used for measurements of manufactured parts.

In old times of manufacturing, metrology was often left as a last step in the manufacturing process. The part was designed based upon two-dimensional (2D) views and a fixed set of primitive features such as holes, flat surface, or edges. As each feature was made, there might be a go, no-go check such as using a plug gage to verify if a drilled hole was of the right diameter, but little other in-process measurements were done. When the part was complete, a limited set of key parameters might be checked using micrometers or surface plate tools such as mechanical gages (see Figure 1.1). But ultimately, the check of the correctness of the part was purely functional. Did the part fit where it was supposed to fit, and if not, could we do minor adjustments (without measurement) to make it fit?

For many years, many automotive parts would be sorted into large, medium, and small bins. As a system like an engine was assembled, parts would be tried out. If a cylinder is a little large for the bored hole that was made, try the smaller size. This fitting process was commonplace and accommodated the many manual operations and variability such as tool wear that would lead to small part variations.

This type of metrology began to change with the introduction of more automated processes such as computer numerical controlled (CNC) machining and robotic assembly. With CNC machining, it was possible to make parts in a much more repeatable manner. To accomplish this repeatability, touch probes, probes that determine a part location by touching the part, were added to many CNC machines to check for such things as part setup position and tool offsets due to either the mounting of the cutting tool or wear on the tool.

The touch probe works by using the actual machine tool's electronic scales that are used by the machine to position cutting tools (see Figure 1.2). The probe is loaded into the spindle or tool holder of the machine tool just like any cutting tool. However, in this case, the machine slowly moves the probe toward the part surface until the probe just touches the surface. The probe acts like a switch. As soon as the probe tip is displaced slightly

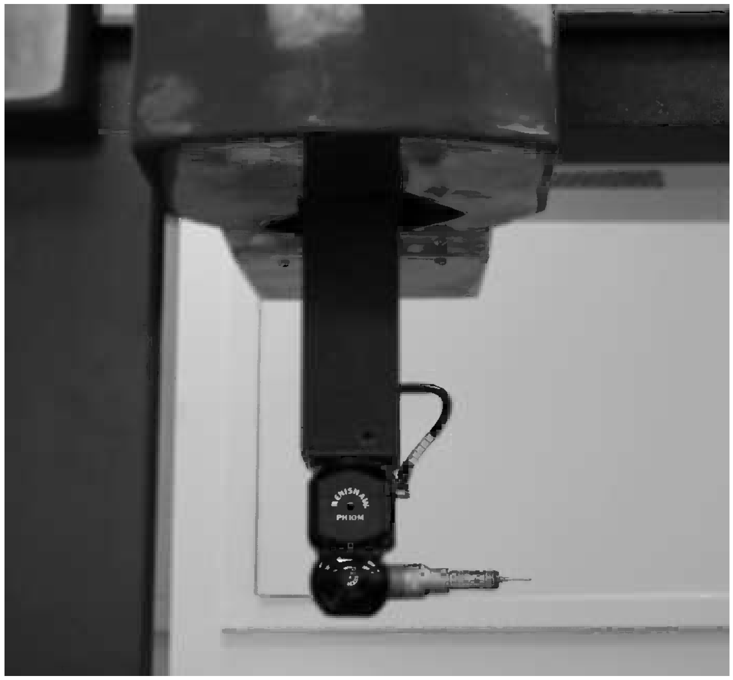


FIGURE 1.2
A touch probe used to set the offsets on a machine tool.

by the touch on the part, it sends a signal telling the machine tool to stop. The machine tool then reads out the position of the touch probe using the built-in position scales needed by the machine to do automated machining.

This type of touch probe check allows the CNC machine to verify the position of a feature on the part, and to use any changes from the ideal location to correct or offset the path, the actual cutting tool will need to take to do the desired machining. This process can be slow. On a high value part, such as a critical part in an aircraft engine, where a small mistake may mean the part cannot be used, costing the manufacturer thousands of dollars, it is not unusual for the CNC machine to spend 10%–20% of the machining time checking features or positions with touch probes.

On a CNC drill, manufacturers have learned to use power monitoring to verify the drill is actually cutting something and may even look for a characteristic signature of how the power to a motor should change during a processing operation. With a modern manufacturing process such as a laser material processing, this type of monitoring based upon force or vibration feedback, resulting from the physical interaction of the tool and the part, may not be possible as there may not be any such physical interaction. Different interactions, not involving contact, may be needed to monitor the process.

With the right information, the flexibility of modern manufacturing can offer many advantages to correct small problems with a part during processing, providing a high-quality part every time. In many cases, even issues of tool wear become irrelevant with modern tools such as laser or electro-discharge machining (EDM). Making sure the process is done right makes possible the opportunity of highly repeatable manufacturing results.

Fortunately, there is a wide range of metrology tools capable of measuring points, lines, or surfaces at speeds thousands of times faster than a touch probe or manual operation that can be integrated into these new energy field manufacturing systems. The rest of this chapter will review these metrology tools, including the pros and cons of each of them. Finally, we will look at how new capabilities being developed today may provide even more options for the future of manufacturing that may provide the means to completely rethink manufacturing methods and strategies.

1.1.1 Sensor Technology Justification

The advent of automated manufacturing processes has placed new demands on the controls to those processes. In the past, the human machine operator was expected to monitor the manufacturing process and insure that the finished product was of high quality. High-quality products have long been associated with the skilled craftsman. Now, after a period of growth in automation that often compromised quality for volume, there is a new emphasis in industry on the production of "quality" product. To be competitive in today's marketplace requires not only that you make your product cheaper but that you must also make it "better" than ever before. The drive toward quality has forced a rethinking of the role of sensors in manufacturing and how the results of those sensors are used.[1–6] The days of the skilled craftsman with the caliper in his back pocket are giving way to untended machines which must perform all of the tasks formerly done by the craftsman that were taken for granted.

Machines may be getting smarter, but they are still a long way from the sophistication of the skilled craftsman. When a person looks out the window and sees a tree, they recognize it as being a tree no matter whether it is a pine or an apple tree, in full bloom or dead. That person has used a variety of sensors and knowledge to recognize the tree. He may have used stereo perception to estimate its size and distinguish it from a painting, he may have heard leaves rustling in the breeze, or he may have caught a whiff of apple blossom. The actual interpretation of these data about the tree has drawn upon many years of experience of seeing other trees, smelling flowers, or listening to noises in the woods. What actually distinguishes the sound that leaves make in the breeze from that of a babbling brook or a slow-moving freight train? These may seem obvious questions to you or me, but a computer has no such experience base to draw upon. The sensory data received by a machine must be of a very succinct nature. The data must be unambiguous in what it means and there needs to be a clear understanding of what the machine must do with that information.

1.2 Understanding the Problem

For a sensor to be effective as a tool for controlling quality, the implementation of the sensor must be right. At first glance, we may say we want to measure the wear of the cutting tool, but is that really what we are interested in measuring, or is it the part surface finish or shape we want to measure? A dimensional measure of a diameter may seem an obvious application for a micrometer but what of the environment and materials handling in the system? Should the micrometer become broken or bent, we will receive incorrect data. The error may be obvious to the operator, but will not be obvious to a deaf, dumb, and blind machine. The right technology must be matched to the task. There are many ways to make a measurement, but only one of them will likely be the best, and even then may not be optimum. Beyond the technology, implementation of sensors requires

- An organizational strategy, incorporating such points as management acceptance and cost justification
- Training of and understanding by the operators who must maintain the equipment
- Interfacing to the environment of the physical plant, users, equipment, etc.
- Some means of using the information provided by the sensor

A sensor without a useful "receptacle" for the sensed data is like a leaky faucet, at best an annoyance and at worst a waste of money.

The purpose of sensing and metrology is to measure some parameters which will help the manufacturing process, either by keeping the machines at their peak through machine monitoring or by verifying the quality of the finished product at each step of operation to minimize the cost of a mistake. It has been said that "any good inspection system should be self-obsoleting." Throwing away the bad parts is at best a stop gap measure in most cases. To insure quality, we would like to improve the process so that is does not make bad parts in the first place! Once we no longer make bad parts, we should no longer need to sort the parts.

1.2.1 Basic Terms for Sensor Technology

The first step in applying sensors is to understand the language. There are many good references that describe these terms in more detail, so only a general review will be given here.[1,2,7]

1.2.1.1 Repeatability

Of primary interest in an automated process is the issue of repeatability. A sensor can have a high precision, that is, output 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 insure quality. Repeatability is effectively a measure of how reliable the results are over the long haul. To repeat a number does not insure that it is correct in the eyes of the technical community at large, but at least the number is consistent.

Example 1—Photoelectric Proximity: A typical photoelectric proximity sensor has a repeatability of 0.001 in. This means that if a particular part is brought in proximity of the sensor in a consistent manner over and over, the sensor will produce a particular signal, typically a simple switch closure. The switch will close at the same part position each time. However, if the part is brought to the sensor from a different direction, the sensor switch will likely close at an entirely different part location. The sensor was repeatable, but does not alone tell whether the part is in the correct place.

Example 2—Electrical Scales: Electrical scales are used on many systems to measure linear distances. Such a scale may have a repeatability of 1 μin. but an accuracy of 50–80 μin. (2 μm). At a particular location on the scale, the sensor will produce the same reading very consistently, but the relation between that point and some other point on the scale is only correct, by conventional standards, to the 0.00008 in. In this case, the repeatability alone is not sufficient to provide the information we want.

1.2.1.2 Resolution

An often quoted number as related to measurement is resolution. In 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 being a change in the measurement, and therefore, it will not be repeatable.

Example 1—Photoelectric Proximity: A rating of resolution for a photoelectric proximity sensor might be 0.01 in. but still have a repeatability of 0.001 in. In the case of a proximity sensor, the resolution indicates to how small of a change of part position the "switch closure" of the sensor can be adjusted. This does not mean the sensor will actually measure the change, just as the human eye cannot measure stars in the sky, but the sensor will detect it.

Example 2—Electrical Scales: The resolution of an electrical scale is generally set by the counting mechanism used to read the scale. In this case, one count may be on the order of 20 millionths of an inch (20 μin.), but four counts would be needed to make a reliable reading. Therefore, the resolution is necessarily better than the actual usable measurement obtained from the sensor.

1.2.1.3 Accuracy

The issue of accuracy is an even more difficult one to address. To metrology, accuracy requires that the number be traceable to some primary standard, accepted by the industry and justifiable by the laws of physics. Accuracy is the means to insure that two different sensors provide numbers which relate to each other in a "known" manner. When the supplier makes a part to some dimension and tolerance, the original equipment manufacture (OEM) builder wants to be able to measure that part and get the same results, otherwise the part may not fit mating parts made by other suppliers.

