# Simple scanners reveal shape, size and texture

Do you want to measure the surface of an object without touching it? **Tim Clarke** explains how a laser, a lens and a linear sensor measure distance to within a few micrometres more than 60 000 times a second.

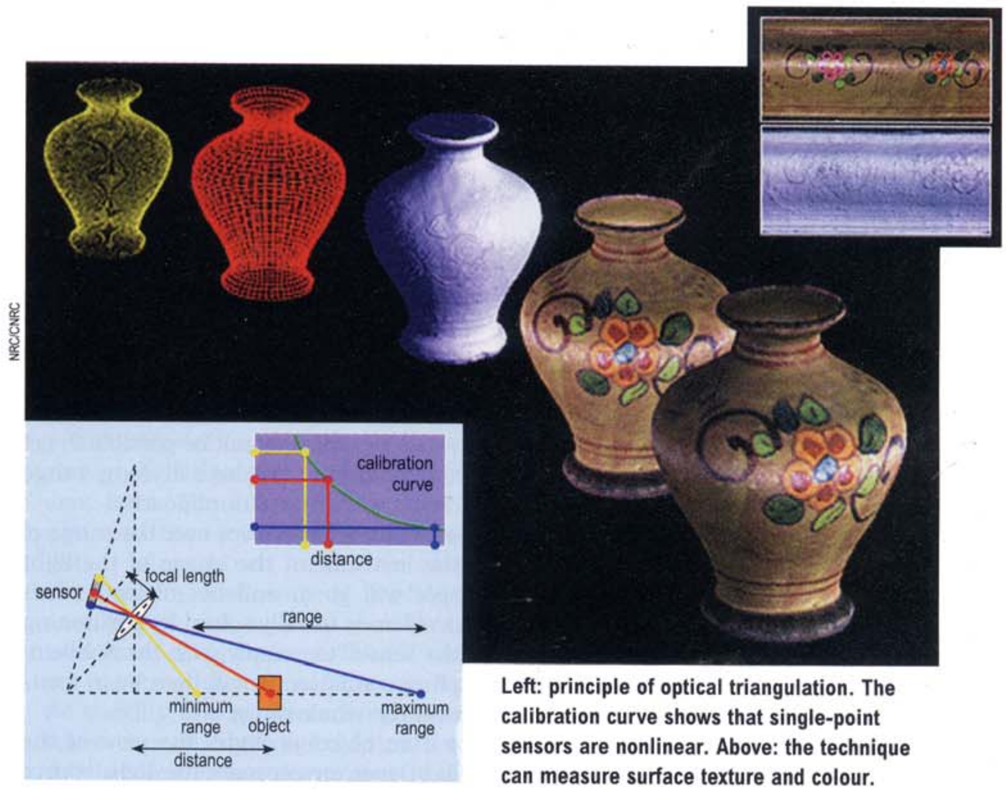
Instruments that exploit the ability of cameras to measure the angle subtended by a scanned spot of light come in many shapes and sizes. One of the simplest measures an object's surface with an accuracy of micrometres over a range of a few millimetres or distances of a few metres with millimetre accuracy.

These single-point optical triangulation instruments are simple to use and measure distance information – such as surface texture – both quickly and easily. They need not touch the object to be measured and therefore have many desirable characteristics.

## No contact

Some of the objects that have been measured with these sensors include manufactured goods, tyre treads, archaeological artefacts, turbine blades, printed circuit boards, coins, road surfaces, and pipes found in sewers, process industries, tunnels and ships.

The sensors can obtain information about size, thickness, depth, opaque liquid levels, length, vibration amplitude and frequency, gauging pass-fail, robotic tool stand-off, the number of manufactured goods, two-dimensional shape and three-dimensional surface. The benefits of a triangulation probe can include lower inspection costs, better quality control, faster production, smaller tolerances, fewer defects and the reverse engineering of components.




