TRIANGULATION SENSORS
An Overview

By Dr. Walt Pastorius

Triangulation sensors are non-contact replacements for contact and older non-contact devices which measure distance from a sensor to a surface, such as dial indicators, LVDT's (linear variable differential transformers), capacitive, inductive and ultrasonic devices.

Non-contact sensing is very desirable in many measurement situations. Non-contact sensors are free of probe wear or bounce, collect data at much higher rates than contact devices and do not influence the object being measured. Compared to capacitive and inductive devices, laser triangulation sensors have much larger standoff (distance from the sensor to the part). Compared to ultrasonic sensors, triangulation sensors are available with much higher resolution and accuracy specifications.

Triangulation sensors are ideal for monitoring fragile parts, parts which have surfaces that are easily damaged, parts or features that are too small to be contacted, and for in-process checks on surfaces that are wet or soft such as sealants, adhesives, inks and solder pastes, where non-destructive operation is important.

Triangulation sensors are widely used for inspection of dynamic materials, such as monitoring thickness of moving webs, monitoring tire dimensions while rotating at high speed, and dynamically monitoring profiles and roughness of pavement. Other uses are in closed loop control of pouring of molten metal and dynamically 3-D contouring profiles of logs and boards to optimize output of lumber mills. Laser triangulation sensors are also ideal for monitoring vibrations, without adding the mass of a sensor to a component, which would alter the vibration characteristics of the object.

Like contact type sensors, triangulation sensors today are available with a wide variety of specifications, sizes, and configurations that replace and outperform older types of sensors. When selecting a triangulation sensor for a specific application, it is important to understand the basics of triangulation and the importance of the parameters required for successful implementation. The purpose of this paper is to explain the principle of triangulation, and to provide an overview of the parameters involved.

The principle of optical triangulation has been understood and used for centuries. For example, triangulation is the basic principle used in navigation with a sextant, using angles to determine position.

The use of triangulation for automated measurement, however, is a relatively new technology not because of knowledge of how to make a sensor but rather because of availability of suitable components. Practical triangulation sensors for industrial applications started to become available about 1971, enabled by the commercialization of solid state position sensing detectors (PSD's) and early microcomputers. Some of the first commercial triangulation sensors were developed by Diffracto Limited (Canada), Dynavision (Canada) and Selcom (Sweden), all now part of Laser Measurement International (LMI).

HOW TRIANGULATION WORKS

The basic principle of triangulation is shown in Figure 1. A light source, almost always a laser, projects a beam of light onto the surface to be measured. This technique is sometimes referred to as "structured light", and is the equivalent of an automated light section microscope. At the surface, the laser projects a spot of light at position A. At some angle to the laser beam, a lens is used to form an image or "picture" of this spot at an image plane at position A1. If the surface is farther away from the sensor, the spot on the surface is formed at position B, and the location of the spot shifts to position B1. By determining the position of the imaged spot and calculating the angles involved, the distance from the sensor to the surface can be determined.

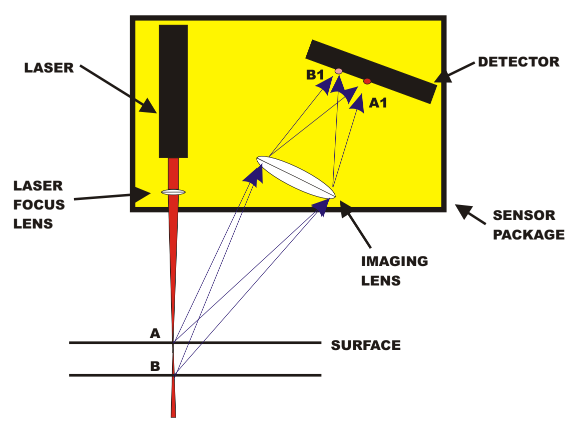

Figure 1 TRIANGULATION PRINCIPAL

It is important to understand that triangulation involves imaging of the spot (essentially taking a picture of the spot on the surface), and not just collecting reflected light from the surface. It is the imaging of the laser spot on the surface that makes triangulation an elegant measuring tool. The imaging technique allows flexibility in the design of the triangulation sensor. For example, by selecting the optical magnification of the imaging lens or the angle between the laser beam and the imaging axis, the sensor resolution and range can be changed.