Example—Electrical Scale: The accuracy of the scale was given before as around 0.00008 in. If we have two scales with this accuracy and we measure a common displacement, they should both provide the same reading. In fact, if we compare the reading of the scale for any displacement it can measure, we should be able to compare that number against any other sensor of the same or better accuracy, such as a laser interferometer, and get the same reading. Accuracy provides the only common ground for comparing the measurements across many sensors and from company to company. In comparison, the optical proximity is, for this reason, not accurate at all, but rather just self-consistent.

The need for common numbers is the reason for industry-wide "standards" of measurement. When the woodworker is making that cabinet you ordered for your dining room, he can make the door fit just right and not need to know exactly the size of the door. The woodworker is using the same measures for the door and the opening, even if it is just a piece of cut wood, so it does not matter if his measures do not match anyone else's. He needs resolution, but not accuracy. He is effectively inspecting the part to fit, not to tolerance. When a similar situation occurs between a supplier of car doors and the auto manufacturer such that the doors are made to one measure and the door openings to another, it requires the time and expense of a worker with a "big hammer" to bring the two measures into agreement. A common standard of measure is not being used in this example, so the measurements are not accurately related.

Obviously, if a number is not repeatable or resolvable, it cannot really 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 good to a certain number, you need to measure it to 10 times better than the resolution of that number to insure that it is accurate. I call this the wooden ruler rule because the number 10 seems to relate more to the resolution of divisions on a wooden ruler or the number of fingers of the metrologist than any statistical significance.

A more statistical rule of measurement is the 40% rule (ala Nyquist sampling) which says that you must sample the number to within 40% to know which way to round it for the final answer. The 40% rule seems to inherently imply a rule of ten in any case, but it can slow down the “runaway specification.” When these rules of ten start getting piled on top of each other, a measure can easily become over specified to the extent that you may be measuring to a factor of a hundred times more accuracy than the process can manufacture to in any case, leading to the leaky faucet of information.

As an example of how rules of 10 pile up, consider a part that must be correct to 0.01 in. A tolerance of 0.001 in. would be placed on the part’s dimensions to insure a 0.01 accuracy. To insure meeting the 0.001 in., that part is measured to an accuracy of 0.0001 in. In order to assure the 0.0001 in. accuracy, the sensor is required to have a resolution of 0.00001 in. or 10 μin., to measure a part whose dimension is important to 0.01 in., a factor of a thousand times coarser. The actual measurement tolerance, and not the rule of thumb, is what we must keep in mind when specifying the sensor needed.

An interesting question arises when a surface dimension is specified to be measured to an accuracy which is much finer than the surface finish of the surface. Since we want the number to be repeatable by anyone, perhaps we must ask whether we measure the top of the surface finish “hills,” the bottom of the surface finish “valleys,” or perhaps “which” hill or valley we should measure. It is for this reason that a location relative to a common datum (e.g., 1 in. from the leading edge) should be specified for the measurement for the tolerance to be meaningful.

1.2.1.4 Dynamic Range

The dynamic range relates to the “range of measurements” that can be made by the sensor. There is often also a standoff (the physical dimension from the sensor to the part), which is not part of dynamic range, and a working range which is the high and the low value of the measurements. The working range of a sensor divided by the resolution, the smallest change that can be measured, gives an indication of the dynamic range. If the dynamic range is 4000–1, this implies there are 4000 resolvable elements that can be distinguished by the sensor. If this is now read out as 8 bits of information, which only describes 256 numbers, the significance of the 4000 elements is moot unless only a limited part of the entire range is used at a time.

Example 1—Optical Proximity: The working range of a typical proximity sensor might be 3 in. This means the sensor will detect a part as far away as 3 in., as well as closer. However, once set to a particular detection level, the proximity sensor tells nothing about where the part is within that range. Proximity sensors are inherently on–off devices and as such do not have a range of measurements or dynamic range to speak of but rather only a static standoff range.

Example 2—Electrical Scale: Scales typically produce a measurement along their entire distance of use. So if we have a measurement resolution of 0.00004 in., and a working length of 4 in., the scale would have a dynamic range of 100,000–1. Since with a scale we are concerned with actually accuracy, it may be more relevant to consider the dynamic range with respect to the usable number produced. So, if we have an accuracy of 0.00008 in., and a range of 4 in., the dynamic range is just 50,000–1 (about 16 bits of information). The dynamic range of measurement sensors is typically very important in considering how good of a measure you can obtain over some range. With many modern sensors, this range is in fact limited to the digital data that can be used, so a 16 bit sensor can only describe 64,000 measurements over whatever range you chose to measure. Beyond the basic range, sensors such as scales are often cascaded together to obtain a larger dynamic range.

1.2.1.5 Speed of Measurement versus Bandwidth

A similar question of dynamic range arises with respect to speed of measurement. When we speak of the speed of measurement or the rate at which we can make a measurement, we are referring to the rate at which actual data points can be completely obtained to the extent that they are usable as a measurement of the part. The bandwidth of the sensor is not necessarily the speed at which data can be obtained but relates to the electrical or other operating frequency of the detector.

For example, a 2000 element array of detectors can have a bandwidth of 5 MHz but to get the measurement requires that the 2000 elements be read out, each in 200 ns, sequentially, and before that happens, the detectors may require some integration time to obtain the energy or force they are sensing. The result would be a detector which can be read out every 1 or 2 ms, with a bandwidth of 5 MHz. The bandwidth will generally limit the signal to noise ratio that can be expected. For optical detectors, the response is actually specified for a specific bandwidth and changes as the square root of the bandwidth. If you want to know the speed of the data output, ask for the data output rate and not the bandwidth. Speed can be over specified by looking at the wrong number. Many controllers can only respond on multi-millisecond or multi-second time frames, so using a detector which tells you of impending disaster a millisecond before it happens becomes hindsight in reality.

1.3 Process Control Sensors: Background

Modern production lines are making and moving parts at speeds much faster than any other time in history. The standards of six sigma quality have demanded much better control than ever over even small, cosmetic defects. Industries such as primary metals, automotive, textiles, and even plastic extruders have found that having about the right dimensions and being "functional" just isn't enough. Manufacturers are finding that any appearance of quality problems, be it pits and scratches or a bad overall appearance, can mean rejections of full lots of product, costing millions of dollars to a company, and affecting their bottom line. At modern speeds of production and tight defect tolerances, human inspectors have trouble keeping up to production. Studies have shown that even after 2 h of such work, the human inspector becomes distracted. The same mind that provides for high-defect discrimination can "fill in" missing pieces, even when they are not present.

After seeing 1000 parts with a hole in the center, part 1001 will appear as though it has a hole, whether it does or not.

Computers and the Internet have provided the tools to deal with large amounts of information very quickly. The same limitation that requires that a task be completely spelled out for a computer insures that it will find that missing hole in part 1001 as consistently as in part 1,000,001. In addition, the simple act of reporting a variation, inherent to the philosophy of statistical process control, becomes a quick transfer of data over Internet lines, in the digital form needed for SPC software. So, computer-based inspection and monitoring not only affords the programmable flexibility demanded by flexible modern manufacturing but also provides the quick data collecting and tracking abilities needed for high-speed repetitive operations.

Simple sensors such as touch probes have been used in traditional metal-cutting machines for some years. There are many instances where sparse occasional data are all that is needed, and as such, touch probes are a reasonable tool to use. A touch probe, however, does not provide any measurement itself; it is merely a switch that says "I have touched something." The measurement actually comes from a machine axis, such as on a traditional milling machine. With the advent of energy field manufacturing, the machines often do not have the traditional tool holder and may have a much different type of axis system than is needed to slowly approach and touch a part with a touch probe. So, although touch probes can still be a viable tool, the flexibility and speed of noncontact optical metrology probes will generally be a better fit with the demands of flexible manufacturing methods.

Optical noncontact sensors made for large standoffs include optical systems such as machine vision, laser-based probes, and three dimensional (3D) mapping systems.[3,4,8] We will review the details of these optical-based measurement systems within the context of fast, flexible manufacturing methods, then contrast some of the application challenges and errors with the contact-based systems.

1.3.1 Machine Vision Sensors Overview

Manufacturing has employed contact probes and gages in regular use since the turn of the twentieth century. Coordinate measurement machines (CMMs) have gone 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. For loading these gages, robotic systems are able to load and unload parts in a highly repeatable manner, so good that they have revolutionized the electronics fabrication industry. But this option means a dedicated set of gages for each part, demanding rooms full of gages and billions of dollars in expenses each year.

At the billion dollar costs of fixed electronic gages, 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 machine vision to check hundreds of points on one part, then a different set of points on the next part, all in a matter of seconds has provided a capability not before available with traditional fixed gages.

The progression of machine vision as a tool in process control and metrology within the manufacturing process has not been an overnight occurrence.[9] Early applications of machine vision as a sorting tool and part ID aid were little more than a hundred thousand dollar bar code scanners. High-speed, low-cost, and flexible changeover in the fast-moving computer and semiconductor industries has acted as a catalyst to increase the speed of

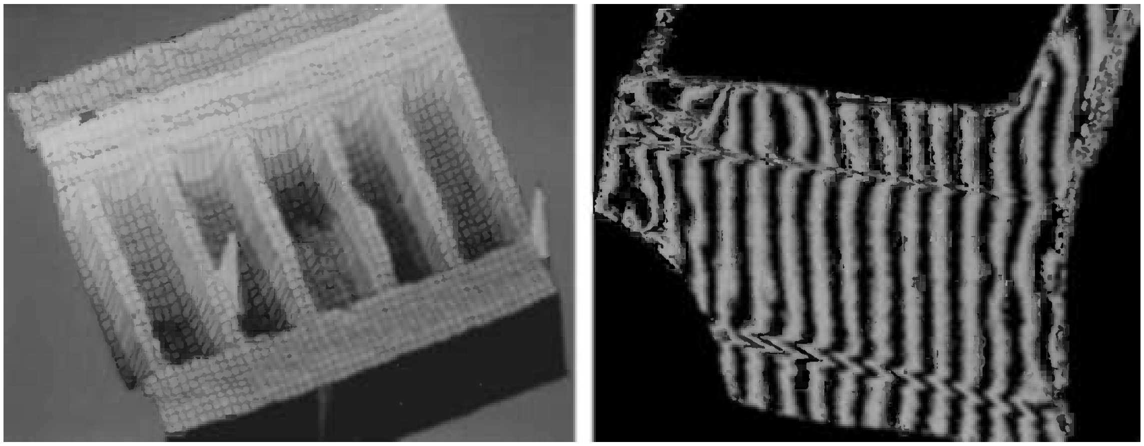
FIGURE 1.3
The electronics industry has made extensive use of machine vision for part inspection to allow automated processing and assembly. Verifying all the leads are in the right place on a chip and the chip number allows a robot to automatically place it on a PC board.

these machine vision systems. Early machine vision systems using simple processor chips progressed to dedicated integrated circuits (ICs), gate arrays, digital signal processing (DSP) chips, and now integrated internet devices. The dynamic nature of the electronics and semiconductor market segment has kept these areas as the largest current application of machine vision, still accounting for over 50% of sales in a multibillion dollar worldwide machine vision market today (see Figure 1.3). New processors, special lighting and cameras, and advanced algorithms have all greatly improved the capabilities of machine vision.[10] The competition for tighter quality control will push vision technology into even the most conservative metal-cutting and metal-forming operations and when applied to flexible manufacturing may offer a natural marriage of fast, new manufacturing technologies. Machine vision will be discussed in more detail in Chapter 2.