**Left: principle of optical triangulation. The calibration curve shows that single-point sensors are nonlinear. Above: the technique can measure surface texture and colour.**

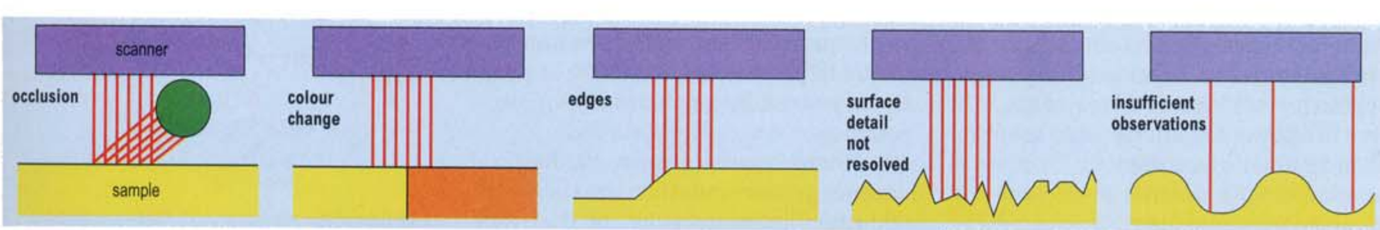
To understand the value of this technique it is useful to compare the method with similar processes. Many existing contact-based methods deliver acceptable results. However, touching the product may limit the speed of a process or mark the surface, or the probe can wear or sustain mechanical damage. Sometimes contact measurements are impossible, for example with molten metal or thin panels.

Optical triangulation instruments are desirable because of the small measurement spot, the high accuracy available and the high speed of measurement. Other techniques, such as ultrasonics, are fast but are unable to produce such a small measurement spot or such great accuracy. Time-of-flight light techniques are not accurate enouth at close range and are not sufficiently fast.

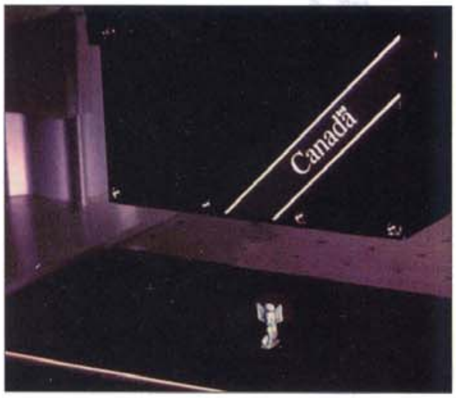
## Optical triangulation

The geometry of an optical triangulation system is essentially nonlinear. A light source illuminates a point on an object. A lens system then forms an image of the light spot on the sensor surface.

As the object moves, the image will move with respect to the sensor. >>>




**Common sources of error with single-point triangulation systems. As with any measurement system, the instrument must suit the task in hand.**




Synchronized scanner (top) scans the British Museum's 3 cm Figurine of Shu (above) with red, green and blue light (see box).

Measuring the location of the image in the sensor plane determines the distance of the object from the instrument, provided that the baseline length and the angles are known. Often it is unnecessary to know these if the instrument is precalibrated and a look-up table used.

## Detailed geometry

A more detailed look at the geometry will assist in understanding some of the benefits and limitations of this system:

- If the object is moved in equal increments, the position of the image on the sensor will not move in equal increments – the device is inherently nonlinear.
- If the object moves over a relatively small range, the instrument will be approximately linear.
- For a given range, if the baseline is extended the instrument will be more linear but it will also become large and possibly awkward to use. If the baseline is shortened then the instrument can be smaller but it may not be possible to get the accuracy required at long range owing to increased nonlinearity.
- As the object moves over the range of the instrument, the image of the light spot will go in and out of focus. This problem is usually solved by positioning the sensor to comply with the Schliempflug condition. It will then be in focus over the whole range.
- If an object occludes the view of the light spot, or prevents the light source from illuminating the object, measurement will not be possible.

NRC/CNRC

Digitized three-dimensional and colour data from the synth
low-end machines such as PCs to rotate the model in real

- Instability of the direction of the light source will generate errors.
- If the light source impinges on an uneven surface texture or colour measurement accuracy will be degraded.
- If the configuration of an optical triangulation sensor is altered, through tem-

## Raster scan and twin iris measure three dimensions

A synchronized laser scanner combined with optical triangulation allows a raster scan by a single laser spot to measure people, scenes and objects in three dimensions. The system, developed by the Visual Information Technology group of Canada's National Research Council, also measures the intensity and colour of reflected light. A monochrome version called Biris is for machine vision.

