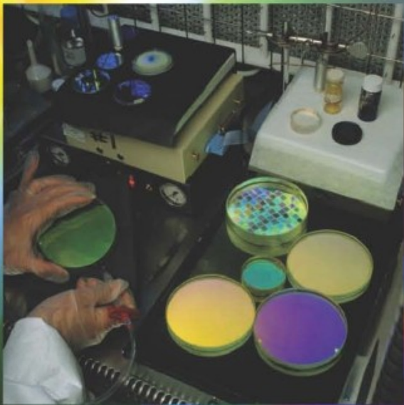
Photonics-Enabled Technologies

Lasers in Testing and Measurement: Alignment, Profiling, and Position Sensing



OP-TEC

Optics and Photonics Series

Lasers in Testing and Measurement: Alignment, Profiling, and Position Sensing

Photonics-Enabled Technologies: Manufacturing

OPTICS AND PHOTONICS SERIES

STEP (Scientific and Technological Education in Photonics), an NSF ATE Project

National Center for Optics and Photonics Education

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PREFACE

This module is one of four pertaining to manufacturing as a photonics-enabled technology. The combined series on photonics-enabled technologies (comprising both STEP and OP-TEC materials) consists of modules in the areas of manufacturing, biomedicine, forensic science and homeland security, environmental monitoring, and optoelectronics, as listed below. (This list will expand as the OP-TEC series grows. For the most up-to-date list of modules, visit http://www.op-tec.org.)

Manufacturing

Laser Welding and Surface Treatment

Laser Material Removal: Drilling, Cutting, and Marking

Lasers in Testing and Measurement: Alignment Profiling and Position Sensing

Lasers in Testing and Measurement: Interferometric Methods and Nondestructive Testing

Environmental Monitoring

Basics of Spectroscopy

Spectroscopy and Remote Sensing

Spectroscopy and Pollution Monitoring

Biomedicine

Lasers in Medicine and Surgery

Therapeutic Applications of Lasers

Diagnostic Applications of Lasers

Forensic Science and Homeland Security

Lasers in Forensic Science and Homeland Security

Infrared Systems for Homeland Security

Imaging System Performance for Homeland Security Applications

Optoelectronics

Photonics in Nanotechnology

The modules pertaining to each technology can be used as a unit or independently, as long as prerequisites have been met.

For students who may need assistance with or review of relevant mathematics concepts, a review and study guide entitled *Mathematics for Photonics Education* (available from CORD) is highly recommended.

The original manuscript of this document was prepared by Jack Ready (consultant) and edited by Leno Pedrotti (CORD). Formatting and artwork were provided by Mark Whitney and Kathy Kral (CORD).

CONTENTS

Lasers in Testing and Measurement: Alignment, Profiling, and Position Sensing

INTRODUCTION

Many different types of measurement, testing and inspection in industry can be performed with lasers, often providing advantages compared to conventional techniques.

One area in which laser technology has found wide application is in fabrication and construction processes where it is important to have an accurate, easily accessible reference point, line, or base. The reference might be simply a straight line that can be used to position components or structures. Or the reference can be the direction of gravity, so that structural members can be positioned level, upright and "square" with each other. With a straight line, it is also possible to measure accurately the deviation of some point (like a tool point on a long lathe bed) from a given reference axis.

Other alignment applications Involve angular alignment, in which the angular orientation of different structures can be determined or the axes of rotating parts can be lined up with each other.

In this module, you will study the techniques by which photonic systems can be applied to alignment problems, the component technology that makes such systems possible and some representative systems.

This module will also describe laser-based methods for testing of manufactured products, including methods for measuring the dimensions of products, to ensure that they are within the prescribed tolerances, and methods for measuring the surface roughness and contours. This module will also describe diffraction-based methods for determining things like wire diameter.

Laser-based technology has thus become widely used in industry for a variety of alignment and measurement tasks.

PREREQUISITES

The following modules in Courses 1 and 2 form an ideal background for a study of modules devoted to lasers in manufacturing. However, one can begin a study of this module—*Lasers in Testing and Measurement: Alignment, Profiling, and Position Sensing*—after a study of modules 1-2, 1-3, 1-6, and the two manufacturing modules listed on the following page.

Course 1: ***Fundamentals of Light and Lasers***

Module 1-1: *Nature and Properties of Light*

Module 1-2: *Optical Handling and Positioning*

Module 1-3: *Light Sources and Laser Safety*

Module 1-4: *Basic Geometrical Optics*

Module 1-5: *Basic Physical Optics*

Module 1-6: *Principles of Lasers*

Course 2: ***Elements of Photonics***

Module 2-1: *Operational Characteristics of Lasers*

Module 2-2: *Specific Laser Types*

Module 2-3: *Optical Detectors and Human Visions*

Photonics-Enabled Technologies: Manufacturing

Laser Welding and Surface Treatment

Laser Material Removal: Drilling, Cutting, and Marking

OBJECTIVES

Upon completion of this module, you should be able to do the following:

- Define the terms *elevation angle, azimuth angle,* and *radian*. Draw and label diagrams illustrating the rotation of an optical axis in elevation and in azimuth.
- Describe the basic elements of angle-tracking systems. Your description should include an angle-sensitive receiver.
- Describe how angle measurements may be deduced from measurements of the lateral displacement of the image at the focal plane of the objective lens in an angle-tracking system.
- Describe, in terms similar to the text, the following types of position-sensitive detectors: *quadrant photodiode, silicon position sensor,* and *vidicon*. Include a drawing of each detector.
- Draw and label a diagram of a typical commercial alignment system and describe the operation of the system. The components shown in your drawing should be similar to those in the text.
- Given the necessary parameters for an angle tracking system, correctly perform calculations related to angle tracking.
- Given the necessary parameters of a surface profiling system, correctly perform calculations related to surface profiling.
- Given the necessary equipment, assemble and operate a laser angle-tracking receiver employing a silicon position sensor and measure the angular displacement of a laser that is mounted on a linear translator.

- Given a laser and other necessary equipment, correctly measure the diameter of a sample of wire using a diffraction method. The measurement will also include correct determination of the effect of positional and angular misorientation of the wire.

SCENARIO

Susan is a photonics technician who works in the development laboratories of a major automobile manufacturer. She works with a group of engineers who are responsible for development of components for new automobiles. As part of her duties, she tests components for the brake systems of the new models of cars. It is important that the new designs of brake systems do not squeal, that is, emit objectionable noise when they are applied. Brake squeal is caused by vibration and distortion of the brake rotor and pads as the rotor turns. Susan sets up the laser testing equipment to measure distortion of the components as they move, using a triangulation method she learned about in her photonics program. She correlates the amount of distortion of the rotating components with noise emitted by the brakes. The engineers perform a computer analysis of the distortion and redesign the components. Susan then retests the new designs. The process is repeated until the noise is reduced to an acceptable level.

BASIC CONCEPTS

Introduction

Lasers for industrial measurement

The lasers most often used for testing, measurement, and alignment in industrial settings have been the HeNe laser operating at a wavelength of 632.8 nm and diode lasers, operating at wavelengths in the red-orange portions of the spectrum.

HeNe lasers—HeNe lasers were originally used for almost all the industrial measurement applications to be described in this module. They were available in stable, long-lived commercial models early in laser history and were relatively inexpensive. Most of the industrial applications first developed involved HeNe lasers.

For alignment applications, in particular, the orientation of the laser beam to the laser housing is critical. Laser manufacturers design the beam to be highly stable and to have minimum wander, relative to the laser housing.

The angular precision of the pointing of HeNe lasers can be in the *microradian* region. For alignment applications at large distances, the accuracy is limited by atmospheric turbulence and by the random wander of the laser beam relative to its housing. A t shorter distances, the resolution of the position-sensitive detectors to be described later becomes the limiting factor.

Table 1 shows typical characteristics of a HeNe laser suitable for alignment applications.

Table 1. Characteristics of a HeNe laser for alignment applications

Power output	2 mW
Mode	TEM_{00}
Beam divergence angle	1.6 milliradian
Beam diameter	0.5 mm
Beam wander	<30 microradian
Long-term power drift	<5%

Diode lasers—Semiconductor diode lasers, emitting at visible wavelengths, were not available at the time that many of the industrial applications of alignment and measurement were first developed. But now, because of their small size, low cost, and high efficiency, they are displacing HeNe lasers in many cases. The diode lasers that have been most often used are AlInGaP lasers (aluminum-indium-gallium-phosphide), emitting at a wavelength near 670 nm.