1.4 3D Sensors: Overview

Just as we can now easily scan a 2D image into computer memory, the tools are commercially available to do the same with a 3D part. There are many tools available for digitizing 3D shapes. Some applications may require a very high density of data over very small areas to capture a complex shape. A quarter or dime would be an example of such a part. For other applications, the sizes in question may be quite large, with only minimal variations from one area to another (see examples in Figure 1.4). There are systems available on both ends of this spectrum and at many points in between. Choosing the best tool for a particular job is the challenge to be met by the designer. Many of these systems have been made to address a range of applications from robot guidance to surface structure analysis.[11,12] No single system is likely to ever address all the possible applications for 3D contouring in the near future.

For example, a system capable of describing the work area of a robot doing welding may be looking at an area of a few square meters to a resolution of a few millimeters, while a surface laser treatment system may be looking at a few millimeters to submicron levels. The density of data is not the same for all applications either. If the concern is the presence of high spots on a part that may lead to cracking, then the sensor cannot skip points. In the



(a) (b)

FIGURE 1.4
For small features, very high density of 3D data may be needed (back of a penny: a), while on larger parts, high resolution may be needed (a car panel: b), but not as much area resolution.

case of many robotic manufacturing applications, only the distance to the part and where one or two edges are located are important. In these latter cases, perhaps just a line or a small array of a dozen points will be sufficient.

One of the early applications of using 3D information was the Consight system developed by General Motors.[13] The purpose of this system was not to measure the 3D shape of the part, but rather to take advantage of the known difference in the 3D shape to sort the parts. The parts in this application were gray metal castings on a gray conveyor belt. These parts were hard to distinguish using only 2D images. The 2D silhouette was not necessarily different, and the features of the gray, cast parts were too low in contrast to pick out of a typical 2D view. In this case, the density of data needed was small. A single white line projected from an angle provided a changing cross section silhouette of the part shape. This information was sufficient for the task of sorting the parts.

In some cases, a sensor made for low data density can be used to build up the data. Scanning a sensor, which measures one point or a line of points, can be used to build up a full, 3D shape. In the case of a complicated shape like an airfoil surface or plastic molding, building up the shape may be a long process one point at a time, suggesting the need for more of a full-field data collection sensor if real-time data are needed to control the shaping process. This does not mean it is necessarily desirable to work with the maximum number of points at all times. A typical video frame has a quarter of a million data points. If there is a depth associated with each data point in such an image, there is, indeed, a large amount of data, more than may be practical to handle in the time available in a production operation.

Because of the variety of applications for 3D sensing, there are a variety of systems available.[11] These sensors can perhaps be broken into a few basic types:

- Point-scanning sensors measure only the specific points of interest, typically in a serial fashion.
- Line sensors provide a single line of points in the form of a cross section of the contour of interest.
- Full-field sensors provide an X, Y, Z map of all the points in the scene, which must then be analyzed down to the information of interest.

Each of these types of sensors has been developed using technology that is suited to the application. In some cases, the technology is capable of multiple modes of operation (finding a point on a surface, or defining the full surface) as well, but this often stretches the technology into a field overlapping other technologies. There has not to date been any single sensor in industrial applications which does everything. The result has been an assortment of sensors finding their best fit to specific applications.

1.4.1 Discussion of 3D Technologies

Before we address the performance of specific sensors, it is useful to establish the basic technologies in use. There are methods that can be used to find the distance to an object.[13–27] A simple version is to focus a beam of light on the object at a given distance. As the object surface moves closer or more distant, the spot on the object surface will enlarge, with the size of the spot being directly proportional to the change in surface height. This method has not seen much industrial use, so will not be further explored at this time. Some of the other methods, such as the scanning and full-field methods, have seen commercial success and have the potential to be used in process control as well as detailed gaging functions.

1.4.2 Point Triangulation

The most popular commercial versions of range finding use the triangulation method where a beam of light is projected onto the object's surface at some angle and the image of this spot or line of light is viewed at some other angle (see Figure 1.5). As the object distance changes, a spot of light on the surface will move along the surface by

$$\text{Change in spot position} = \text{Change in distance}/\left(\tan(\text{incident angle}) + \tan(\text{viewing angle})\right)$$

A wide range of commercial gages exist which can provide a single point of measurement based upon this triangulation principle. To make a discrete point measurement as a process control tool, such a sensor can be directed at the location of interest, with a wide range of possible standoff distances and send data at thousands of points per second in most cases. In order to obtain a contour map, these systems are typically

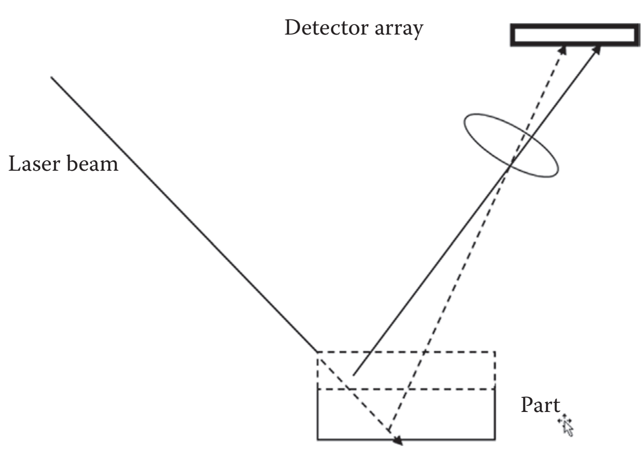


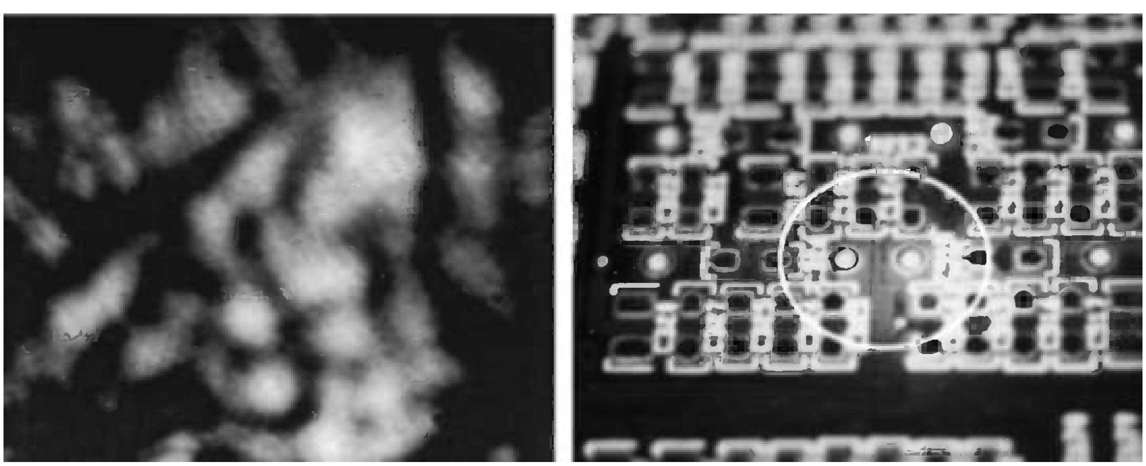
FIGURE 1.5
A triangulation-based system using a point of light to obtain distance.

scanned across the part.[27–29] The scanning has been addressed both by scanning the entire sensor head in a mechanical manner and by using scanning mirrors. Some of the mirror-based systems can collect a full field of data at nearly the rate of data of a video camera. Resolution of a few microns to tens of microns has been realized with point base triangulation sensors.

Most triangulation gages today use laser light. When a laser beam is incident on an opaque, rough surface, the microstructure of the surface can act as though it is made of a range of small mirrors, pointing in numerous directions. These micro-mirrors may reflect the light off in a particular direction or may direct the light along the surface of the part. Depending on how random or directional the pointing of these micro-mirrors may be, the apparent spot seen on the surface will not be a direct representation of the light beam incident on the part surface. The effects of a laser beam reflected off a rough surface include[28]

- Directional reflection due to surface ridges
- Skewing of the apparent light distribution due to highlights
- Expansion of the incident laser spot due to micro surface piping

The result of this type of laser reflection or "speckle" is a noisy signal from some surfaces such as shown in Figure 1.6. Trying to determine the centroid of such a signal will likely lead to some errors in the measurement. In like manner, there can be a problem with translucent surfaces such as plastics or electronics circuit boards. For translucent surfaces, the laser light will scatter through the medium and produce a false return signal. For a laser-based sensor, a smooth, non-mirrorlike, opaque surface produces the best results. Just as a contact probe has problems measuring a soft or delicate part (such as a gasket of a metal foil part), laser probes must be adapted to measure optically unfriendly parts. There have been a number of methods developed for dealing with such parts with laser gages, which are typically based upon restricting the view of the surface to only those areas where the laser beam should be seen and using smart data processing. Restricting the view is perfectly reasonable since the laser probe is only measuring a specific point on the part.



(a) (b)

FIGURE 1.6
Laser light does not always provide a clean spot to use for measurement (a). Scattering surfaces or translucent surfaces (b) can provide an uncertain spot location.