Many of the performance related properties of a triangulation sensor are similar to ordinary amateur photography. A crystal sharp imaging lens will make a better performing sensor than one from a simple toy camera. A proper exposure control (with laser intensity or shutter time control) will avoid images that are too bright or dark. A sturdy mechanical design that protects the camera's internal components will last in a tough industrial environment, just as a professional photographer won't accept a flimsy home camera.

Details of how these parameters affect sensor performance are described in later sections.

DEFINITION OF TERMS

Before entering a description of how various geometry parameters affect triangulation sensor performance, some basic definitions of terms should be reviewed. The definitions refer to Figure 2.

Measurement Range, MR
The range over which the sensor gives a valid distance output signal. The range is given as an absolute value.

Stand Off Distance, SO
The distance from the sensor to the middle of the MR. At the SO is normally where characteristics of the sensor are optimised.

Spot size at SO
The value given relates to the diameter of the spot containing 90 % of the light energy.

Triangulation Angle at SO
The angle between the laser beam and the sensor viewing axis.

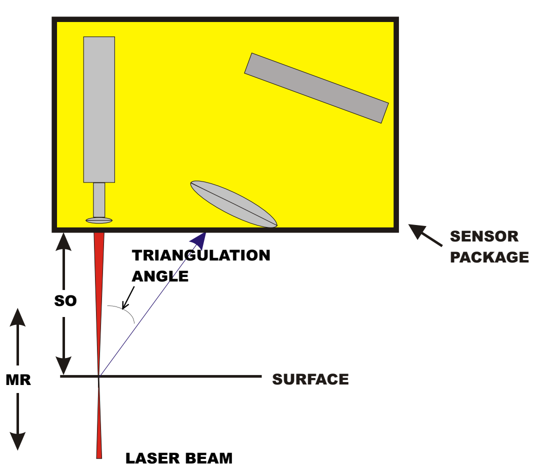

Figure 2 SENSOR GEOMETRY TERMS

GEOMETRY FACTORS

The performance of a triangulation sensor is determined by many factors, with sensor geometry being a major contributor. Effects of geometry are inter-related, and the following section is meant to provide a simple overview.

Stand Off

Stand off of the sensor is a straightforward issue. The sensor must remain clear of the part to be inspected, with some added clearance for safety.

Sensors are available in a variety of stand off values to suit most applications. As a general rule, sensors with higher accuracy will have shorter stand off, to keep the sensor package size as small as possible. As a result of the triangulation equations, for a specific sensor type with common specifications of range, resolution and detector parameters, the sensor package size becomes larger as stand off increases. Therefore, it is usually desirable to select a sensor with enough standoff for clearance, without selecting excessive stand off.

From an optical point of view, sensor resolution and accuracy are best when the surface is closest to the sensor. Sensor specifications for accuracy and resolution should be stated at the far end of the measuring range to represent the worst case figures, and will improve when the surface is closer to the sensor.

Triangulation Angle

The triangulation angle is a major factor in sensor performance determination. In general, as the triangulation angle increases, for a given optical magnification and detector geometry, the sensor range decreases and resolution increases. Practically, the laser triangulation angle may be as low as 10 degrees for a low-resolution sensor and up to about 45 degrees for a high-resolution sensor. The resolution of triangulation sensors improves with smaller measuring range, but this does not necessarily improve the quality or accuracy of measurement.

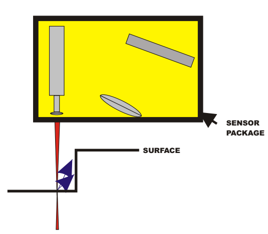

Figure 3a SENSOR BLOCKING

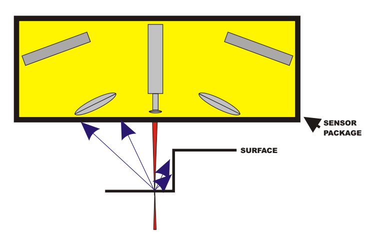

Figure 3b DUAL SENSOR

Because of the triangulation angle, the geometry of the object being measured may cause optical interference. Steps on the part must not block the optical viewing path (Figure 3 a). This issue can be eliminated in many cases by rotating the sensor to another orientation or using a sensor that has dual viewing axes, such as the LTS (Figure 3 b).

