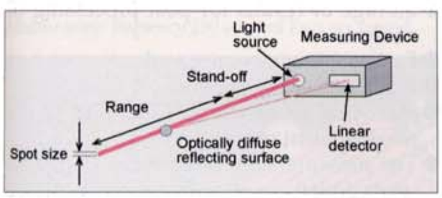
Buyers guide to six non-contact distance measuring techniques

This article by Dr. Tim Clarke[1] & Dr. Mark Williams[2] briefly discusses distance measurement techniques based on triangulation, time-of-flight, and interference.

Non-contact distance measurement is increasingly being used for on and off-line quality control in manufacturing. In some cases such measurement systems are used to enable production and quality control at the same time. As a result it is important to choose the right tool for each job.

The six measurement systems cited can be used to acquire information about surfaces in one, two or three dimensions. Some of the techniques are inherently one dimensional such as: single point optical triangulation, ultrasound, or time-of-flight. To produce 3-D information either the instrument or the object must be scanned in two further dimensions. The light stripe method produces 2-D information directly but requires either the object to be scanned or for the instrument to be moved in one further dimension to obtain 3-D information. Photogrammetry and the laser tracker produce 3-D information directly.

Figure 1:Single point optical triangulation configuration



Optical triangulation

Triangulation is one of the oldest forms of distance measurement. All that is required is that the angle between a single point on an object and two separated views can be measured together with the distance between the two view-points. This is the basis for many measurement systems such as optical tacheometers, theodolites, and one of the distance estimation mechanisms of the human visual system.

Single point optical triangulation is a fast and easy to use method of measuring distances to objects without touching them and requires little operator knowledge or supervision. Distances can be measured with accuracy of a micron to a few millimetres. The range of these devices is from a few millimetres to tens of metres. Measurement rates are from 100 to 60,000 times per second. To operate a light source, a lens and a linear light sensitive sensor are required.

The geometry of an optical triangulation system is illustrated in Figure 1.

The light source (typically a Laser or light emitting diode) illuminates a point on an object. The image of this light spot is then formed on the sensor surface and as the object is moved the image moves along the sensor. By measuring the location of the light spot image the distance of the object from the instrument is determined

Figure 2. An example of a triangulation instrument:Limab LMS 6035S. Sensor range: 2000 mm Stand off: 300 mm Resolution: 0.1 mm Measurement frequency: 500 Hz max

The benefits of this technique are as follows;

- High-speed measurement - up to 60,000 times per second

Typical objects measured by each measuring system

Single point optical triangulation	Laser stripe	Photogrammetry
Tyre treads Archaeological artifacts Printed circuit boards Road surfaces Paper roughness Solder paste thickness Connector pin warp Silicone wafer thickness CD pickup travel Industrial plant scanning Turbine blades Building facades	Logs Road surfaces Human body Industrial components Rare objects Joint tracking Seam tracking Welding Object presence Part positioning Web presentations Virtual reality environments Steel production inspection	Aerospace metrology Automobile manufacture Shipbuilding Mapping Architectural models Building facades, Archaeology Human body scans Gait analysis Missile or plane tracking Antenna measurement Virtual reality Entertainment

Ultrasound	Time of Flight	Laser trackers
Liquid level measurement Counting objects on a production line Thread or wire break detection Robotic sensing for navigation Vehicle obstacle detection Wall-to-wall distance measurement Camera focusing	Civil Engineering surveying Profiling rock faces in quarries Tunnel profiling Hydrographic surveys of buoys, barges and oil rigs Range and bearing information Aerial surveys	Robot tracking, calibration, and testing Shipbuilding Aircraft manufacturing Verification of jig design Reverse engineering Inspection and alignment Surfaces

- Accuracy of approx. 1 part in 5,000 of the measurement range
- Robust design
- The measurement spot is small
- Can work with a range of surface types - rough, diffuse, coloured.
- Relatively cheap and off-the-shelf
- Uses well established technologies
- Movement of the instrument, or its optical path, allows scanning of surfaces in 2-D or 3-D