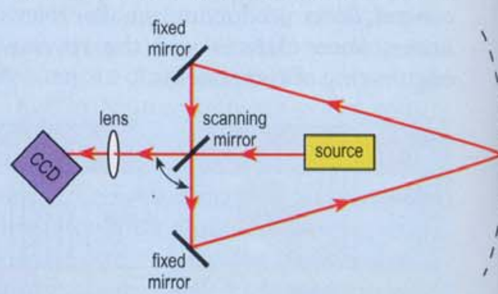
"Our objective is to develop and apply three-dimensional digitizing for the automation of systems and processes," said Marc Rioux, who leads the development work on the two systems. "In particular we are interested in accurate dimensional measurement for reverse engineering, industrial inspection and visual communication."

The basic scanner consists of a double-sided oscillating or rotating mirror. One side of the mirror reflects light from a focused laser across a pair of fixed mirrors, which project a moving point of light. Laboratory prototypes use milliwatt lasers emitting at wavelengths from 400 to 1500 nm. One wavelength measures dimension, but three are needed for both colour and dimension.

Light from the projected point passes back through the system and reflects off the second side of the oscillating mirror onto a CCD. A linear positioning system in one prototype moves the scanner vertically to produce a raster scan of a stationary scene or a cylindrical scan of a rotating object.

A double-aperture mask in the Biris scanner produces two images, each with a distinct intensity peak, of the same point on the CCD. The distance between the peaks is a function of the distance between the object and the camera.

Algorithms exploit the twin peaks to remove errors caused by ambient lighting, noise in the electronics, or optical distortions in the lens or laser systems. An anamorphic lens fitted to the Biris camera increases range accuracy further without any reduction in field of




The Canadian synchronized laser scanner contains a double-sided oscillating mirror.

...nized laser and virtual reality modelling language allow ...time. (See "http://www.vit.iit.nrc.ca".)

perature changes or shock, for example, the instrument will give erroneous results. The user may be unaware of these errors, so, in critical applications, the instrument should be checked to ensure correct operation.

- Laser speckle degrades the accuracy of the location of the image spot and therefore the accuracy of the instrument.

The most important component in the optical triangulation system is the sensor. There are two types: the position-sensitive detector (PSD) and the charge-coupled device (CCD).

Both depend on a silicon sensor. The PSD contains a single slab of silicon and measures charge generated by the light source image by tapping the sensor at several points. The CCD uses a linear array of photosensitive elements (pixels).

Both are capable of indicating the position of the image to within a fraction of a micrometre within 10 µs to 10 ms. It is important to understand the difference between these two schemes.

A PSD sensor produces an analogue output for the position of the image and hence relies on the electrical stability of the system to provide reliable measurement. The CCD sensor, by contrast, has pixels of a fixed size and pitch.

Each type of instrument produces a charge that is proportional to the incident light. The intensities are used to determine the centroid of the image. The PSD is often chosen for devices measuring over a small range to provide an analogue output, which is ideal for use with pass-fail applications. The CCD sensor has the advantage of better geometric stability and produces a signal well suited to providing a digital output.

Other important features of these instruments may include filters to remove unwanted lighting effects; the adjustment of the laser focus and the use of high-pointing stability lasers for long-distance applications; low-expansion materials to avoid temperature-related effects; the correction of nonlinearity for better distribution of the accuracy of an instrument; image processing and algorithmic techniques to avoid systematic errors; and the use of electronic exposure time adjustment to cope with varying surface reflectivity.

## Instrument selection

The shorter the range required, the more likely that a commercial off-the-shelf instrument will be available. There is a considerable choice for the 5 to 50 mm range. Fewer devices exist for longer distances, owing mostly to the fact that smaller numbers are required.

Only a few scanning systems are available worldwide. Such instruments are likely to be expensive as a result of their sophisticated mechanical design and the lack of economies of scale.

The cost of a single short-range instrument may be in the region of a few hundred pounds, the cost of a longer-range instrument is likely to be a few thousand pounds, and the cost of developing a system for a particular purpose may be tens of thousands of pounds.