LIGHT SOURCE TYPES

Triangulation sensors can operate with almost any type of light source. For best performance, the light source should be of relatively high intensity, and should create a small spot on the surface. As a result, almost all triangulation sensors use a laser as the light source, and most standard sensor designs today use a solid state laser, similar to the type used in common laser pointers. The solid state laser diode provides a compact, efficient, long-lifetime light source for sensors.

Laser diodes also emit light in a narrow band of frequencies, essentially as one colour. This property is useful for triangulation sensors, since it allows a narrow band pass optical filter to be placed in front of the detector. This filter allows only light of the laser wavelength to reach the detector, and blocks other wavelengths, which reduces potential errors caused by stray light from ambient conditions entering the sensor. Stray light can be a significant problem in conditions such as applications where the sensor must be used outdoors in sunlight or near arc welding operations.

Laser diodes can be operated continuously or can be easily modulated or pulsed. Using a modulated laser can be useful in reducing ambient light by filtering the detector output at the modulation frequency or using lock-in amplifier technologies.

When implemented with an analog or PSD detector, combining use of a band-pass filter to allow only light at the laser wavelength to reach the detector, and electronically filtering to analyse only signals at the laser modulation frequency provides unprecedented capability to work under extreme conditions such as close to arc welding or measuring the level of molten steel (Figure 4).

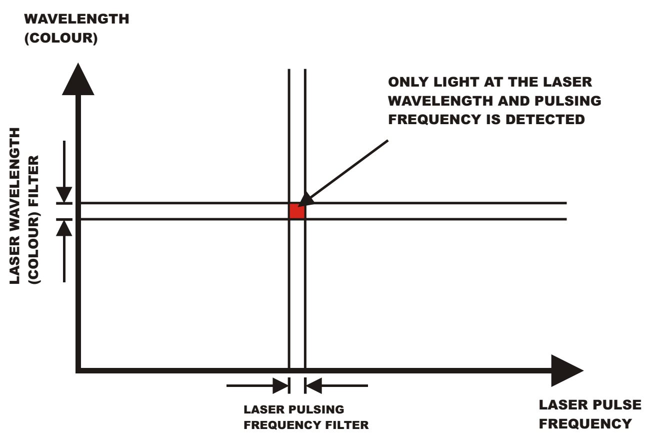

Figure 4 FILTERING

Some low-resolution sensors have been manufactured with light emitting diodes (LED's) as light sources, but the LED beam is large and is not easily made into a small spot required for most applications.

Laser wavelength (color of the beam) has no significant influence on sensor performance, provided that the detector can sense the wavelength. From a practical point of view, use of a visible wavelength laser is desirable. An operator can easily see that the laser is on when a visible source is used, a source of comfort for the user and a quick check for diagnostic purposes.

Current trends in laser development (for use in DVD and CD players) towards higher power output and long lifetime at visible wavelengths, has made it possible to use visible light in most applications. This includes some of the most demanding areas such as measuring the surface of shiny molten aluminium or very black non-reflective rubber.

Use of a visible laser source is one of the fundamental requirements for laser sensors to be rated as "Laser Class 2" devices, which limits the safety precautions necessary on the plant floor.

If an infrared laser is used, phosphor cards or handheld infrared viewers can be used to "see" the laser beam to aid in diagnostics and to help aim the laser beam for set-up of the sensor.

SPOT SIZE

A general rule for best sensor performance is that the spot size on the surface be small. For large flat uniform surfaces, this is not a major issue, but for small objects or surfaces of large curvature, spot size becomes very important. As shown in Figure 5, the spot size can be no larger than the feature to be measured. If a small feature is precisely positioned beneath the laser beam, the beam must only be smaller than the feature. If however the sensor is to be scanned over a surface and a small feature found, a good rule of thumb is that the spot size must be less than one-tenth the size of the smallest feature to be measured.