They do have a much larger beam divergence than that of the HeNe laser, perhaps as much as 0.3 radian, so that collimating optics are needed. Commercial diode lasers are available with collimating optics integrated into a housing with the laser.

In more recent times, blue semiconductor diode lasers have become available, with adequate power for alignment and measurement. They provide operation in the 410–430 nm region with adequate output power for the type of industrial applications that we are considering. They offer the advantage of shorter wavelengths, which allows focusing to a smaller spot. We may expect to see them used for industrial applications in the future.

Tracking and Alignment

A variety of manufacturing and assembly operations require components to be aligned properly, both in position and angular orientation.

Angle tracking

Angle measurement units—Before beginning the discussion of angle tracking and alignment devices, you should understand the terminology that describes those concepts. Two systems of units are frequently encountered for angular measurements. The first uses the *degree,* defined as 1/360 of a circle. The second uses the *radian,* defined as $\frac{1}{2\pi}$ (approximately 1/6.28) part of a circle, as the basic unit. The two systems are compared below.

Basic Unit	*Degree* (°)	*Radian*
Subunit	Minute (1/60 degree)	Milliradian (10^{-3} radian)
Subunit	Second (1/60 minute)	Microradian (10^{-6} radian)

You should memorize the following conversion factors:

1 radian = 57.3 degrees = $360°/2\pi$
1 degree = 17.45 milliradians

When one is using the degree system, the terms *arc-minute* and *arc-second* are often used to avoid confusion with units of time.

To specify precisely the direction that you must point an optical instrument or system to cause the optical axis to fall on the desired spot, we must define how we will manipulate the instrument. This should be done in a way that will allow another person to duplicate the direction and achieve the same result. Gravity (the plumb-bob direction) is the reference to which most systems are aligned. In the gravity system, we define the following two angular measurements:

- *Elevation angle*—The angle, as seen from the side, lies between the optical axis and the gravitational horizontal plane, as in Figure 1a. Changing the elevation angle causes the axis to sweep up or down. This angle is sometimes called the *pitch angle*.
- *Azimuth angle*—The angle, as seen from the top, lies between the optical axis and some arbitrary reference direction in the horizontal plane, also shown in Figure 1b. Changing the azimuth angle causes the optical axis to sweep to the left or right. The term *yaw angle* means the same thing.

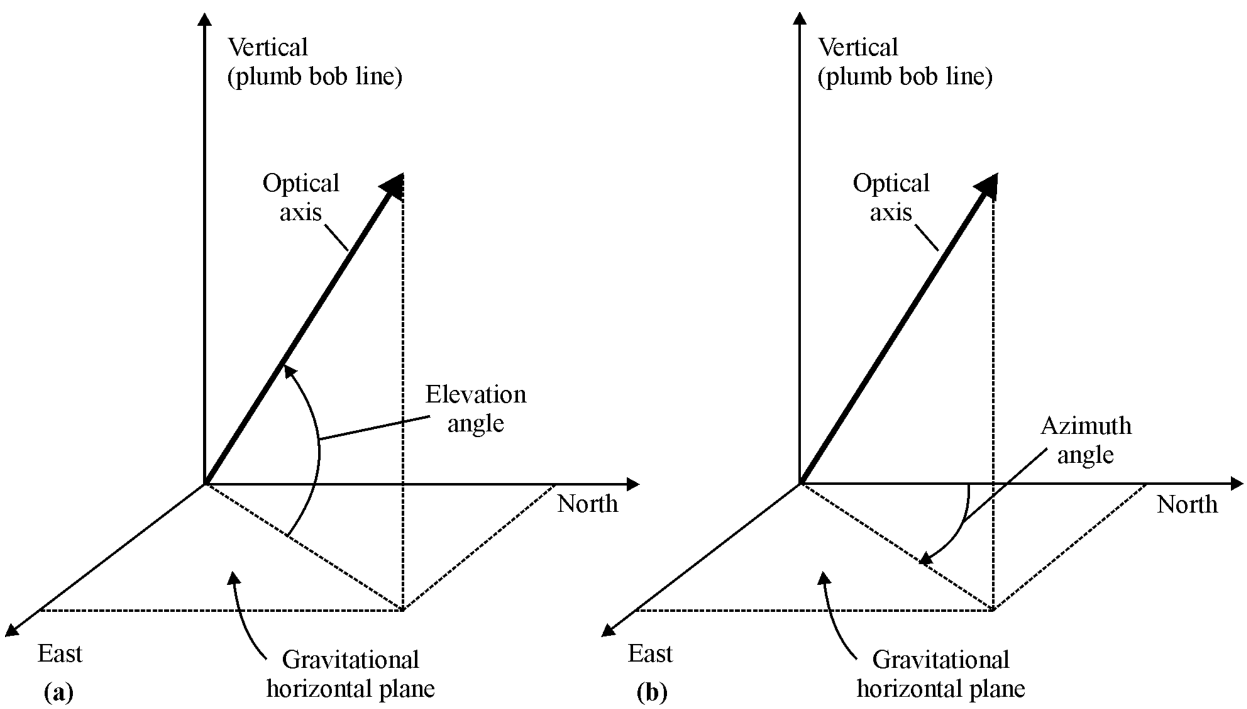


Figure 1 *(a) Rotation of optical axis in elevation. (b) Rotation of optical axis in azimuth. The arrow denotes the optical axis. The directions denoted north, east, and vertical are three mutually perpendicular axes.*

The proper rotation in elevation and azimuth angles allows the optical axis to point in any direction in space.

Angle-tracking techniques—An optical angle-tracking system consists of (1) an angle-sensitive receiver and (2) an object (or target) to be tracked, such as a laser, an LED, a retroreflector, or any other such object that can be optically differentiated from its background.

In its simplest form, the *angle-sensitive receiver* consists of (1) an objective lens with a known focal length, and (2) a photosensitive detector that can indicate the position on the surface at which the target radiation is focused.

We deduce angular information from the known focal length of the optics and the known position sensitivity of the detector, as shown in Figure 2. Suppose light from a source at a large distance (distance much larger than any of the dimensions of the optical system) is collected by the objective lens and focused on the position-sensitive detector at point y. From geometrical optics, we can calculate the angle between the incoming bundle of light rays from the distant target and the optical axis common to the tracking system as in Equation 1.

$$y \simeq f\alpha, \text{ or } \alpha \simeq \frac{y}{f} \qquad (1)$$

where α = angle in radians between the incident ray and the optical axis,
y = lateral displacement of the image at the focal detector plane of the lens, and,
f = focal length of the lens. We note that y and f must be in the same units.

If α is more than 5 or 6 degrees, Equation 1 must be replaced by Equation 2,

$$\tan \alpha = \frac{y}{f} \qquad (2)$$

if precise results are desired.

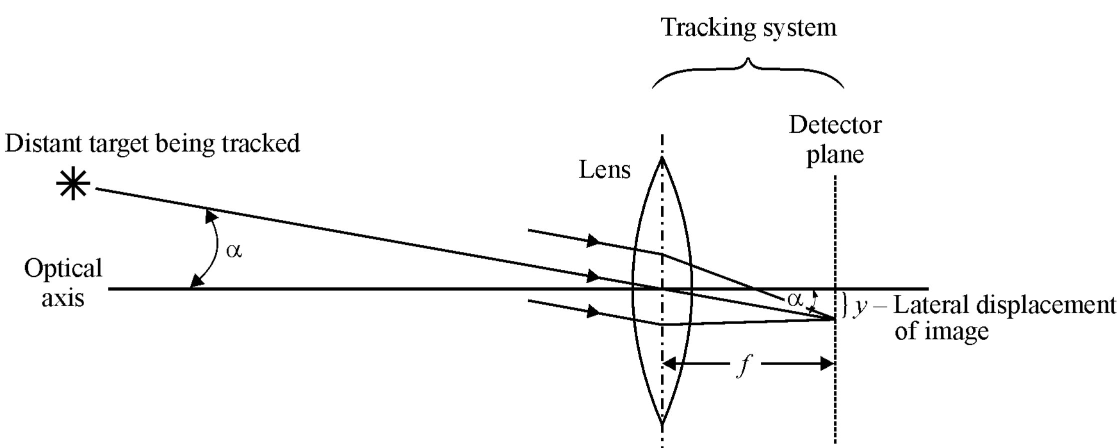


Figure 2 *Formation of an image from a small target positioned along an angle α measured from the optical axis*

It is worth noting that receiving systems with a relatively long focal length produce a larger displacement in the focal plane than do systems with shorter focal length. Thus systems with longer focal length are more sensitive for detecting off-axis displacements.