To select an instrument for your application have a careful look at the task in hand and define the following:

- The range of measurement required – it is often desirable to over-specify;
- The accuracy required – be >>>

view associated with a standard lens.

"The system scans up to 20 000 points per second, but this may fall to 2000 depending on the object's distance, how it reflects and its texture," said Rioux. "Its resolution increases as the volume of the object decreases."

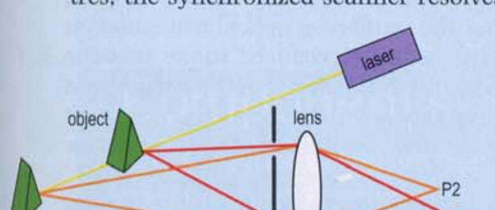
For an object of a few cubic centimetres, the synchronized scanner resolves 50 µm in the horizontal $x$ or vertical $y$ image axes and 5 µm in the $z$ axis. The typical resolution falls to 250 µm in the vertical and horizontal axes and 400 µm in the $z$ axis for an object with a volume in the order of a cubic metre.

Three-dimensional digitizing in colour depends on an optical fibre to deliver red (600 nm), green (500 nm) and blue (400 nm) light to the camera and a modified linear CCD to separate the reflected colours. "The CCD's signal contains position and colour information about each digitized coordinate," said Roux. "A unique feature of this arrangement is the perfect registration between geometric and photogrammetric data."

The Canadian group has developed hand-held and robot-mounted versions of the scanner. It has built random laser scanning for eye-safe operations and a video-rate range camera. Another technique under development is fast searching and tracking of targets in three dimensions of targets at ranges between 0.5 m and 2 km, a technique that synchronizes optical triangulation with time of flight.

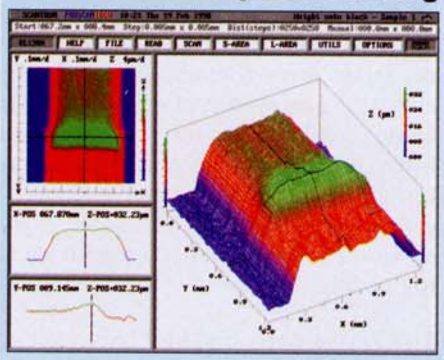
The council licenses the scanning and Biris cameras for on-line OEM applications. Licensees sell profilometers for prosthetics, to measure road surfaces from a vehicle travelling at normal traffic speeds and to estimate the volume of timber in felled trees. There are other potential applications in three-dimensional anthropometry; robots for guidance, assembly and inspection in space; medical and visual communications; and forensic science.

Typical prices for a digitzer range from £10 000 to £30 000. **JB**



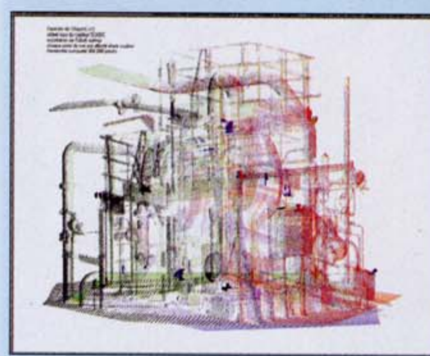

**Dual-iris system produces two distinct images of a scanning laser spot.**

## Commercial optical triangulation systems



Scantron

SOISIC



The Proscan scanner (left) measures surface finish. Soisc's system produces CAD data (above) from multiple scans of a scene (right).

### Ultra-short range

*Keyence LC-2420*

| | |
|---|---|
| Meas. freq. | 50 kHz |
| Resolution | 0.01 µm |
| Range | 0.4 mm |
| Stand-off | 10 mm |

**Applications: paper roughness, connector pin warp, solder paste thickness, silicon wafer thickness and CD pick-up travel**

### Short range

*Matsushita LM 300 series*

| | |
|---|---|
| Meas. freq. | 50 kHz |
| Resolution | 0.2 µm |
| Range | 6 mm |
| Stand-off | 30 mm |