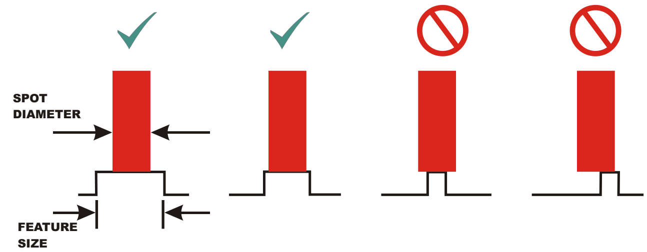

Figure 5 SPOT SIZE

Lasers make ideal light sources for triangulation sensors, since they project narrow, relatively intense beams of light. The beam can be focused to a small diameter spot with simple lenses either built into the laser package or external to the laser inside the sensor package.

Common sensor design practice is to focus the laser beam to create the smallest spot at the sensor stand off distance. This is the point where the laser spot size is specified. The size of the beam is then smallest at the stand off point, but it is larger both inside and outside this point. The beam size is shaped like a Coke bottle, Figure 6. The increase in size is related to the stand off and how tightly it is focused. Where smallest spot size is required, the sensor will perform best for objects near the stand off (best focus).

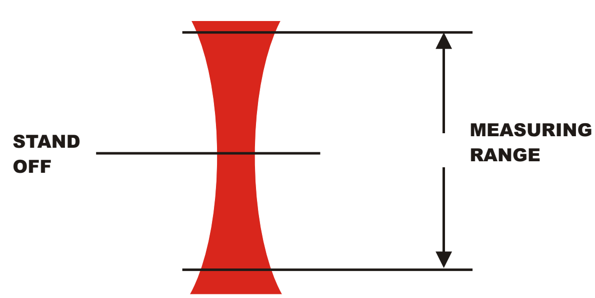

Figure 6 SPOT SIZE CHANGE

In applications where spot size is important, the sensor should be mounted with the laser beam as close to perpendicular to the surface as possible. If the laser is at an angle to the surface, the spot size on the surface will be elongated, proportional to the angle away from normal (Figure 7).

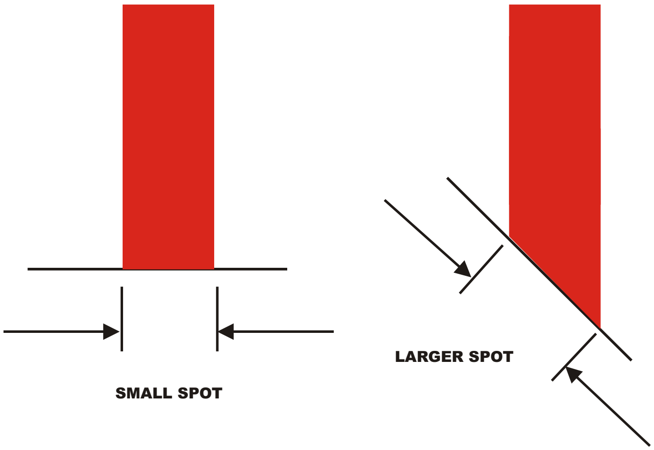

Figure 7 SPOT SIZE - ANGLE TO SURFACE

In some sensors where extremely large measuring ranges are required, the laser beam is collimated (kept parallel) rather than focused at the nominal stand-off, to keep the spot size reasonably small over the full measuring range, such as in SPR02, SPR04, DLS2000, M8 and M24 sensors.

SURFACE EFFECTS

As shown in Figure 1, triangulation operates by imaging the spot of light from the surface onto a position-sensing detector. Most materials are optically a combination of diffuse (light scattering) and specular (reflective) they scatter light in many directions. As an example, ordinary paper surfaces may range from very dull (diffuse) for common laser printer paper to very specular or reflective for glossy print paper. A surface with some diffuse properties, when placed under a sensor of the geometry of Figure 1 will scatter at least some of the light reflected from the surface to the detector, and the sensor will perform properly.