Example 1

Given: Light from a distant object is collected by a lens with a 10-cm focal length. It is focused to an image located 2 mm from the center of a position-sensitive detector.

Find: The angle between the direction of the incident light and the optical axis

Solution

From Equation 1, the angle is

$$\alpha \simeq \frac{y}{f} \simeq \frac{2 \text{ mm}}{100 \text{ mm}} = 0.02 \text{ radian, or approximately 1.2 degrees}$$

We notice that this angle is small enough so that we can use Equation 1, and not Equation 2.

Position-sensitive detectors—Recall that if the focal length of the objective lens and the linear displacement of the image from the optical axis are known, the angle α between the object heading and the optical axis can be calculated. The devices that allow this measurement of angular displacement usually produce a voltage that corresponds to the position of the image on the face of the detector.

Figure 3 shows some of the more common position-sensitive detectors. They include:

- Quadrant photodiodes,
- Silicon position sensors, and
- Vidicons.

We will describe the characteristics of each of these detectors.

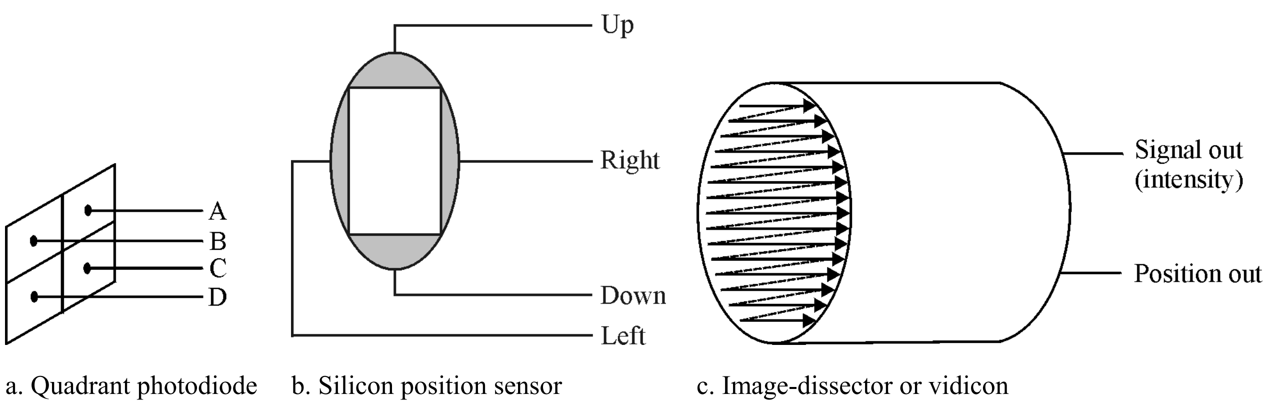
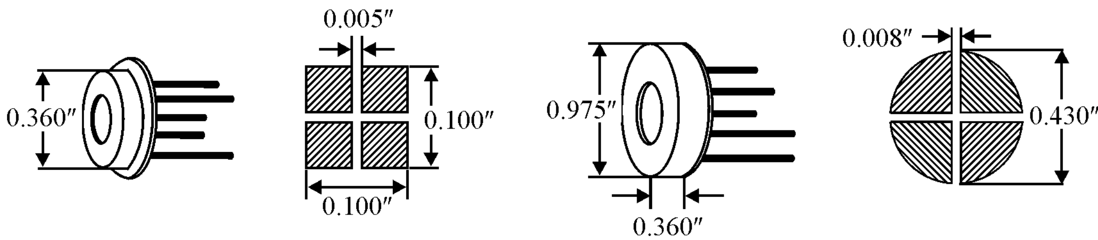


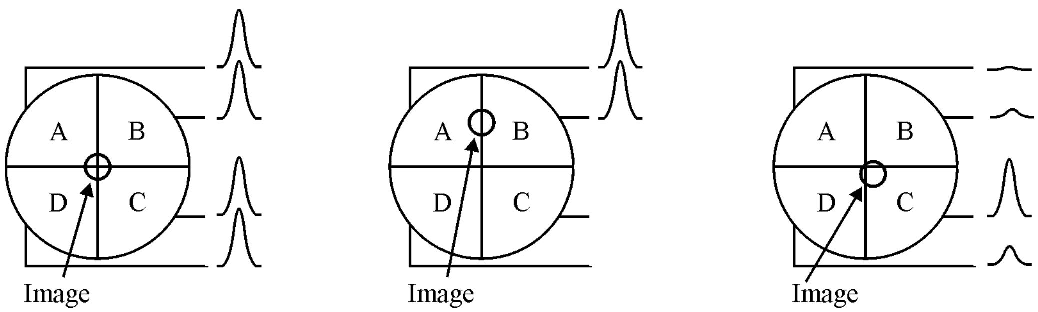
Figure 3 *Typical position-sensitive detectors*

Quadrant photodiodes—A quadrant photodiode is an imaging surface that has been physically separated into four equal-area segments. Each segment has a separate connection for signal output, as shown in Figure 4a. Position information is derived from the relative signal output from each segment, as shown in Figure 4b. When the focused image is centered on the quadrant detector, each segment receives the same amount of optical radiation and all four signal outputs are equal. As the image moves around on the detector surface, corresponding to an angular change of the object being tracked, more radiation falls on one or two of the segments and less on the other segments.

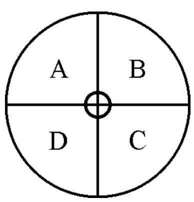
Figure 4c shows how position information is provided by a quadrant photodiode. If more optical energy falls above the horizontal line, more photocurrent flows through the upper segments (A and B) than through the lower segments (C and D). In trying to determine the up-down position of the spot, we are concerned with the relative amplitudes of the quantity (A+B)-(C+D). Similarly, the quantity (A+D)-(B+C) gives information about the left-right position. In practice, it is usual to perform this analysis electronically, using operational amplifiers to compute the appropriate sums and differences.



a. Quadrant photodiode construction



b. Comparative outputs for a pulsed image falling in different positions on the detector



Up-down centering: Compare signal from segments A and B (upper) to signal from segments C and D (lower).

Left-right centering: Compare signals A and D (left) to signals from B and C (right).

c. Deducing spot position from output signals

Figure 4 *Quadrant photodiodes*

Quadrant photodiodes are fabricated from silicon and have the same spectral response, rise time, responsivity and noise characteristics as single-element silicon photodiodes.

There is some amount of nonlinearity in the response of quadrant photodiodes. When the image is near the center of the device, all four quadrants are illuminated approximately equally and small movements of the image result in small changes in the energy reaching any one quadrant. But when the image moves near the edges, there will be at least one quadrant receiving little energy and small movements will result in large percentage changes in the signal from that quadrant. To reduce this problem, one may use an objective lens that yields a larger image size, so as to keep the energy in each quadrant more nearly equal.

Another problem is that if the image is very small and falls on the finite width of the separation between segment, the output may be distorted. This effect may also be reduced by defocusing the image or by using a longer focal length lens.

Silicon position sensors—A silicon position sensor consists of a segment of photodetective silicon with either two or four terminals for signal output and a terminal for application of a back-bias voltage, as shown in Figure 5 for a four-terminal device. This structure is sometimes called a lateral-effect photodiode. Note that there is no separation into segments, as in a quadrant photodiode.