**Applications: pass-fail, for instance checking for the correct filling of packages**

### Medium range

*Precimeter CDR680R200 (single spot)*

| | |
|---|---|
| Meas. freq. | 600 Hz |
| Resolution | 0.01 mm |
| Range | 200 mm |
| Stand-off | 680 mm |

**Applications: thickness measurements, alignment, level detection, vibration and flatness**

*Proscan 1000 (moving object)*

| | |
|---|---|
| Meas. freq. | 2 kHz |
| Resolution | 0.01–6 µm |
| Range | 160 µm – 80 mm |
| Stand-off | 7–105 mm |

**Applications: surface roughness and flatness, surface topology, radius measurement and solder paste thickness**

*SELCOM No. SPS 2301 (sector scan)*

| | |
|---|---|
| Meas. freq. | 64 kHz |
| Scan freq. | 30 Hz |
| Scan angle | 30° |
| Resolution | 15 µm |
| Range | 60 mm |
| Stand-off | 130 mm |

**Applications: tracking of tyre tread extrusions, dimensions of rubber parts such as seals or gaskets, measurement of tyre tread depths**

*OMC 2D-Scan (360° scan)*

| | |
|---|---|
| Meas. freq. | 2 kHz |
| Scan freq. | 360°/ 0.2 s |
| Scan angle | 360° continuous |
| Resolution | 0.05–0.3 mm |
| Range | 0.160–1.2 m diameter |
| Stand-off | 80 mm |

**Application: pipe internal diameter measurement**

### Long range

*SOISIC (3-D scan)*

| | |
|---|---|
| Meas. freq. | 100 Hz |
| Scan angle | 46°×320° |
| Resolution | 0.1–40 mm |
| Range | 9 or 38 m |
| Stand-off | 1 or 2 m |

**Applications: nuclear and chemical plant scanning, three-dimensional archaeological recording, building facades and turbine blade measurement**

careful not to overestimate your requirements without good reason:

- The speed of measurement – remember that this will relate to whether the object is static or moving.

You should also analyse the characteristics of the situation:

- Is relative accuracy or a pass-fail required? Consider a PSD sensor.
- Is absolute accuracy required? Consider a CCD-based sensor.
- Is occlusion likely? Look for a dual-sensor device or one with a short baseline.
- Is the environment harsh? Find a sensor that is suited to the conditions.
- Are the lighting conditions severe, such as in a welding application? Then use an instrument that is optimized for this environment.

If an off-the-shelf solution is possible, obtain the manufacturer's literature, have a discussion with the sales person or technical department of the company concerned, and install the instrument yourself. If the application is part of a complex problem or an off-the-shelf product cannot be found, there are a number of companies that specialize in metrology and non-contact measurement systems. They will be able to advise and, if necessary, assist in commissioning the design of a custom unit.

## Repeat measurements

Instruments of this type can be extended to provide measurement in two or three dimensions, for instance:

- triangulation probes instead of mechanical probes are routinely used with coordinate-measuring machines:
- rotation of the triangulation probe about the baseline axis can measure complete cross-sections of sewers, pipes and tunnels or partial cross-sections of moulded sections, such as tyres.
- moving mirrors can scan large and small structures from a stationary position to construct CAD models, such as process industry pipes.

In conclusion, optical triangulation sensors provide reasonable accuracy and the design can be scaled up and down to suit applications with range requirements from millimetres to 50 m.

The advantages over other techniques are high speed and accuracy, plus robustness of design. Against these should be placed the problem of occlusion, the necessity of a laser light source in the majority of cases and limits to the physical size of the instrument.

Other important factors, such as traceablity to National Standards and data transfer standards, plus issues relating to data use and visualization, may be important. Optical triangulation instruments can be recommended where their unique benefits outweigh the chief disadvantage of occlusion.

If line-of-sight sensors with the same specifications were available they would be preferable. Some products do exist, but the number of optical triangulation sensors being produced shows that the cost, accuracy, speed and robustness of optical triangulation sensors cannot yet be beaten for a variety of applications. ●

Tim Clarke is the director of the Optical Metrology Centre at City University, London, UK. The centre specializes in fundamental research into non-contact measurement systems, such as photogrammetry and optical triangulation. It also undertakes projects to apply such technologies in industry.