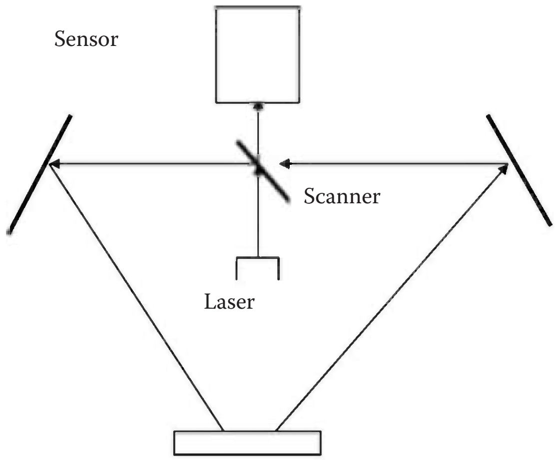


FIGURE 1.7
A synchronized scanning system with a limited range of view.

An active variation of restricting the view uses synchronized scanning.[29] In the synchronized scanning approach (see Figure 1.7), both the laser beam and the viewing point are scanned across the field. In this manner, the detector only looks at where the laser is going. This method does require an active scan but can be made more selective to what view the detector sees. The view cannot be completely restricted with synchronized scanning if an array or a lateral effect photodiode is used.

1.4.3 Line Triangulation

In contrast with a single spot of light, if a line is projected onto the surface by imaging or by scanning a beam, as shown in Figure 1.8, the line will deform as it moves across a contoured surface as each point of the line moves as described earlier.[18–23] The effect is to provide an image of a single profile of the part (see Figure 1.9). In applications requiring only a profile measurement, these techniques offer good speed of measurement. If the full contour is of interest, then the line is scanned over the part, requiring a video frame of data for each profile line of interest.

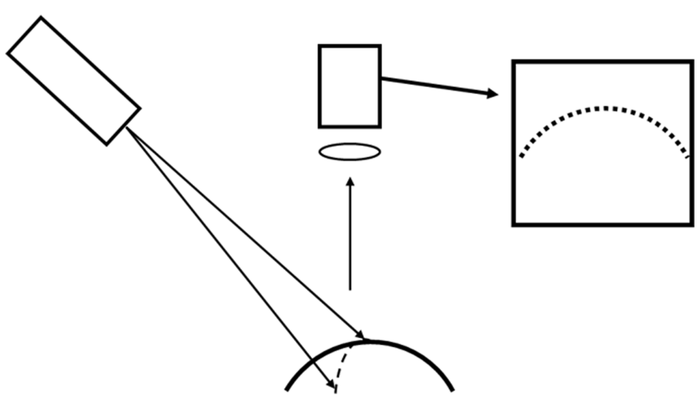


FIGURE 1.8
A line of light-based sensor showing the surface profile.

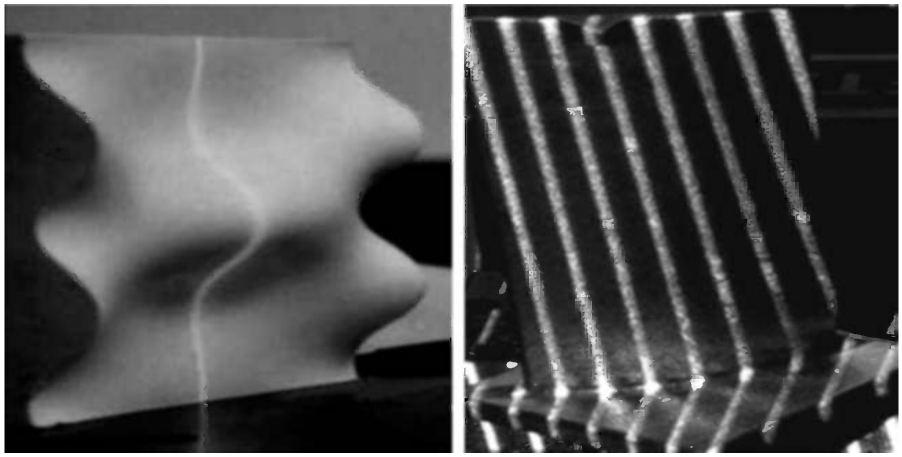


FIGURE 1.9
One or more lines of light on a part provide cross sections of the shape.

1.4.4 Area Triangulation and Moire Contouring

A popular extension in industry for the individual line of light system has been the use of multiple lines or patterns such as reticles, to cover more area at a time.[19,20] These patterns can take the form of encoded dot patterns, distorted grid lines, or simple gratings. Today many of these systems use white-light sources rather than lasers to reduce the noise associated with laser light. The structured light patterns are often analyzed with a technology known as phase shifting, which allows the system to produce an X, Y, Z point at every pixel (picture element) within the image (see Figure 1.10). More on this technology and the analysis will be covered in Chapter 7.

One special case of structured lighting using simple gratings is moire contouring.[11,30,31] In the case of moire contouring, it is not the grating lines that are analyzed directly, but rather the result when the initial grating as seen on the part is beat against a secondary or submaster grating. The resulting beat pattern or moire pattern creates lines of constant height that will delineate the surface the same way that a topographic map delineates the land (see Figure 1.11). This beat effect provides an extra leverage, since the grating line changes do need not to be directly detected and data are available at every point in the field to be captured within a single video image. This leverage can be useful in special applications such as flatness monitoring, as the depth resolution can be made much finer than in the X–Y plane.

The optical system for a moire system is more complicated than that of simple structured light (see Figure 1.12). So, only in some specific applications where very high-depth resolution is needed, such as sheet metal flatness as shown in Figure 1.13, has this technology been used. The other drawbacks of a moire contour include the difficulty in distinguishing a peak from a valley, ambiguity over steps, and the large amount of data generated. With the current commercial systems and computing technology, most of these issues regarding moire and structured light in general have been addressed. The methods of analyzing such patterns have been well established.[32–42] In fact, many commercial structured light systems, which directly analyze a projected grid pattern, use the same type of analysis as is used in interferometry in the optics industry. Interferometry provides nanometer level resolutions, which are typically beyond most applications in manufacturing, so will not be further explored here.

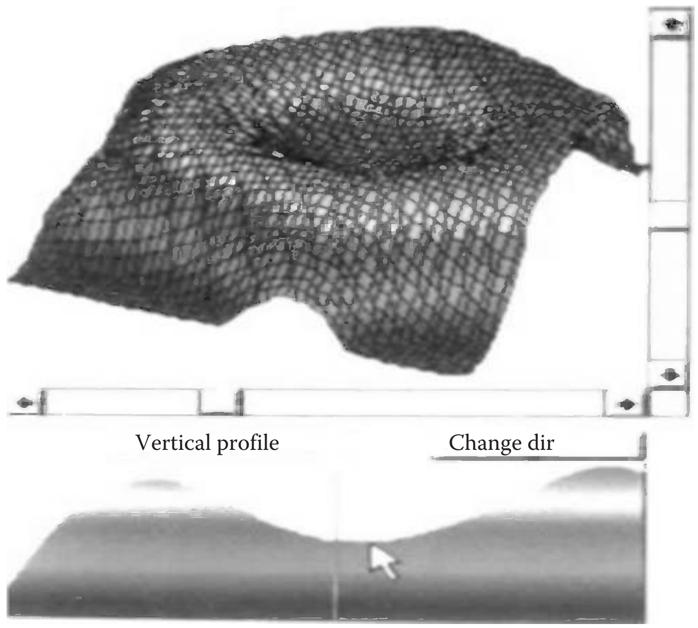


FIGURE 1.10
Three-dimensional data taken with a system using a structure light pattern, generating an X, Y, Z measurement at each picture element in the image.

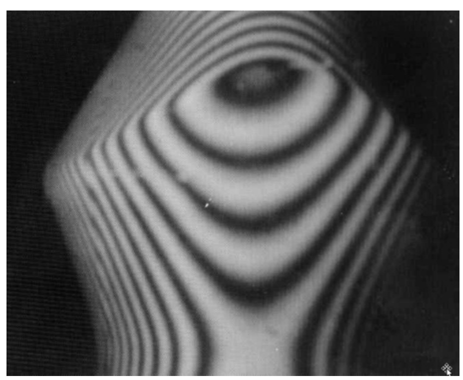


FIGURE 1.11
The moire beat lines delineate the shape of a plastic soap bottle.

1.4.5 Current Applications of Laser Probes

Triangulation-based distance sensors have been around since the time of ancient Egypt. Modern sensors have resolutions approaching a few microns. The most common industrial uses are in semifixed sensing operations where a fixed set or a few fixed sets of points are measured in a fixture. Entire car bodies, engine blocks, or other machined parts are measured by this means. For the purpose of reverse engineering metrology, the flexibility of the "scanning" triangulation sensor offers some attractive capabilities.

The individual laser probes have seen nearly 10-fold improvement in resolution in the past few years. The application of such probes in energy-based manufacturing has been a great benefit as a feedback control in systems where monitoring the force of a mechanical contact may not be possible. Scanning and fixed triangulation systems have been used to contour

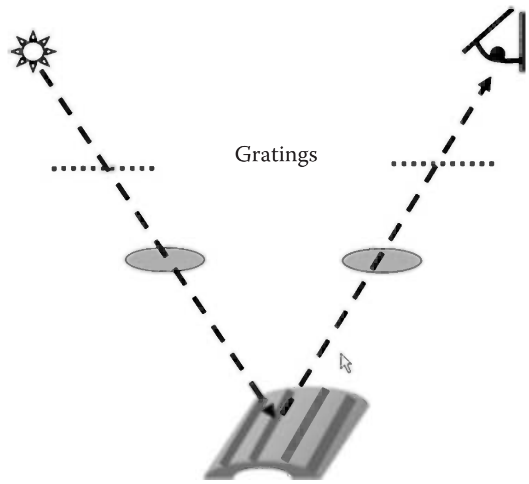


FIGURE 1.12
Moire setup showing two gratings used to create the beat pattern.