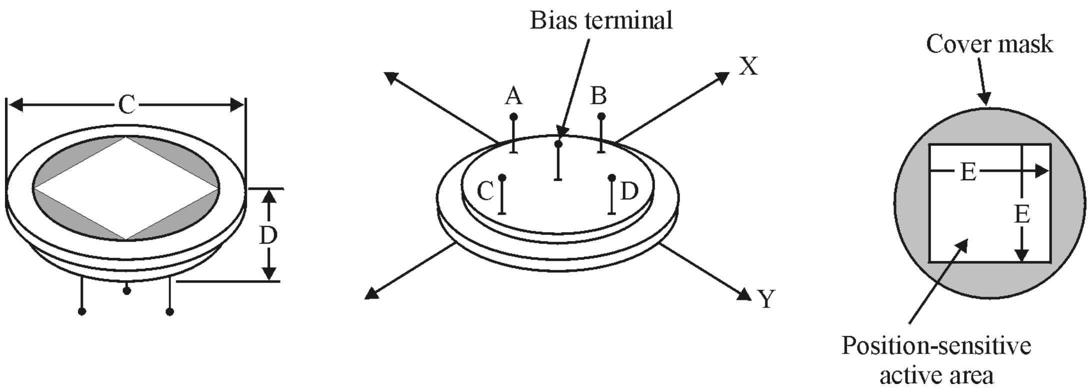


Figure 5 *Silicon position sensor*

Position information with a silicon position sensor is also deduced by comparing the signal outputs from each terminal. Assume that an optical image is focused on the detector as shown in Figure 6. The light will cause a current to flow. But because of the construction of the device, the current can flow only by traveling through the silicon to each of the four output terminals. One measures the flow from the output terminals A, B, C, and D to ground. Because the silicon has a given resistance per unit length, more current will flow through the nearer terminals (lower resistance) and less through the terminals that are farther from the focused image (higher resistance).

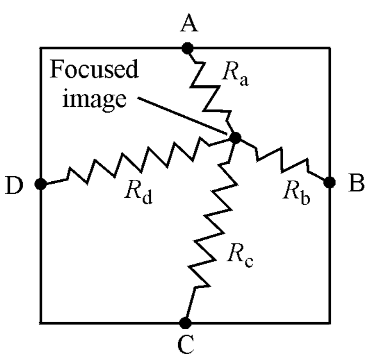


Figure 6 *Unequal resistance paths on the silicon sensor*

These devices have some advantages over quadrant photodiodes. Because there is no gap between different segments in the active area, the size of the image is not subject to constraints on the minimum diameter. A second advantage is that position information is available as long as the image falls somewhere on the active area of the detector.

Vidicons—A vidicon is a type of imaging detector used in closed-circuit television cameras. The structure of a vidicon is shown in Figure 7. The photosensitive surface is photoconductive, that is, incident light produces free electrical charges that migrate through the surface from the front to the back side. Electrical charge on the photosensitive surface changes with the intensity of incident light. An electron beam is scanned in a raster pattern over the photosensitive surface, on the opposite side from that struck by the light. The amount of charge that is replaced by the scanning electron beam is monitored, along with the beam's position to give information about the position and intensity of the image. This gives the information needed to determine the displacement of the image in an alignment system.

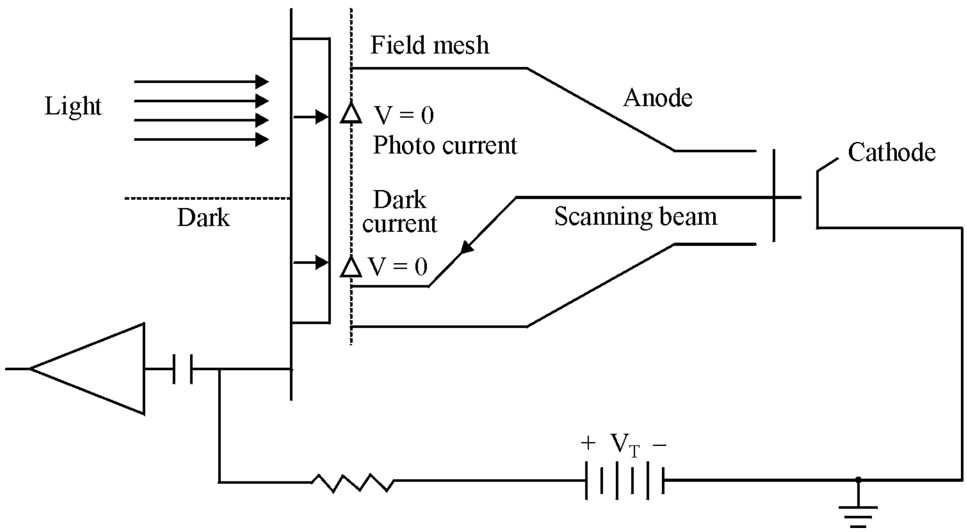


Figure 7 *Vidicon construction*

Applications—Laser angle-tracking systems are used to track the location of objects as they move about in space. They also are used to determine their orientation. These could be objects such as machine tools or robot arms.

A representative system to track the motion of an object could include a laser, a collimator, a retroreflector mounted on the moving object, an angle-sensitive receiver such as we have described earlier and a servo-controlled pedestal that keeps the optical system pointed at the object.

In an instructive example of the need for angular alignment in manufacturing, two rotating shafts had to be aligned so that the directions of the shaft centerlines were parallel. Four angular orientations had to be measured. Two components were measured for the direction of each shaft relative to the line between the shafts. A position-sensitive sensor and a 670-nm diode laser were mounted on each shaft. The four angles were measured and the amount of adjustment required for each shaft was determined. The system allowed the two shafts to be aligned to an accuracy of 0.001°. This measurement would have been very difficult with any other technique.

Alignment

One obvious use of low power lasers is to align objects, such as parts of manufactured products. Objects can be aligned relative to a laser beam with high accuracy.

Alignment systems—Laser-based alignment systems are used in manufacturing for fabrication of large-scale devices. They allow positioning of components along a straight line.

In the general alignment process, one projects the laser beam, locates its center with a position-sensitive detector, usually a quadrant photodiode, and then measures the displacement of the component to be aligned from the center of the beam. The quadrant photodiode can be attached to the part that is to be positioned in some cases. It is possible to measure vertical and horizontal displacement from a straight-line reference established by a low-power laser, either HeNe or diode, and thus to position components accurately.

A block diagram of an alignment is shown in Figure 8. The laser is a HeNe laser or diode laser with output power around 1–2 mW. It is amplitude-modulated at a frequency around 10 kHz in order to reject ambient radiation by using an electronic filter in the readout unit. The detector is a quadrant photodiode that is capable of reading displacements of less than 0.002 inch.

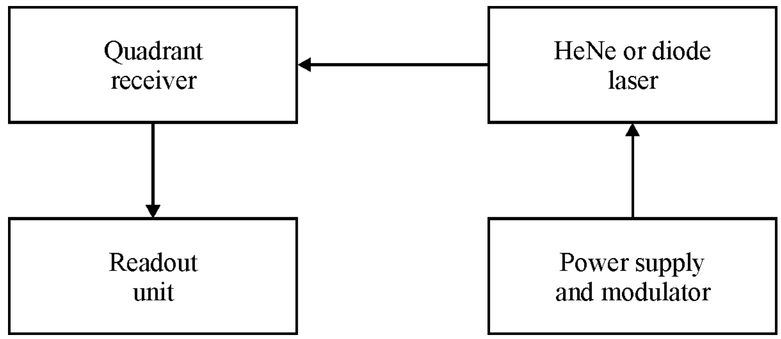


Figure 8 *Laser alignment system*

Laser alignment offers significant advantages compared to conventional mechanical alignment, which can be difficult and cumbersome. Laser alignment has been used to align large machines and aircraft assemblies to greater accuracy and at lower cost than mechanical methods.

Optical square—An optical square (Figure 9) aids in the vertical alignment of upright structures (such as bulkheads) and other structures perpendicular to the optical axis.

The optical square uses a pentaprism (a five-sided prism) that is rotated about the axis of the incoming beam. The pentaprism deflects the beam by 90 degrees, so as to sweep the beam into a plane as it rotates. Then structures can be aligned with respect to this plane defined by the scanning beam of light.