An important issue in proper sensor operation for a specific application relates to the surface being measured, and how it's reflectivity may change. Since triangulation operates by imaging light reflected from the surface, a change in reflectivity will change the level or intensity of light reaching the detector. Reflectivity is influenced by several factors, including colour and surface finish of the materials being measured. Many processes do not have a significant change in surface reflectivity from part to part, or over time for a continuous process.

In cases where the surface changes dramatically, such as components that are different colours, the sensor must be able to respond to these changes automatically. Depending on the type of sensor detector used, several methods can be used to provide what can be termed an automatic gain control. In applications where this is a factor, a very fast feedback scheme is required that controls the laser intensity or some other exposure feature in "real time" to insure stable and reliable data is obtained.

A further reason for small spot size relates to a surface effect known as differential reflectivity. This is a potential source of error when measuring a surface which has changing reflectivity. If part of the laser spot is on a low reflectivity and part is on high a reflectivity area, the centroid of the image of the spot can be falsely biased, creating an error in the measurement. The differential reflectivity influence may be found on both a large and small scale, such as caused by a sharp edge between different colours on the target or the fine scale where the microstructure of the target, such as a brushed, machined or rolled surfaces. The effect is illustrated in Figure 8. Making the laser spot as small as possible reduces the possibility of differential reflectivity having any affect on sensor performance.

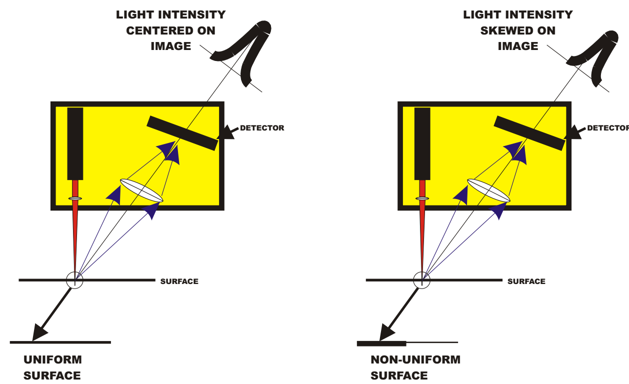

Figure 8 DIFFERENTIAL REFLECTIVITY

In the special case of a specular surface (very reflective or mirror-like), the sensor geometry of Figure 1 will not work. The laser beam is simply reflected back on itself by the mirror like surface and no light reaches the detector. For specular surfaces, different sensor geometry, Figure 9, must be used to insure that the detector receives enough light to operate correctly. The SLS7000 sensors are designed for operation on specular surfaces. When properly implemented, specular reflection type sensors can provide unprecedented resolution in the sub-micron range.

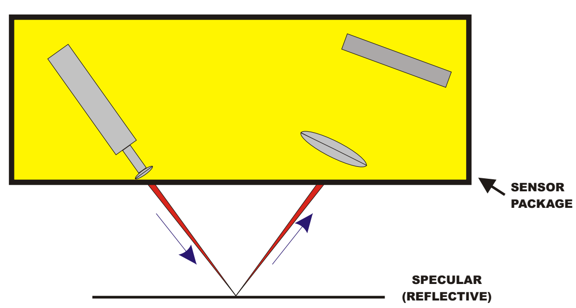

Figure 9 GEOMETRY FOR SPECULAR SURFACES

DETECTOR TYPES

Since triangulation requires finding the location of the center of the imaged spot, the imaging detector must be capable of detecting the spot location. While a number of types of detectors are available, two main types of detectors are used in triangulation sensors. Both are fully solid state, and are integrated circuit chips with rugged construction and reliable performance, even in hostile environments when properly packaged in a sensor housing. The first is a PSD or position-sensing detector, also known as a lateral effect photodiode. The second is the CCD or charge coupled device. Each of the types of detector, and their variations are described below.