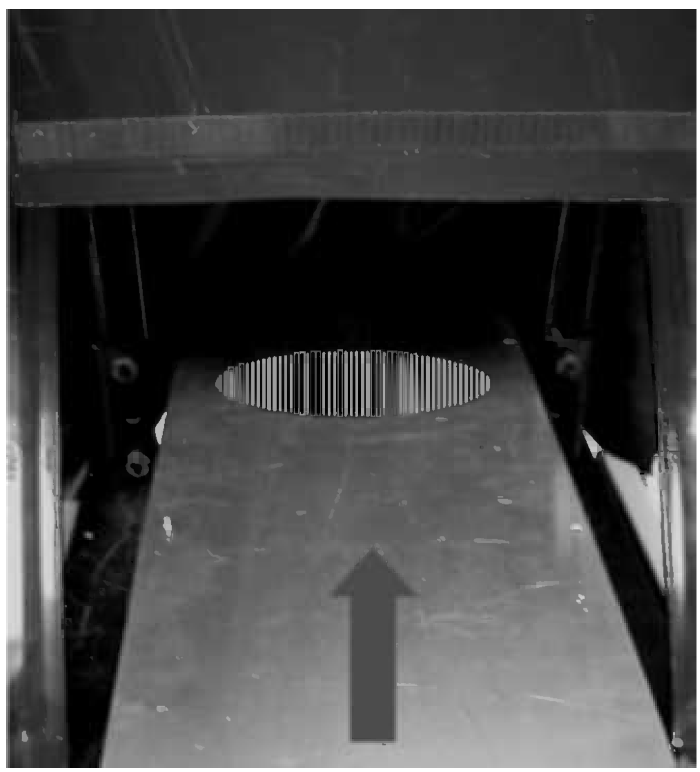


FIGURE 1.13
Moire systems have been used for online steel flatness monitoring.

large structures such as airplanes, airfoil shapes, and flatness of rolled metal. The large area systems primarily have used one or multiple lines of light to obtain a cross-sectional profile at a time. In many cases, these line sensors are connected with a machine tool axis of motion to extend the working range of the sensor. The resolutions of such systems need typically be less than a millimeter and more typically are around 2.5 μm (0.0001 in.).

Because of the long time the triangulation-based systems have been around, and the well-ordered nature of the line profile, there has been very good progress in adapting this technology to the needs of energy field manufacturing such as welding. A number of systems are available with direct CAD interface capabilities and would be capable of generating CAM type data as well. There is extensive second source software available that permits the large "clouds" of data to be reduced to CAD type of information for direct comparison to the computer data of the part. Most such comparisons have been largely specialized in nature, but as computer power increases, the user friendliness of such software is increasing.

Scanning triangulation sensors have been used in the manufacturing of small parts, such as precision parts made by laser machining.[43,44] The resolutions for these smaller sensors have been in the micron range, over distances of a few millimeters at a time, with data rates approaching a Megahertz. Dedicated inspection systems which work like full-field coordinate measurement systems for small parts are commercially available, gaining wide use particularly in the electronics industry (see Figure 1.14). The use of these sensors in manufacturing has been a significant tool in the electronic data transfer of dimensional information.

Full-field structured light systems, based upon projected grids by direct sensing of the grid or related to moire are also commercially available. The primary application of this type of sensor has been the contouring of continuously curved, non-prismatic parts such as turbine airfoils, sheet metal, clay models, and similar shaped parts, as shown in Figure 1.15.

Special compact sensors for use on machine tools are also available with this technology. Most of the applications of this technology have been on applications requiring dense data but have also been engineered to enhance video data for the purpose of 3D "comparator" type measurements on objects ranging from rolled sheet metal (for flatness) to car bodies.

FIGURE 1.14
Point-scanning system with small X–Y table serves as a noncontact coordinate measuring system for parts such as circuit boards.

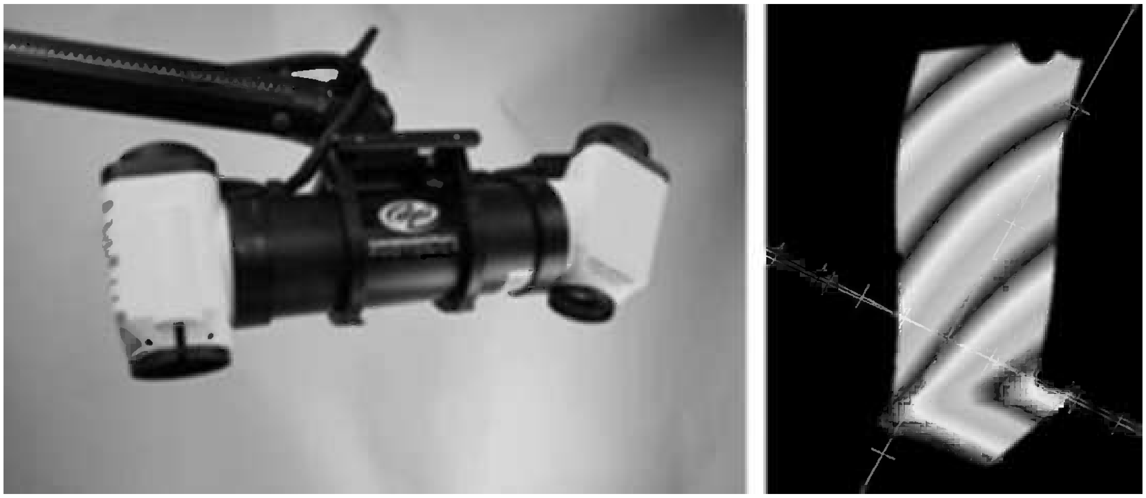


FIGURE 1.15
Structured light 3D systems are available and are used for mapping continuous shapes such as a compressor blade.

Coverage of 2 m^2 areas at a time has permitted very high-speed relative measurements of large structures to several micron resolutions. Typical resolutions of commercial full-field structured light systems are in the range of submillimeter to several microns (down to 0.0001 in.), with data collection taking from one to five frames of video in a few seconds or less. This technology has benefited greatly from the advances in computing power due to the large amounts of data involved (up to a quarter of a million data points in a few seconds). These systems have also been interfaced to provide direct CAD data inputs. Area-based structured light systems offer better speed in applications requiring dense data over complex shapes as opposed to selected regions of a part.

1.5 Application Error Considerations

As discussed previously, noncontact probes may be better suited for energy field manufacturing than touch probes. Touch probes are used in traditional machining for process control. The tool holders and mechanical scales are not adaptable enough to use touch probes in manufacturing system. However, to best understand the errors that may be encountered in any process control, we will examine both contact and noncontact probes.

Both touch-based probes and optical probes have certain errors associated with their operation. The errors tend to be inherent in the nature of the sensor. Each sensor technology has operations it is good at measuring, while with other operations, it has problems. In the case of touch probes, measuring any feature on a sharply curved surface, be it the diameter of a hole or going around a corner edge, requires more points to compensate for how the touch probe makes measurements. In the case of optical probes, the biggest errors tend to come from the edges of parts, either because the probe cannot see past the edge or because the measurement point is larger than the edge. Understanding what these basic errors are with the probes used for control of a process is an important step in correctly applying the technology and getting useful data to control the process.

1.5.1 Contact Probe Errors

In the case of touch probes, the operations are geared toward the types of potential errors specifically found in these sensors. Touch probes used on machine tools have errors associated with the direction of touch.[45–47] These errors fall into two categories. First, since the end of the touch probe is a ball of finite size, the measurement that the machine tool axis provides must be combined with the offset of the radius of the ball and added to the measurement to offset the measure in the direction of the normal of touch to the ball. Of course, knowing precisely what the angle of the normal of touch can be a difficult question. As a sphere, the touch can be in any direction over nearly 360°. Therefore, in operation, additional points are taken around the first touch point to try to establish the local plane of the object. The orientation of the plane of the object is used to determine the direction of offset of the measured values.

Much work has been done to minimize these touch offset errors, both in determining the minimum number of points needed to establish the direction of touch as well as the means to devise durable small point touch probes to reduce this potential of error on high-precision machines. However, as can be seen in Figure 1.16, there remain many error conditions that may still provide an erroneous reading. Features such as corners and small holes necessarily remain a problem for touch probes. A sharp corner location is typically inferred from the intersecting surfaces forming the corner (see Figure 1.17).

The second type of error associated with direction of touch is the so-called lobing errors present in many touch probes (see Figure 1.18). The lobing error is the result of the design and operation of the probe. The probe responds faster to the touch in some directions than in other directions. The result is an additional error that is systematic and consistent with respect to the orientation of the touch probe. Any calibration test must map the response of

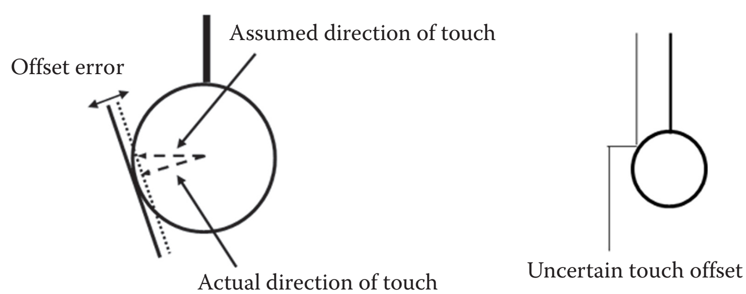


FIGURE 1.16
Errors from touch direction on contact probes due to an uncertainty in the direction of touch on the ball tip.

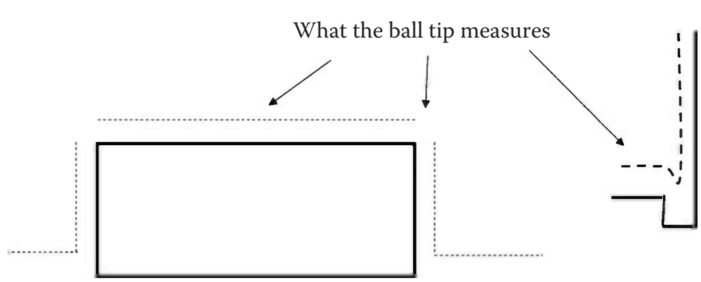


FIGURE 1.17
Actual shapes versus what is measured by a touch probe where the ball can not follow the corner due to touch direction (left) or may not fit into a feature (right).

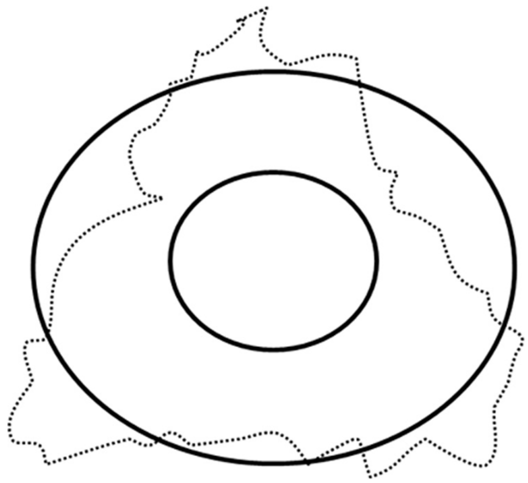


FIGURE 1.18
Typical lobing errors from a touch probe caused by the directional response of the electronics in the probe. These errors are canceled out by probing in multiple directions, such as on a sphere or hole, or by adding a correction factor.

the probe at a full range of angles and approach speeds. Touch probes are typically tested using a sphere of known size. By finding the center of the sphere, the errors associated with lobing and ball touch angle can be corrected.