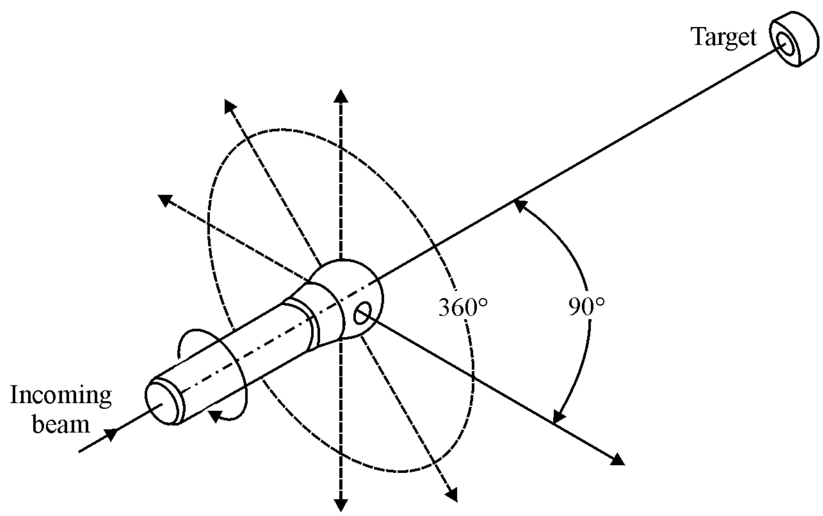


Figure 9 *Optical square*

The pentaprism is used for this application because it has the property of accurately deflecting the beam by 90 degrees, even if it is not accurately aligned, or even if vibrations or wobble are present in the mechanically rotating pairs. Figure 10 shows a pentaprism and how an incident patterns is projected at 90 degrees from its incident direction.

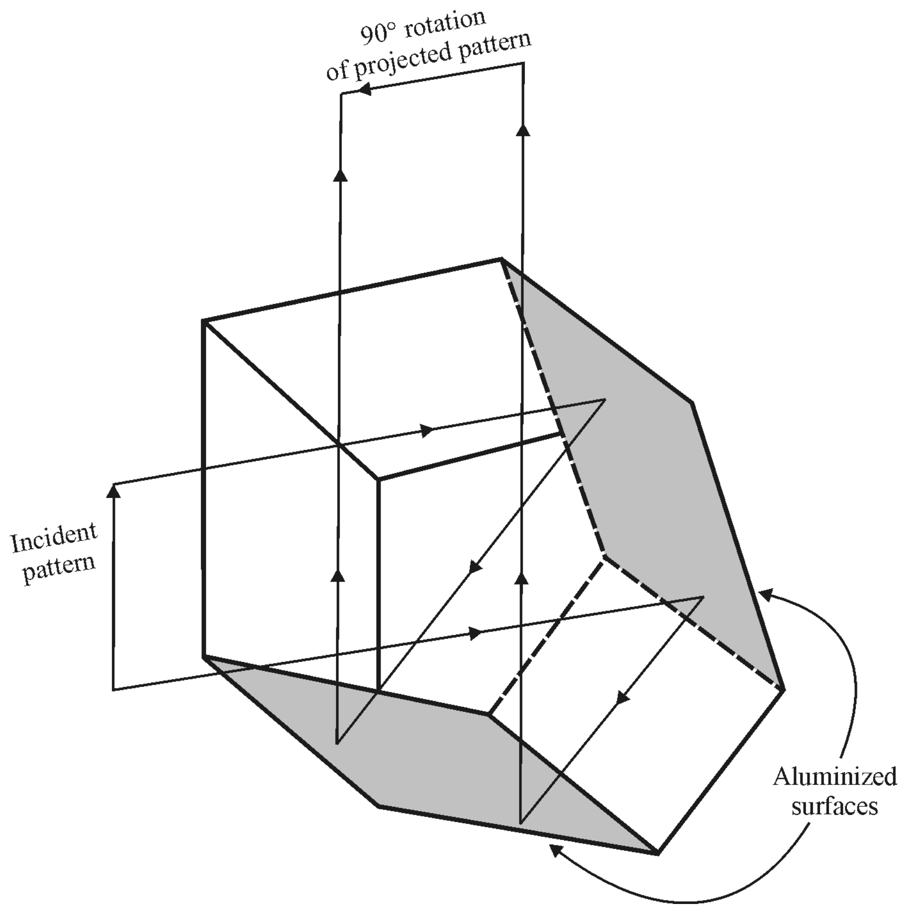


Figure 10 *Drawing of pentaprism and 90° rotation of an incident pattern*

Applications—Laser alignment systems have been used in many assembly jobs where precise positioning is mandatory. Laser alignment has been used in the aircraft industry, where it is necessary for wing and fuselage sections to be accurately aligned over large distances. In one case, for a jet, a HeNe laser was used to align the wing engines in supersonic transport prototypes to an accuracy of plus or minus 0.04 mm.

In another aircraft application, fuselage sections for jumbo jet aircraft were lined up. Alignment holes were drilled in the sections, which were then lined up along the beam, one by one, for distances around 100 feet. The accuracy of the alignment was ten times better than that of other techniques.

In another industrial application, the straightness of the motion of large machine tools was checked. In one example, the motion of a boring mill was measured to an accuracy of 0.0005 inch over a total motion of 22.5 feet. Measurements were made in both the horizontal and vertical directions. Knowledge of the straightness of the runout of the machine allowed compensation of the variations, so that the quality of the manufactured parts was improved. Making such measurements to this degree of precision is extremely difficult with other techniques.

Laser alignment offers advantages over mechanical alignment for large structures and machines. Mechanical alignment of such items tends to be difficult and cumbersome. Laser alignment is lower in cost and offers greater accuracy.

Example 2: Error in position with a quadrant-detector-based alignment system

Given: The HeNe laser described in Table 1 and a suitable quadrant-detector-based-alignment system

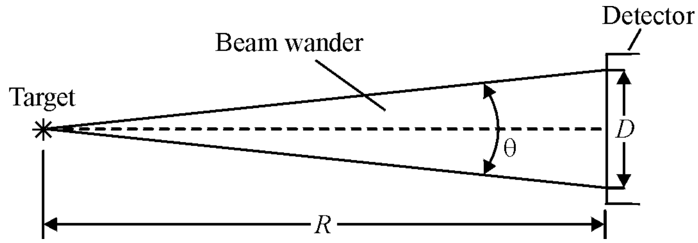
Find: The error in the position of an object aligned to the center of the beam at a distance of 100 feet from the laser. Neglect possible effects of atmospheric turbulence. (Table 1 gives beam wander as $<30 \times 10^{-6}$ radians.)

Solution

The error will be dominated by the beam wander. At a distance *R,* the change in position of the center of the beam (*D*), and therefore the error in determining the position, will be:

$$D = R\theta$$

where θ (in radians) is the angular deflection of the beam as it wanders.



Thus we have:

$$D = 100 \text{ feet} \times 30 \text{ microradians} = 3 \times 10^{-3} \text{ feet} = 0.036 \text{ in.}$$

Metrology and Inspection

Lasers are used for many applications in surface profiling, measurement of product dimension and nondestructive testing.

Surface profiling

Profiling of surface contours is important in many manufacturing operations. It is used to determine surface finish, dimensional tolerances, and the thickness of manufactured products in automated processes, with feedback control to keep the thickness within prescribed limits. In addition to determining the shape of the surface, it can be used to determine the position of a surface as it changes.

Conventionally, surface contouring has been done mechanically with a sharp probe in mechanical contact with the surface. Use of laser profiling offers a number of advantages. There is no physical contact with the surface, and thus no possibility of damage to the surface and no contamination. There is no wear on the measuring probe. And laser profiling is highly compatible with automation.

A number of laser profiling methods have been developed. We will describe several, including *triangulation* devices, *two-spot* systems, and a *focus* method.

Triangulation devices—Triangulation devices, illustrated in Figure 11, involve a common method for laser profiling. A spot of light is projected from the laser source onto the surface. Light reflected from the surface is imaged on the detector, which may be a silicon position-sensitive photodiode, as described earlier in this module, or an array of photodiodes. When the position of the surface changes by Δz, the position of the imaged spot changes by Δx. The detector measures Δx, and the change in surface position is determined from Equation 3:

$$\Delta z = \frac{\Delta x \sin \phi}{m \sin \theta} \qquad (3)$$

where m is the magnification of the lens, ϕ is the angle between the plane of the detector and the direction of the light striking it, and θ is the angle between the initial light beam and the reflected light. We note that the magnification is the distance from the lens to the detector divided by the distance from the surface to the lens. This equation is an approximation. It is valid when the angles and distances do not change much as a result of the change in the position Δz of the surface.