PSD Detectors

PSD detectors are available in one and two axis forms, with single axis types generally used in triangulation sensors. The PSD is a single element detector that converts incident light into continuous position data. The single axis PSD is shown in simple form in Figure 10. The detector chip has outputs at both ends, A1 and A2. The amount of current from each output is proportional to the position of the imaged spot on the detector. If the spot is centered on the detector, equal currents are seen from the two outputs. If the imaged spot moves off center, the two outputs change, and the spot position can be calculated from the relative values of the outputs by a simple equation.

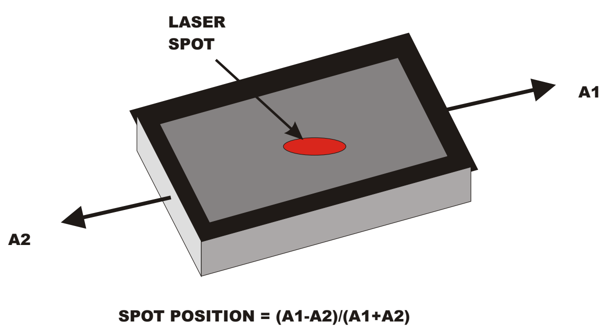

Figure 10 POSITION SENSING DETECTOR

The PSD is essentially an analog device. It offers advantages in several areas, particularly in speed of reading. It can provide data rates of up to 200 kHz or faster. It can be implemented with very fast light level control, has a good dynamic light reception capability, is virtually impossible to saturate (to overload with too much light), and has very high natural resolution, in principle limited only by the resolution of the signal conditioning circuitry used.

Disadvantages of the PSD include lack of ability to display an image or profile of the detector pattern. Also, the PSD determines the center of all light that falls on the detector area. If more than one spot or other light falls on the detector, it will report the position of the center of all light, possibly giving an erroneous signal.

CCD Detectors

CCD detectors are essentially a form of television camera, and come in both one dimension and two dimensional forms. In the two dimensional form, the CCD detector is a television camera, essentially as used in a camcorder. In most simple point triangulation sensors, a single dimension CCD is used, as drawn conceptually in Figure 11. The detector consists of a single row of discrete photodetectors, often referred to as pixels. This device is essentially a one line TV "camera". These linear arrays are available in different sizes, from essentially 256 pixels up to 4000 pixels or more.

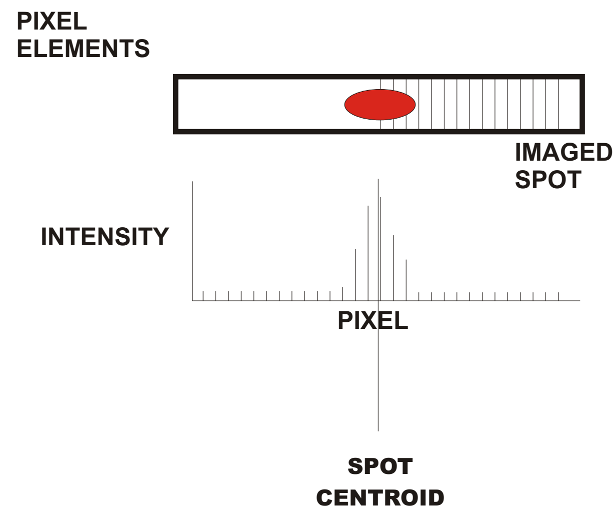

Figure 11 CCD DETECTOR

In operation, the individual pixels are electronically scanned sequentially, resulting in train of pulses which can be electronically analyzed. Each pulse represents the level of light on its related pixel. A typical output of a linear array used in a point triangulation sensor is shown in Figure 11.

The sensor electronics determine the center of the imaged spot for triangulation processing. This centroid determination can be done by simple fixed thresholding or by more complex curve fitting and analysis. The simple fixed threshold approach is easy to implement, but limits the resolution of the sensor to one pixel. Also, if light levels change, the simple threshold approach may fail to obtain a reading. In most sensor designs, more complex gray scale processing is used to subdivide each pixel, resulting in sub-pixel resolution.