For most point probes used on a machine tool, the measurement is actually being made using the scales on the machine. A touch probe itself does not really provide any measurement directly; it only acts as a switch to indicate when to take a measurement. There are available analog touch probes that provide some small measurement range directly. If part of the measurement comes from the movement of a machine tool and some from a sensor, the alignment and calibration of one source of measurement to the other is very important to the overall performance of the measurement. In either case, the machine scales are playing a significant role in the measurement of the part. The machine axes themselves are what is often used to do material processing, and as such, any measurement made with them will be self-consistent, whether they are right or wrong.

1.5.2 Machine Axis Errors

The errors associated with the linear axes of the machine include errors in the read out of the stages, as linear errors in X, Y, and Z, as well as the squareness of these three axes. The specific nature of these errors is unique to the machine tool operation. Scale errors tend to be linear, often as a result of the axis not being in line with the assumed direction, but rather at a small angle. The result of a small angle in the axis is referred to as the cosine error effect (see Figure 1.19).

The straightness of the Cartesian motion axis of machine tool can also contribute to the cosine error. However, the motion axis alignment is more a design parameter than something that can be fixed by some user alignment. That is, the axis may actually be slightly bowed or twisted, due to mechanical sagging of the beam carrying the cutting head or tool holder. In addition, the initial straightness of the ways used to build the machine may not be perfect. Because it is the composite performance that is important, touch probe positions on machine tools are usually calibrated using a ball bar. The balls at the end of the bars

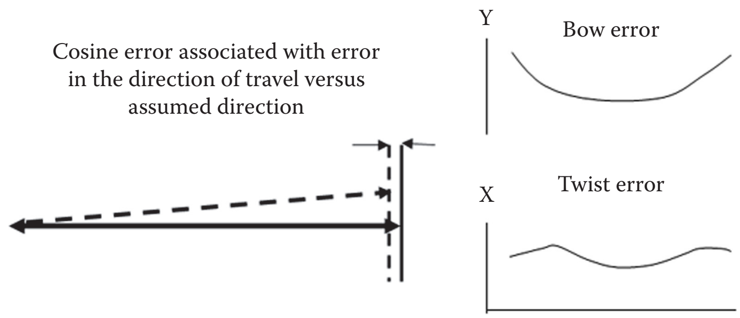


FIGURE 1.19
Cosine errors due to axis alignment errors will cause the measurement to be larger than the actual motion.

permit the errors of the touch probe to be taken into account, while the length and various angle positions of the bar tests out the machine scale accuracies and the squareness of the movements of the machine axis.

1.5.3 Noncontact Probe Errors

In the case of noncontact gaging systems, the potential causes of errors are different, requiring different types of tests to isolate. Unlike the touch probe on a machine tool, whose variations tend to be not in what movements or errors it may poses, but rather the particulars of how it makes these movements. Optical measurement systems are much more varied in the basics of what they do. The variety of 3D optical systems might be classified into three basic areas:[48]

1. Radial scanners measure the distance along a line of sight from some central location, such as laser radar or conoscopic systems. Errors in these systems are related to errors in scan angles.[49] The base coordinate system is typically R theta in this case (Figure 1.20a). A special case of such a scanner would be when the scan center is at infinity. In this case, the scan is telecentric or parallel. There is no angle effect if the scan is parallel, but the linear translation may have a small error.

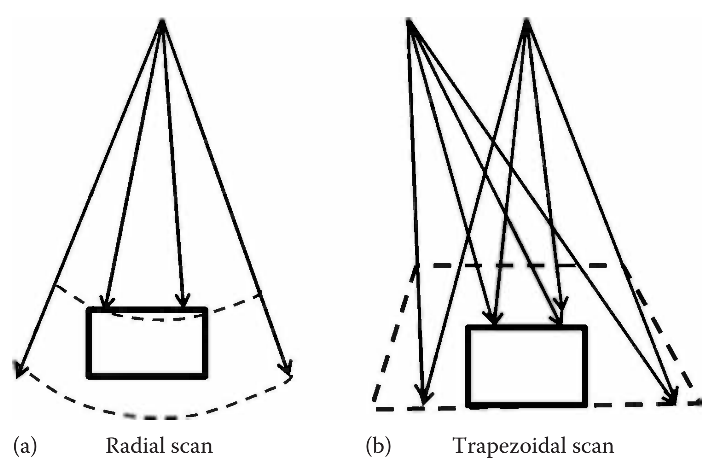


FIGURE 1.20
Coordinate systems formed by different 3D optical scanning methods create either a (a) radial or (b) trapezoid shaped measurement format.

2. Triangulation-based systems, such as point laser probes and structured light probes, rely on obtaining information from two angles of view. Both views can be passive as with a stereo view, or one view can be active in the form of a projected dot or pattern of some sort. The coordinate system with triangulation systems is typically taken as Cartesian but in fact is at best trapezoidal (see Figure 1.20b). The errors associated with triangulation-based systems tend to produce a field that is curved or saddle shaped. The errors in a curved field include magnification effects and the change in the triangulation angle. Both the magnification and angle can change with position across the field and with changes in distance.[50,51] The interaction of the two or more optical systems must be taken into account when addressing the actual calibration.
3. Interferometric-based systems, such as classic interferometry or so-called phase shift structured light systems, make measurements based upon the distance light travels relative to some reference surfaces (real or virtual). In this case, the calibration is tied to the real or effective wavelength being used to measure this difference. Moire contouring is an example that can be analyzed using interferometric analysis based on an effective period of light (typically much longer than the optical wavelength). However, moire is also a triangulation method and therefore subject to the variations and constraints of magnification changes and angle of view.

Clearly when applying a noncontact 3D system to an application currently done by machine tools, the very basic question of what coordinate system is being used must be answered. Machine tools typically are built around three axes all perpendicular to each other. An optical 3D system may have a curved measurement area, one that is trapezoidal or even spherical. Much of this variation in coordinate system is accommodated for in the calibration routines of the sensor. It is not necessarily the case that a spherical coordinate system is incorrect, but typically, parts are specified in square Cartesian coordinates.

In order to apply optical methods, the coordinates are translated from the inherent system coordinates of the optical sensor into the equivalent Cartesian space native to the machining operation. Such transformations always have their errors and approximations. In the case of a trapezoidal or spherical measurement, this may mean reducing the accuracy of the measurement to that obtained in the worst area of the measured volume. This worst area is typically the points furthest or most off-center from the sensor. If machines were initially made with spherical coordinate geometries, then the transition to some types of optical-based measurement tools might be a simpler task. For some manufacturing systems, this might be an option. One type of coordinate system is not necessarily superior to the other; it is just a matter of what is being used.

In applying optical-based measurement systems to on-machine operations, the other primary issue is how optical-based measurements handle edges. We have already described the potential errors that occur when a touch probe goes over an edge and the uncertainty in offsets that can arise depending on the angle of attack to the surface. Optical probes that are based upon finding the center of a laser spot typically have just the opposite problem from a touch probe. As the laser spot goes over the edge (see Figures 1.21 and 1.22), part of the spot is no longer seen by the sensor. The center of the spot actually seen is not in the same location as it would be if the whole spot were visible. The result is a measurement suggesting that there is a raised lip on the edge that is not really there.

Typically, a laser spot in a triangulation sensor is less than 50 μm and perhaps only a few microns in size. Even so, this finite spot size produces an offset error that increases

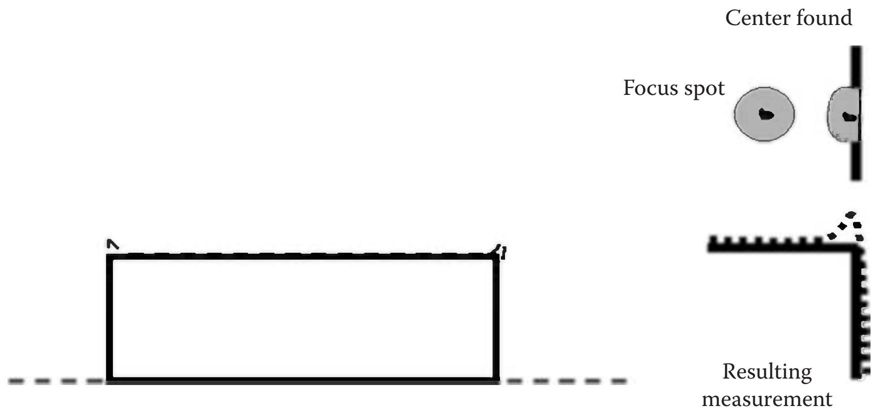


FIGURE 1.21
Edge error associated with many laser probes causes an apparent liftoff at the corner, due to part of the laser spot being lost over the edge.

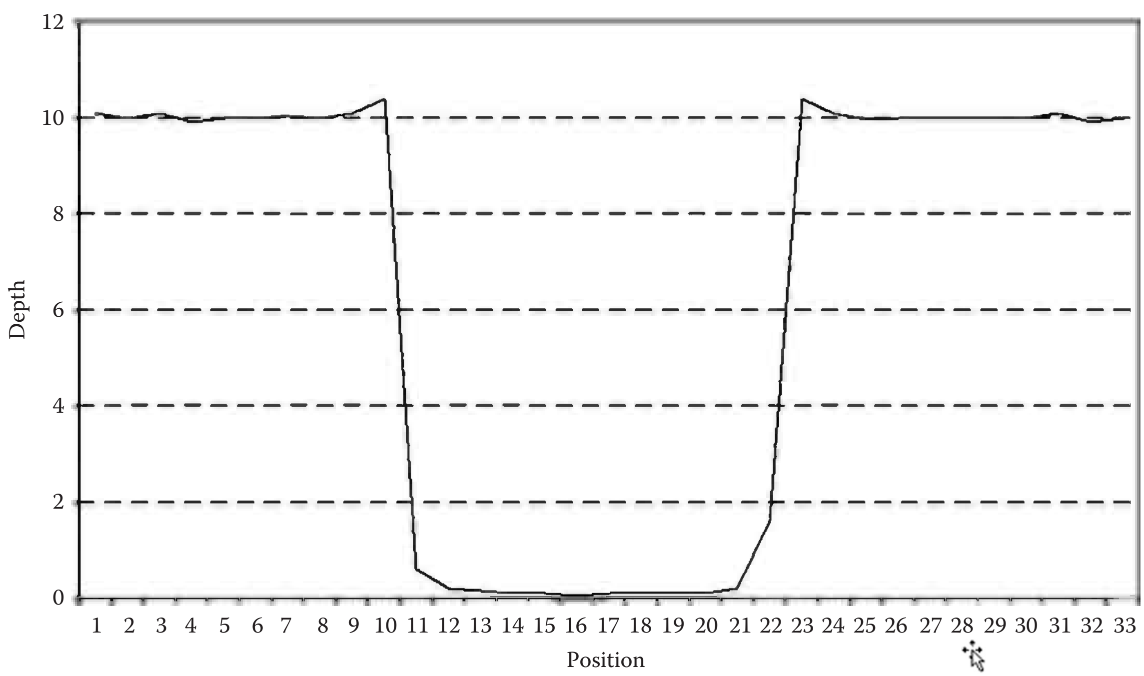


FIGURE 1.22
Graph of laser point sensor performance at an edge showing upturns at the top and round offs of lower inside corners.

as the spot goes across the edge. The actual centroid calculation may depend on the intensity of the spot, the surface finish, the shape of the spot, and the algorithm used to estimate the center. For many optical-based systems (other than interferometric or laser radar), this edge liftoff exists whether there is a real edge or just a transition from a bright to a dark area.