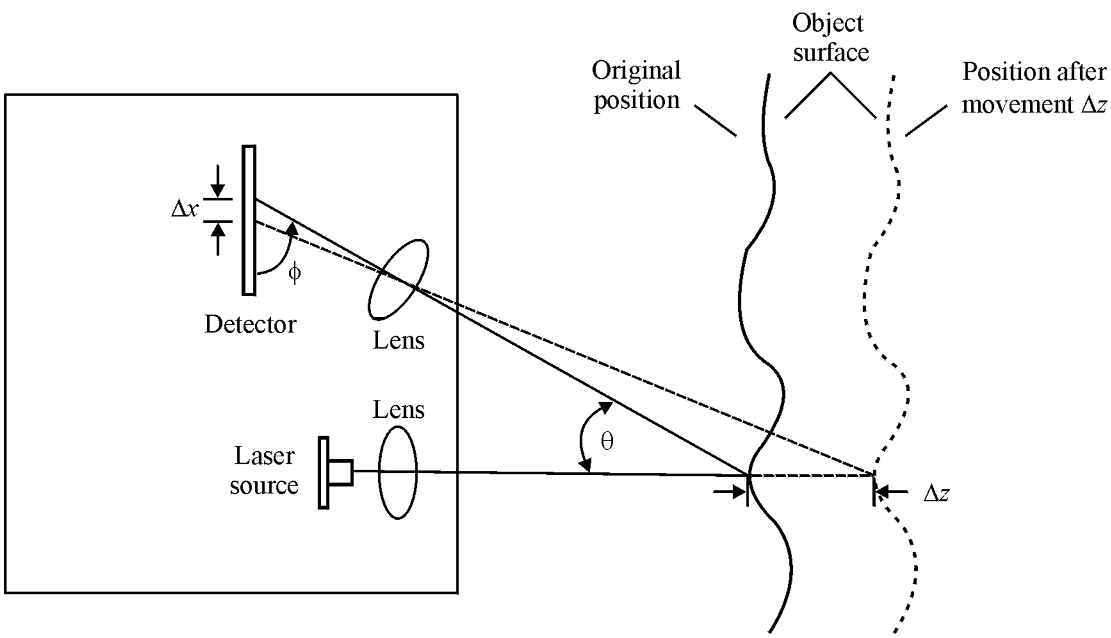


Figure 11 *Optical triangulation measurement. Δx is the motion of the beam on the detector when the surface moves by Δz from its original position, indicated by the dashed line.*

Commercial models of optical triangulation equipment are available, offering resolution down to the micrometer range. Although the method was originally developed using HeNe lasers, current devices seem to use diode lasers more often.

Example 3: Calculation of displacement Δz of a surface

Given: An optical triangulation device in which the angle θ is 20 degrees, the angle ϕ is 70 degrees, and the magnification m is 0.3

Find: The displacement in surface position if the image movement Δx on the position-sensitive detector is 0.5 mm

Solution

Substituting in Equation 3, $\Delta z = \dfrac{\Delta x \sin \phi}{m \sin \theta}$, we have:

$$\Delta z = \frac{0.5 \text{ mm} \sin 70°}{0.3 \sin 20°} = \frac{0.5 \text{ mm} \times 0.940}{0.3 \times 0.342}$$

$\Delta z = 4.58$ mm

Two-spot systems—A different profiling system uses two laser beams that strike two spots of light on the surface. This system is shown in Figure 12. The separation of the spots depends on the distance from the sensor head to the surface. The separation *S* of the spots is given by Equation 4:

$$S = \frac{2D}{\tan \theta} \tag{4}$$

where *D* is the displacement of the surface from a nominal reference position and θ is the angle between the surface and the laser beams. When the surface is at its reference position, the two spots overlap. When the surface moves closer to its reference position, the spots move closer together. When the surface moves away from its reference position, the spots separate.

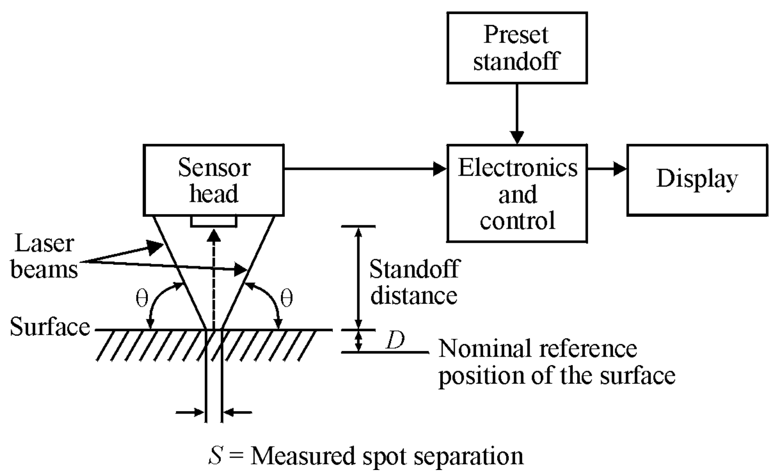


Figure 12 *System for surface position measurement using two laser beams that strike the surface at angle* θ

In order to measure the separation of the spots, the sensor head contains a lens that focuses light from the spots and a detector which is scanned rapidly across the focal plane. The detector generates two pulses as it scans through the spots. The separation of the pulses in time is proportional to *S,* and thus to *D*. Because θ is known, the value of *D* can be obtained using Equation 4.

Focus method—In a different method of laser profiling, an objective lens focuses the laser light onto the surface. Reflected light is collected by the same lens and directed by a beamsplitter to an array of small photodetectors. The pattern of the reflected light is analyzed to determine whether the focal point of the lens is above or below the surface. Then the detection system generates a signal that repositions the lens and restores the focal point to the surface. The lens movement accurately follows the surface contour. This movement is monitored by an inductive displacement transducer that generates a signal indicating the profile of the surface. Such systems can provide accuracy *down to the nanometer range*.

Applications—We have described several methods of measuring surface profiles and contours. These methods form the basis of a class of instruments that are used to measure the surface properties of manufactured parts. The measurements can be fast, accurate and highly automated.

A variety of commercial instruments have become available. One can use them to measure surface roughness or the general shape of a manufactured part to determine whether it falls within specified tolerances. The laser beam is scanned over the surface as the contour is mapped. Parts that are out of specification, either in surface roughness or in shape, can be automatically rejected or returned for remachining.

Laser profiling measurements have been used in industry for a wide variety of applications. Some applications have included determining the thickness of photopolymer strips in integrated circuit production, determining the waviness and surface roughness of valves in the automotive industry, and noncontact measurement of the dimensions of soft clay models of new products.

The choice of a particular instrument for a specific measurement will depend on the accuracy required in the surface position, the range over which the measurements must be made, the resolution required on the surface and the speed required. The wide variety of laser-based profile measurement devices allows the user the capability to find an instrument that matches the needs of a particular application.

Measurement of product dimensions

The emphasis in the preceding discussion has been on the measurement of *surface profiles,* things like shape and surface roughness. It is often important also to measure the *dimensions* of manufactured objects—to ensure that the product size is within prescribed limits. Three main methods have been used for such measurements: separate measurements of the positions of two sides of the object (called *dimensional comparison*), *obscuration* of a laser beam passing over the object, and *diffractive* measurements, suitable for measuring small dimensions.

Dimensional comparison—Such measurements may be made by using two sensors, one measuring the position of each side of the object. The thickness is then simply the difference in the two positions. If the object is on a supporting structure (a conveyer belt or rollers), the measurement may be made from one side, measuring first the position of the support and then measuring the position of the top surface of the object.

The triangulation method, described above for surface profile measurements, is frequently used in this application. It has been used to measure parts moving on a conveyer belt, using the top position of the belt as a zero reference. Then, as manufactured parts move under the sensor head, the thickness is determined by comparison of the position of the top of the object and the zero reference.

Beam obscuration—In this method a laser beam scans over the product. The scanning may be accomplished either by moving the beam or by keeping the beam stationary and moving the object through it, usually on a conveyer belt. The beam is detected by a photodetector. When the object is in the path of the beam, the beam is blocked and does not reach the detector. The length of time that the beam is blocked, together with knowledge of the speed of the scan, allows one to determine the dimension.

Of the various methods for determining product dimension, this is probably the easiest to implement and to interpret. Measurements may be made in one, two or three dimensions. Closed loop control of the manufacturing process can be implemented to change the dimensions and keep them within specifications.