The CCD detector has several advantages. First, the "video" output of the sensor can be viewed to display light levels, cleanliness of the image and to show any stray light effects. Since the pixel train can be processed, the image can be filtered or otherwise processed. This can remove unwanted multiple spots, reflections or other light. An example of this advantage is shown in Figure 12.

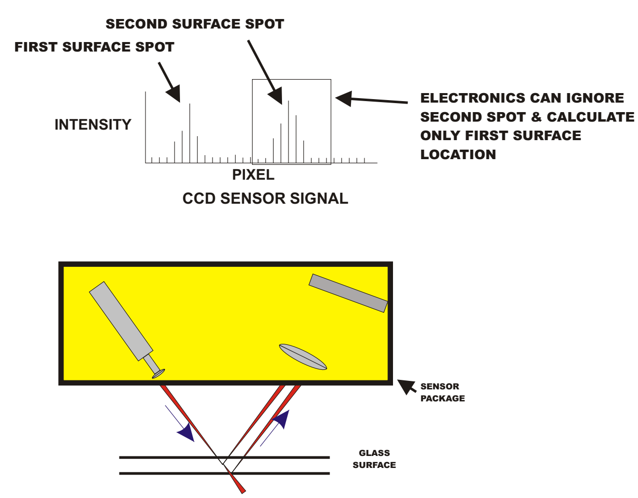

Figure 12 CCD SENSOR FOR GLASS MEASUREMENT

Disadvantages of the CCD detector are related to speed of operation, which typically is less than can be achieved with a PSD. Gain control in CCD based sensors is not as fast as in PSD based sensors, a drawback in applications where surface reflectivity changes rapidly.

LASER LINE SENSORS

A more sophisticated version of the CCD based sensor is available which collects data at multiple points in a single frame, generating contour information along a line on the part being inspected, such as the L1 sensor family. This sensor as illustrated in Figure 13, projects a line of laser light onto the surface rather than a single point. It uses a 2-D CCD as the detector. As shown in the figure, the image of the laser line on the detector maps out the contour of the surface. Analyzing multiple points along the laser line using the triangulation equations generates a profile of the part. If the part is moving under the sensor, a 3-D map of the surface can be generated.

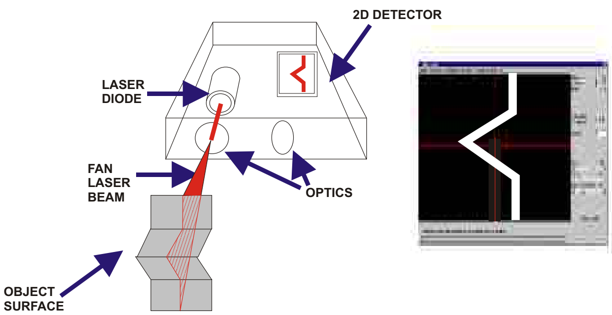

Figure 13 LASER LINE SENSOR

The 2-D line sensor has certain areas of application where contour information is required, since each frame of data contains multiple points of information. This type of sensor is often used in obtaining contours of logs and boards in saw mills.

The line approach is slower in data acquisition rate than a single point triangulation sensor, and typically provides medium accuracy specifications. It also requires that part surfaces be reasonably uniform in reflectivity, since gain control can only be provided over the full field of view.

SUMMARY OF IMPORTANT POINTS

- Triangulation sensors are a non-contact replacement for LVDT's and other sensors, and are particularly useful in acquiring high-speed data (200 kHz or faster), and in inspecting delicate, soft or wet materials where contact is unacceptable
- Spot size of the laser on the surface should be as small as possible, and small spot size is achieved when the laser is perpendicular to the surface
- For inspection of surfaces with changing reflectivity or colour, select a sensor with an automatic gain control, and choose a sensor that suits the applications demands for speed and dynamic range
- Specular and diffuse surfaces require different designs of the sensor geometry
- PSD detector based sensors provide highest data rates, up to 200kHz, and have fastest rates of gain control, very important for surfaces of varying texture, colour and reflectivity
- CCD detector based sensors provide ability to deal electronically with varying image conditions such as multiple reflections from the part surface

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