Clearly, 3D systems that rely more on area-based averaging will have more of a problem with how close they can measure an edge before errors start to come into play.

Some methods, such as the interferometric or phase step-based systems that calculate a range at each pixel, can typically measure closer to the edge than a system that uses a spot or a line that may be many pixels wide. Such differences in offset errors and how systems see edges often mean one type of system is seen as superior over the other. A sensor that can measure closer to a physical edge may be judged better than one that can only measure to within a millimeter of the edge. That fact is, just as touch probes can be used around an edge and the offset compensated for in the analysis, the same can be said about the optical probes. The correction for the edge offset is different for optical versus touch probes, but not less predictable for either method of measurement.

For example, in the case shown in Figure 1.21, the laser spot is shown as being a round spot, with the measurement based upon finding the centroid of that spot. Therefore, we can predict that the spot centroid error will change as a quadratic function of the form:

$$\text{delta}(Z) = Z + \frac{P \times X^2}{R^2}$$

where
- P is the triangulation factor of Z(X)
- R is the spot radius
- X is the displacement past the edge

As the laser spot hits the bottom of an edge, some of the spot will highlight the side wall. Depending on the steepness of the wall, this may then lead to the complimentary effect of a rounded bottom corner that follows the form:

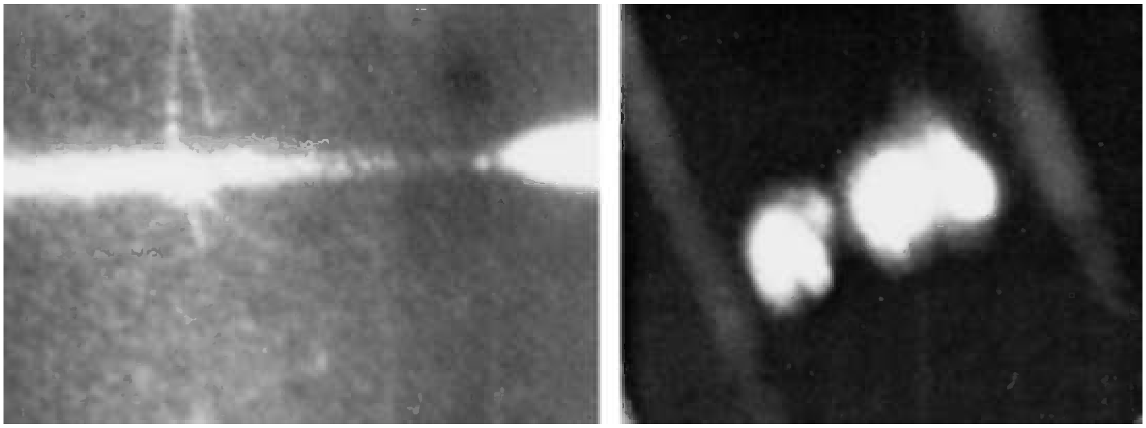
$$\text{delta}(Z) = Z - \frac{P \times R^2}{X^2}$$

which is just the inverse as seen on the top of the edge (see Figure 1.21). This basic form agrees fairly well with what is typically seen from experimental data of this type, as shown in Figure 1.22. Once the laser spot center has moved one half of the spot diameter from the wall, then the spot is completely on the bottom, and a correct measurement is available directly. This correction to triangulation sensors assumes that the triangulation angle has not been occluded by the wall, which would block the beam. Occlusions going past an edge are really more of a problem than the liftoff, since there are no data to correct. For this reason, many triangulation sensors that are used for this type of application will view the laser spot from two or more perpendicular directions to avoid occlusion issues.

The point of this discussion is to show that the errors from optical sensors near the edge are both understandable and predictable and can be corrected in the same manner as touch probes accommodating the ball radius. As an additional complication, if the edge causes a bright glint of light, the error in a standard centroid-based triangulation system can be compounded. Some manufacturers monitor the change in light level to recognize such glint conditions, either to reject the data or to attempt to correct that spot.

In like manner, if the side of a step is not steep, then light may be seen from the detector on the side wall, as shown in the left image in Figure 1.23, creating a very elongated spot and again increasing the error. A groove may appear to be two spots, as shown on the right side of Figure 1.23, confusing the interpretation of the centroid.

These reflection problems are a function of the surface finish and the geometry of the edge, so are more difficult to predict. For phase- and frequency-based sensors, a bright



(a) (b)

FIGURE 1.23
Two laser spots showing part of the spot bouncing off a side wall (a) and one being broken into two bright but irregular spots (b) as the laser spot seen in a groove.

glint is typically not a problem assuming the sensor has the dynamic light range to accommodate the extra light. For that matter, if the triangulation sensor can be used with the plane of triangulation along the edge, then relatively little offset would be seen. However, depending on how the spot is sensed, an area-based system can still misinterpret the Y displacement as a change in Z.

1.5.4 3D Probing Errors

In the case of 3D measurements, the issues described earlier can produce a range or errors that are inherently different from the ones encountered in a mechanical measurement system when measuring real parts.[52,53] The issues discussed, such as radial coordinates, edge effects, and even such effects as light source variations and optical aberrations can warp and displace the measurements made with an optical system of any type.[54] Following the example of the calibration done for touch probes and CMMs, there are similar tests that can be done to detail the performance of an optical metrology system. We will discuss some example potential tests that can be used as a starting point. These tests are intended to both highlight the likely errors with optical metrology systems but also exercise the optical systems in a manner appropriate to the preferred means of use. Given the sensitivity of optical system to such a wide range of factors from surface finish and reflectivity to surface angles, no performance test is likely to be completely inclusive of all factors. For any specific application, specific artifact tests may prove to be the best tool to define the performance of the system as the user wants to employ the system.

The 3D optical system equivalent to a touch probe sphere test would be to measure the angle between two flat surfaces, oriented with the edge horizontal and then vertical, or by viewing the apex of a cube or pyramid, using data away from the edges to define the surfaces then calculating the intersection of those surfaces (see Figure 1.24). This measure provides a separable quantification of the in-plane and depth scale accuracy over a local region, which is the purpose of the measurement. Adding in surfaces onto the measurement object at more than one angle allows a determination of the angle sensitivity of the system as well. Measuring beyond the angle where the measurement points are acceptable

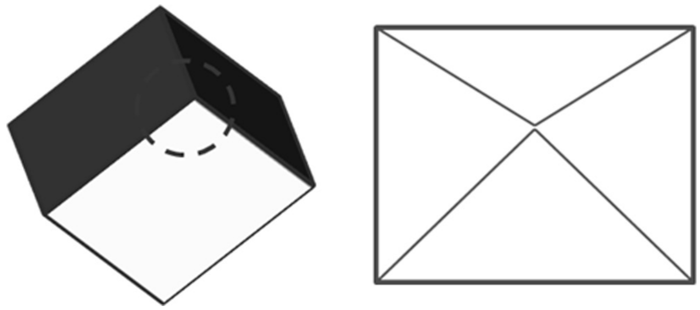


FIGURE 1.24
Fitting planes to the surface of a cube or the surfaces of a four-sided pyramid, then using the intersections to define the apex provide a consistent reference point that uses the best sensor data.

is the equivalent of trying to reach too far around a corner with a touch probe and hitting the shaft of the probe, rather than the tip.

A common test used on CMMs to determine volumetric errors in measuring point to point distances is the use of a ball bar. A ball bar is a long bar with a sphere on each end that can be moved around the measurement volume of a system. The length of the bar should always come out to be the same anywhere within the measurement volume. To do the equivalent ball bar test for a 3D optical system requires measuring from multiple approach directions with the optical system, just as is done with a touch probe to define the sphere. However, rather than compensating for errors relating to direction of touch, the method as described using sphere diameters compounds the long-distance calibration of the 3D sensor with variations due to angle of view, which should be measured separately as described earlier. To avoid combining the angle sensitivity and distance calibrations, the measurement should be made based upon the calculated center of the spheres using the limitation of the data used from the sphere as described earlier, as this separates the measurement of the sphere spacing from a measurement of the sphere diameter.

In order to be sure, sufficient points are used to find a sphere center, typically a minimum of 10,000 points should be used. As stated before, if sphere centers are used, no points should be used that are further around the sphere than 90° minus 30° minus the triangulation angle from normal for triangulation-based systems or the point at which liftoff exceeds the process tolerance should be used in defining the sphere center. If insufficient points are not available over the usable surface, a larger sphere should be used. Alternately, an end artifact, which contains intersection points of flat planes (cube, tetrahedron) whereby an area-based sensor can well define the intersection of three surfaces to define a point, uses the strength of the 3D optical sensor to provide a higher confidence local measure and focuses the test on the long-distance, volume calibration, which is the point of the ball bar test, such as suggested in Figure 1.25. These corner points can then be used to measure the separations of the cubes.

When making this type of measurement with a CMM, the measures are made a point at a time. As such, on a CMM, it takes little more time to use one ball bar and move it around the volume as it would to use multiple ball bars. In the case of 3D optical systems, they have the capability to measure multiple points in parallel. The time spent moving the bar around, particularly if handled by a person, can cause changes due to thermal expansion and drift which can be confounded with the intended measurement of volume accuracy.