Measurement of small dimensions by diffraction—Another use of lasers for measurement of product dimensions involves the use of diffraction. Measurement of small product dimensions can be achieved with high accuracy by the use of the diffraction pattern produced when a laser beam bends around a small object.

Light waves are diffracted (or bent) around the edges of opaque objects, so that some light is present in the geometrical shadow of the object. The detailed structure in the shadow region depends on the profile and dimensions of the edge (or edges) that cause the diffraction. This allows one to gain information about the profile of the edge through measurements made on the diffraction pattern. This is the underlying principle for the use of diffraction to measure the size, shape and displacement of objects.

Diffraction was known as a physical phenomenon long before the advent of lasers. It was not used for testing because of the lack of coherence of the available light sources. Diffraction patterns tended to be dim and good diffraction patterns were obtained only with very small objects. The availability of lasers has changed this. The brightness and coherence of lasers allow for easy observation of well-defined diffraction patterns.

The use of diffraction for measurement of manufactured products still is applied mostly to relatively small objects. As an example of the measurement of product dimension, we consider the measurement of wire diameter. The diffraction pattern produced by a wire inserted in the beam of a laser with diameter larger than the wire is a pattern of dots as shown in Figure 13. There is a central undiffracted spot, surrounded by less bright spots at distances whose separation varies inversely with the wire diameter *D,* according to Equation 5:

$$\sin \phi_n = \frac{n\lambda}{D} \tag{5}$$

where ϕ_n is the angle between the dotted line to the *n*th spot from the direction of the laser beam, *n* is an integer (*n* = plus or minus 1, 2, 3, etc.), and λ is the laser wavelength. The positive values for *n* refer to spots above the undiffracted laser beam spot on the screen and the negative values to spots below. As the wire diameter decreases, the diffracted spots on the screen spread farther apart. Equation 5 can be used to obtain *D* from geometrical measurements of the positions where diffracted spots appear.

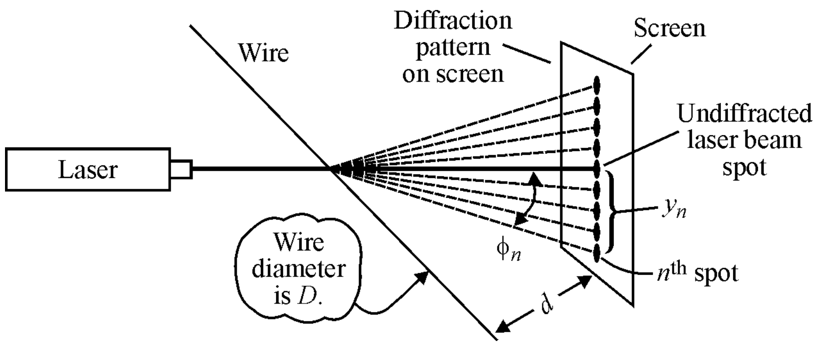


Figure 13 *Formation of diffraction pattern by a wire*

This measurement of wire diameters via diffraction has attractive features. There is no contact with the wire. Movement of the wire *along the direction of its length* does not affect the measurement, so that wires can be measured while moving, for example, during extrusion. Also, motion of the wire *perpendicular to its length* (so long as it remains within the beam) does not affect the separation of the spots, so the measurement is not sensitive to small vibrations. It is also possible to measure dimensions of other small objects, for example, small slits or openings in products.

Example 4: Wire diameter determination

Given: The diameter of a wire is to be measured with an argon laser wavelength of 514 nm. In the measurements, the position of the 3rd diffracted spot is located y_n = 97.3 cm from the center of the undiffracted spot, when the spots are projected on a screen. The screen is located d = 16 meters from the wire.

Find: The diameter of the wire

Solution

Equation 5 relates the parameters of this measurement. If we rearrange Equation 5, we have:

$D = \dfrac{n\lambda}{\sin\phi_n}$ where $n = 3$, $\lambda = 514$ nm, and $\phi_n \simeq \tan^{-1}\dfrac{y_n}{d}$.

From $\phi_n = \tan^{-1}\dfrac{y_n}{d} = \tan^{-1}\dfrac{97.3\text{ cm}}{1600\text{ cm}} = \tan^{-1}(0.0608) = 3.48°$

Thus $\sin\phi_n = \sin 3.48° = 0.0607$

Then $D = \dfrac{n\lambda}{\sin\phi_n} = \dfrac{3 \times 514 \times 10^{-9}\text{ m}}{0.0607} = 2.54 \times 10^{-5}$ m

$D = 2.54 \times 10^{-3}$ cm = 0.00254 cm = 0.0254 mm, a very thin wire.

Applications—Lasers have been used for measuring the dimensions of many different types of manufactured products, such as sheet plastic, sheet metal, piston rings, spark plugs, fuel injector components, valve lifters, fuel rods, munitions, roller bearings and the amount of material used in food products.

Measurement of sheet products, like the thickness of metal sheets emerging from a furnace, have frequently been carried out using the dimensional comparison method. Beam obscuration techniques have often been used to measure the diameters of products like tubes and hoses, and their concentricity by rotating them within the beam. Diffractive measurements are applicable only to parts in which there is a small dimension, either a gap or a narrow feature, to be measured.

Table 2 compares some of the characteristics of these dimensional measurement techniques.

Table 2. Typical characteristics of laser dimensional measurement

Method	Minimum resolution	Accuracy	Typical use
Dimensional comparison	2–10 μm	0.1% of measurement	Thickness of sheet products
Beam obscuration	0.5–5 μm	1.0%–0.1% of measurement	Diameter of rods
Diffraction	0.025 μm	0.12 μm	Wire diameter

EXERCISES

1. Define the terms *elevation angle, azimuth angle,* and *radian.* Draw and label diagrams illustrating the rotation of an optical axis in *elevation* and in *azimuth*.
2. Describe the basic elements of angle-tracking systems. Your description should include an angle-sensitive receiver.
3. Describe how angle measurements may be deduced from measurements of the lateral displacement of the image at the focal plane of the objective lens in an angle-tracking system.
4. Describe, in terms similar to the text, the following types of position-sensitive detectors: *quadrant photodiode, silicon position sensor,* and *vidicon*. Include a drawing of each detector.
5. Draw and label a diagram of a typical commercial alignment system and describe the operation of the system. The components shown in your drawing should be similar to those in the text.
6. In an angle tracking system with a lens that has a focal length of 40 cm, the light from a distant target enters the system at an angle of 0.05 radians from the optical axis. How far from the center of the detector will the image be located?
7. If you are using an optical triangulation position sensor in which the angle θ is 15 degrees, the angle ϕ is 80 degrees, the magnification m is 0.5, and the image movement Δx on the position-sensitive detector is 0.7 mm when the surface is displaced, how large was the surface displacement Δz?

LABORATORY

Materials

HeNe or collimated visible-wavelength diode laser with output power around 1 mW

Digital voltmeter (DVM)

Optical rail (at least 1.5 meters long) and mounts

Transverse mounting stage for optical rail (movable perpendicular to the rail)

Translation stage for optical rail (movable in the direction of the rail)

Silicon position sensor

DC power supply

Lens and lens holder

Goniometer

Miscellaneous electronic components

Wire sample mounted in graduated circle

Polaroid film pack holder

Polaroid camera

Polaroid film

Millimeter graph paper (tracing type)

Meterstick

Procedures

Caution: The laser beam and its reflections may be an eye hazard. Take all necessary safety precautions necessary for the classes of lasers being used.

The procedures consist of two parts. In the first part, you will assemble and operate a laser angle-tracking receiver employing a silicon position sensor and measure the angular displacement of a laser mounted on a linear translator.

In the second part, you will measure the diameter of a sample of wire using a diffraction method.

Angle tracking—In this part of the laboratory, you will assemble and operate a laser angle-tracking sensor and measure the angular alignment of a laser.

1. Fabricate the circuit shown in Figure 14. Use 2-kΩ, 1% resistors for the four resistors: R_a, R_b, R_c, and R_d.
2. Mount the silicon position sensor on the optical rail so that the face of the detector is perpendicular to and centered on the rail.
3. Attach the laser to the transverse mounting stage. Then mount the transverse stage on the rail so the laser beam is parallel to the rail and can be moved in a horizontal direction sweeping across the face of the detector. Adjust the position of the detector so the laser beam strikes the center of the detector's sensitive area. In this portion of the measurement, the lens is not used. See Figure 15.