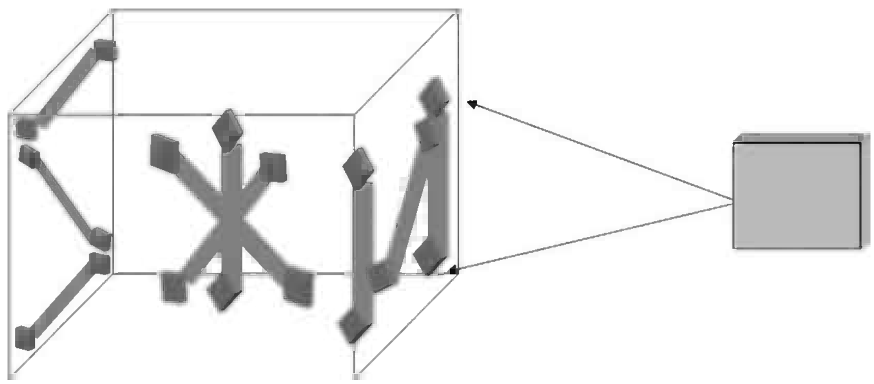


FIGURE 1.25
A bar with a ball or cube (better for optical systems) on each end is positioned to check the volumetric errors of the 3D optical system. Redundant orientations recognize the interdependencies of the position and the axis.

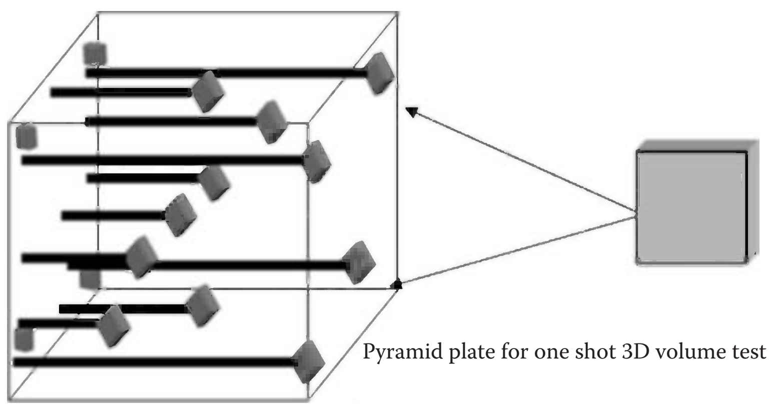


FIGURE 1.26
A ball plate (vertical at left) provides a means to test the volumetric accuracy of a 3D optical system using one data set, without changing angles of view.

A much more commonly used test for 3D optical volumetric systems is to use a ball plate or similar plate with pyramid targets such as shown in Figure 1.26. The objective of the test is to determine spatial accuracy capability, not the ability to measure a sphere in many locations. So, using a fixed plate with all points of interest determined by the intersection of planes uses the optical system to its best capability locally, thereby separating out local noise from volumetric measures (just as the balls do for a CMM) and permits the test to be done efficiently and quickly to avoid any thermal or drift effects.

In any measurement system, the simplest type of measurement is to measure a plane. Ideally, anywhere in the volume of the system, the plane should show as being flat. 3D optical systems can have localized errors such as waves that would not be picked up by a narrow bar. Since one advantage of the optical system is often the ability to take many points quickly, it makes sense to look at a large surface which provides a clear picture of the local as well as global variations over the working field of the system.[55] A normal view of near, middle, and far positions is a good start (vertical lines in Figure 1.27). However, as the performance of optical sensors is a function of the angle of view on a surface, two tilt angles should be used that are different angles tilted in the same plane.[56] Without multiple angle information, significant errors relating to phase approximations (for phase shift–based systems) can be missed.

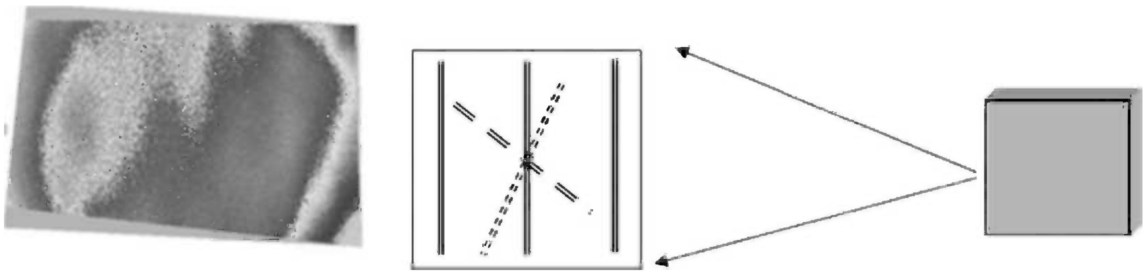


FIGURE 1.27
Positions needed for a test plate to obtain flat plane errors in an optical 3D system.

A diagonal measurement is redundant, as is a vertical angle. When using a larger plate surface, rather than a narrow bar, both the symmetric and asymmetric variations are already measured. These skewed angles are both positions difficult to accomplish and really provide no additional information relative to 3D optical system errors. The types of errors possible with a 3D optical system are not necessarily only spherical in nature and can include saddle points and zonal waves that would tend to be ignored by a spherical (squared) fit, so higher order fitting is in order. Comparison of the measured surface to a plane, considering zonal deviations, can provide greater insights to any errors of on optical metrology system.

The individual tests we have discussed are primarily made using just one view of the part. In reality, a part has many sides and may need to be measured using multiple viewing angles that are then put together. A useful means to consider the overall accuracy and stability of a system is to use some type of golden part or artifact. As we have seen, in an optical system, many errors are interdependent. So, as a test of overall performance, a known part with a shape similar to the part to be tested, with key gage values defined, can be characterized by some other means accepted by the shop. This test can provide local, multisided performance measurement (e.g., repeatability of thickness) appropriate to the final part measurement.

The suggested test procedure could be as follows (see Figure 1.28):

1. Use a reference artifact made to be similar to parts with optically dull surface, on which dense CMM data have been taken, and at least five profiles have been defined with thickness values defined at 20% from the edges of the part and at the maximum thickness location. At least 20,000 points should be used per side of the artifact.
2. Measure the part on both sides at center of volume at best angles and calculate contour and thickness values.
3. Move the part to the top of the volume and repeat tests.
4. Move the part to one side of the volume and repeat tests.
5. Move the part to the rear of the range of the volume at the center and repeat the test.
6. Move the part to the front of the range of the volume at the center and repeat the test.
7. Move the part to one far corner of volume and repeat the test.

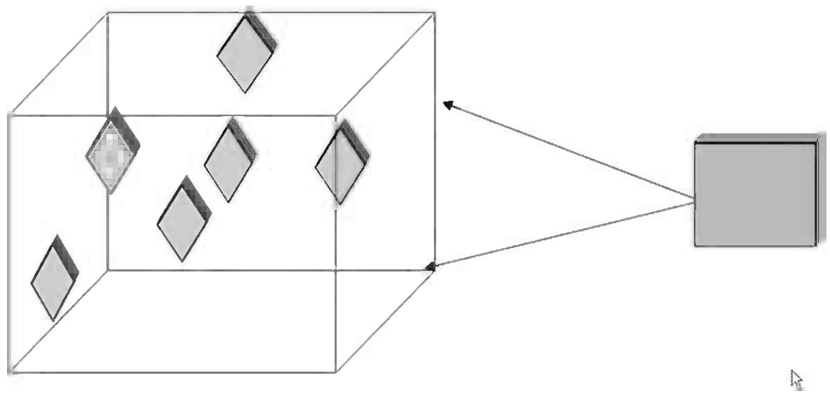


FIGURE 1.28
Positioning of an artifact within the measurement volume used to check overall performance.

Procedures such as described would allow a user to determine the errors inherent within an optical-based measurement system, be it ranging, triangulation, point scanning, or structured pattern based. Such tests can also be used as a means to compare different systems. However, many other considerations must go into a decision on using a particular optical measurement system for use as a production tool. Carefully considering how the part interacts with light, how the total system operates, and how the data from the measurement system are to be used is an important next step in employing these technologies.

1.5.5 Measuring to Datum

When any feature on a part is measured, it is measured at a location and relative to some predefined references or datum points. The datum point may be on the part, on the fixture holding the part, or somehow defined by the shape or fit of the part. Machine-based measurements commonly start a measurement by locating a few key datum features such as planes or holes in the part. These are features a simple point sensor can define with a minimal number of points. For production applications, the part is typically referenced off a fixed position fixture, pre-located on the processing machine tool.

To the extent that the fixture is repeatable and kinematic, the machine axis or other measurement device, such as a hard gage, can expect to make measurements in the correct, prescribed positions. If the fixture is off or the part does not sit right in the fixture, say due to a slight error in the edge geometry of the part, the system will make a good measurement, just not in the right place. Clearly, from the discussion previously, the way in which a measurement can be mispositioned can be very different when using a contact sensor versus a 3D optical gage. In both cases, understanding how to correct these errors is key to making good measurements.

1.6 Summary and the Future

We have discussed a wide range of possible sensors for use with flexible manufacturing operations. The intent of the use of any of these sensors would be to control the process in a situation where there is no traditional contact with the part being machined or formed.

TABLE 1.1

Overview of Primary Sensor Types of On-Machine Monitoring

Sensor	Data Rate (pts/s)	Resolution	Issues
Touch probe	1/s	na	Uses scales to measure
Point optical probe	500–20,000 Hz	1–3 μm	Reflections, edges
Laser line probe	20,000 Hz	10–50 μm	Laser speckle
Machine vision	To 50,000	5–100 μm	Resolution depends on FOV
3D structured light	>1 million (large data sets)	10–50 μm	Resolution depends on FOV

The possible sensors range from point contact probes, currently in wide use on traditional metal-cutting machines, noncontact point laser probes, 2D machine vision camera-based measurement systems, and full-3D mapping systems. A summary of these methods and typical capabilities is shown in Table 1.1.

The right sensor for an application is very dependent on the nature and amount of data needed to provide feedback to the process. To monitor a few key points, a touch or point laser probe can provide sufficient feedback and is in wide use in many industries today as a process control tool.

Laser line probes are typically used in continuous process applications such as extrusions where only a contour section really matters to the process control. One wide use of these sensors is to monitor welds as they are being formed.

Machine vision is widely used as a feature inspection tool, including applications such as aligning and verifying holes made by EDM and laser drilling. The full-field, structured light 3D systems are still new on the market and are primarily being used to verify only the first parts made in production. However, the speed of 3D systems is such that monitoring a fast manufacturing operation is practical.

The processing capabilities of computers will continue to make any of these sensors faster, easier to interface to manufacturing systems, and easier to interpret. The combination of fast 3D sensors with energy field manufacturing has the potential to enable completely automated processes that go from drawing to finished product. The capability exists today to make a 3D copier machine that would work as easily as a 2D document copier. Such a device could completely change the way we do manufacturing in the future.

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