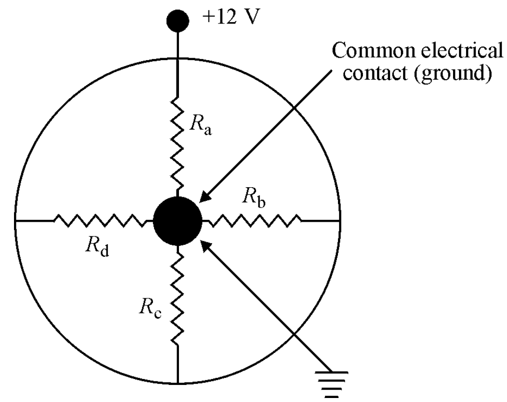


Figure 14 Resistor circuit

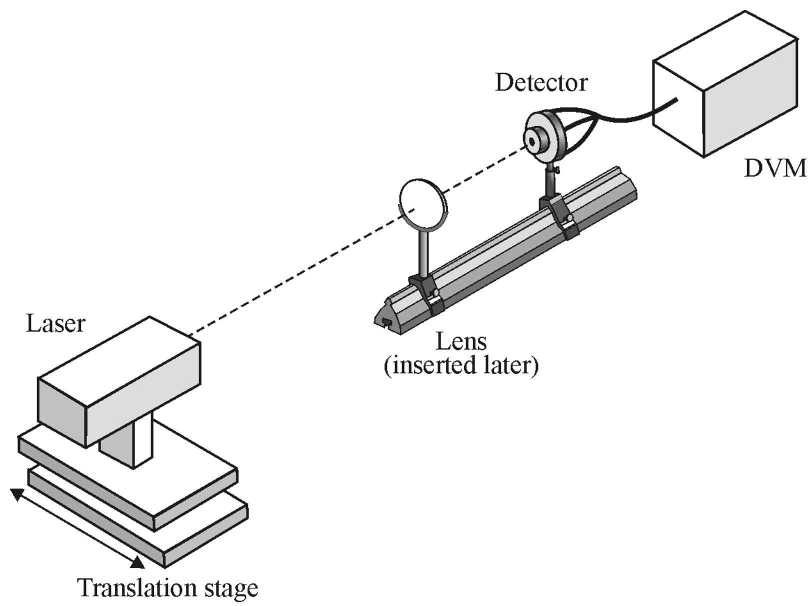


Figure 15 *Test setup*

4. Connect the DVM so that it will measure the voltage across either R_a or R_c.
5. Align the detector so that the beam moves along the horizontal axis of the detector. Do this by moving the laser in the horizontal direction while monitoring the voltage across either R_a or R_c. If the voltage changes, rotate the detector around the axis parallel to the laser beam and repeat the motion. A larger change in voltage indicates that you rotated the detector in the wrong direction. Continue rotating the detector and translating the laser until the voltage remains constant as the beam crosses the detector surface.
6. Connect the DVM so that it measures the voltage across R_b. Move the laser so that the beam strikes one edge of the detector. Move the beam across the sensor in 1-mm increments. At each position, record the voltage V_b and position in a data table similar to the one below.

7. Repeat step 6 but measure the voltage V_d across R_d.
8. Plot the voltage across R_b and R_d—along the y-axis—as a function of the beam position—along the x-axis. You may need to use two separate graphs, depending on your particular data. Note any nonlinearity of the voltage as the beam nears the edge of the sensor.
9. Using the linear portion of the graph, calculate the positional sensitivity, $\Delta V/\Delta x$ (volts/mm), of the sensor for both measurements. Explain any difference in the two values.
10. Insert the lens and lens holder as shown in Figure 15. Move the laser on its stage to one side and then rotate the laser so that the beam is at an angle to the optical rail. Adjust the angle of the laser so that the beam strikes the center of the lens.
11. Measure the output of the DVM and use the results of Step 8 to determine the position of the beam on the position-sensitive detector. Then use Equation 1 to determine the angle of the laser beam relative to the optical rail.
12. Use the goniometer to measure the angle of the laser beam relative to the optical rail and compare the result to that determined in Step 11.

Data Table

Position	V_b	V_d	$V_b - V_d$

Wire diameter measurement—In this portion of the procedures, you will measure the diameter of a sample of wire using the diffraction method described in the text and Figure 13.

1. Mount the graduated circle holding the wire in the transverse stage on the optical rail. Rotate the wire until it is vertical.
2. Align the HeNe (or collimated diode laser) with the axis of the rail. Adjust the laser so that the beam center strikes the wire in the graduated circle.
3. Mount the Polaroid camera pack on the rail, on the opposite side of the wire from the laser. Use the translation stage for this mounting. Adjust the position of the camera so that a minimum of five diffracted spots on each side of the undiffracted beam will fall on the film surface. Record the position of the wire, L_1, and the position of the film pack, L_2. Use

the meterstick for this measurement. The difference ($L_2 - L_1$) equals the distance d in Figure 13.

4. Turn off room lights, open the film pack and turn on the laser long enough to obtain a good exposure. This may take a few trials. Shut the laser off and develop the film.
5. Measure the spacing of four pairs of intensity maxima positioned symmetrically about the undiffracted beam, as shown in Figure 16. Do not measure the first-order diffracted spots. They are probably fogged by the undiffracted beam. Use the center of each spot for the measurements.

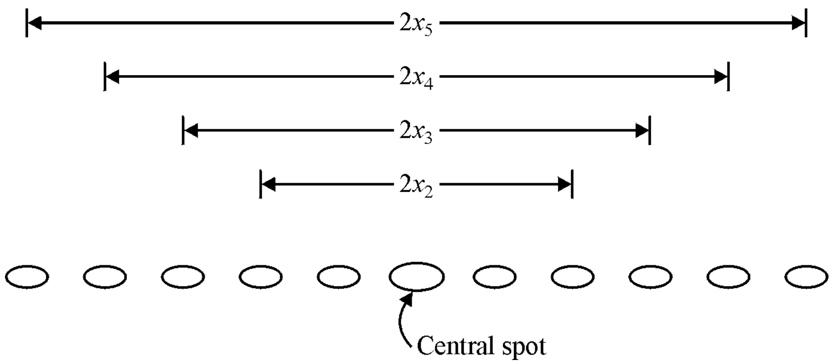


Figure 16 *Drawing of diffracted spots to be measured*

6. For each of the values of x_n, n = 2,3,4,5, as defined in Figure 16, calculate the wire diameter, D_n. Note that x_n is one-half the distance between the spots.

$$D_n = \frac{n\lambda[(L_2 - L_1)^2 + x_n^2]^{1/2}}{x_n}$$; ($L_2 - L_1$) = d in Figure 13.

Here λ is the wavelength of the laser.

Also calculate the average value D_{ave}:

$$D_{ave} = \frac{(D_2 + D_3 + D_4 + D_5)}{4}$$

and the standard deviation σ:

$$\sigma = \left[\frac{(D_2 - D_{ave})^2 + (D_3 - D_{ave})^2 + (D_4 - D_{ave})^2 + (D_5 - D_{ave})^2}{4}\right]^{1/2}$$

Your measured value D_m is then:

$D_m = D_{ave}$ plus or minus σ.

Compare your measured value to the value measured with a micrometer.

7. Draw two intersecting straight lines on the tracing type millimeter graph paper. The lines should each be at 15 degrees to the direction of the ruling on the graph paper. Replace the Polaroid camera pack with a screen made of the graph paper. Center the undiffracted

beam at the intersection of the 15 degree lines. Record the position, r_n, of four diffracted orders on the graph paper.

8. Displace the wire by 0.5 millimeter relative to the beam center, in a direction perpendicular to the length of the wire. Record the position, r_n, of new diffracted spots. Determine the difference in positions of the diffracted spots.
9. Return the wire to the beam center. Rotate the graduated circle by 15 degrees clockwise. Record the angular rotation of the line of diffracted spots.
10. If you were using the diffraction of light to gage the diameter of wire being extruded at high temperature, would you try to control wire position or wire orientation relative to some reference line? Assume that the method for sensing wire diameter uses a linear array of sensors in a fixed location. Use the results of steps 9 and 10 above in formulating your answer.

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