However, several limiting factors also exist

- Optical triangulation instruments are inherently non-linear if they have a range that is comparable or long compared with the base length
- The light spot can be occluded from the sensor stopping measurement
- The instrument may be large compared to the measurement range
- Uneven surfaces can cause problems
- The stability of the instrument may be affected by shock
- A laser beam is used and may pose a safety hazard

Light stripe

Several hundred 2-D measurements of an object surface are produced up to sixty times per second by a light striper. A light stripe system uses a two-dimensional CCD sensor and a light stripe generator [Fig 3]. The image formed of the projected light stripe will reveal the shape of the surface if viewed from an angle. The shape of the imaged stripe will vary depending on the distance each point on the surface is away from the instrument.

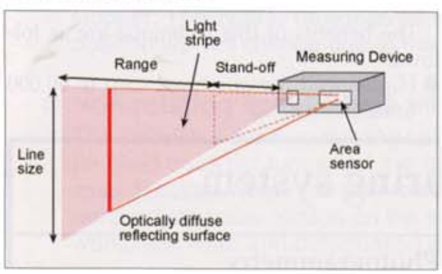


Figure 3. Light stripe system configuration

The benefits of this system include;

- 2-D profile production at a high data rate
- Freeform scanning when attached to a motion control system (e.g. portable CMM arm)
- Range of designs to cater for very short to medium range applications

Typical problem areas of the system include;

- Occlusion due to the optical triangulation characteristic
- Multiple reflections from specular surfaces can cause erroneous measurements
- Calibration procedures may be required prior to use
- Large quantities of data are produced that often has to be processed to become meaningful

Photogrammetry

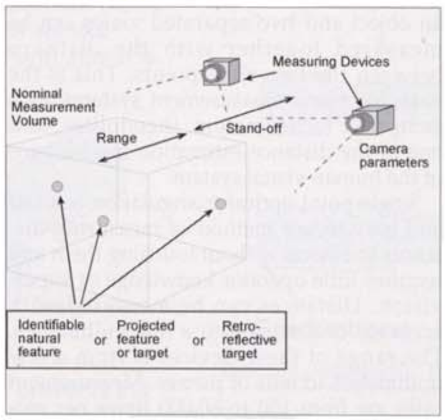


Figure 5. Configuration of a photogrammetric system

Photogrammetry is a non-contact multiple point measuring tool that is capable of high accuracy measurement of 10 to more than 1000 points simultaneously. It typically provides high accuracy results between 1 part in 5000 to 1 part in 150,000 of the largest dimension of the object being measured

Photogrammetry uses images of an object taken from a variety of directions [Fig 5]. The 3-D location of each corresponding point is computed using triangulation. To achieve this it is necessary to know where the cameras are and the direction the cameras are pointing. Accuracy is related to the number of pixels in the sensor and the type of feature being measured to. Sometimes measurements are taken with a single hand held camera that takes pictures from a variety of locations. In other cases a hand held CMM style probe location is measured providing portable CMM functionality [Fig 6].

Figure 6. Photogrammetry example system
Metronor portable CMM
Range:2 metres. Stand off: 8 metres .
Resolution: 0.01mm. Measurement frequency: 1 Hz

Benefits of photogrammetry include;

- Simultaneous measurement of many points at one time
- Storage of results for post processing or analysis
- Fast events can be captured
- Highly accuracy potential
- Statistical feedback on reliability of the measurement process
- The measurement volume can be scaled up or down.
- Incorporation of additional information such as measured distances

Despite the fact that photogrammetry is a well developed and mature technique some drawbacks do exist, they include;

- Clear lines of sight are required for each camera.
- A trained user is often required to get the best results
- Few off-the-shelf systems so expense is relatively high
- Some objects may require controlled illumination especially if edges or features are used
- Set up procedures are required prior to measurement
- High accuracy measurement requires stick on retro-reflective targets

Time of flight

Time-of-flight devices use the time taken for light or sound to travel to a surface and return. The biggest advantage of these sys-

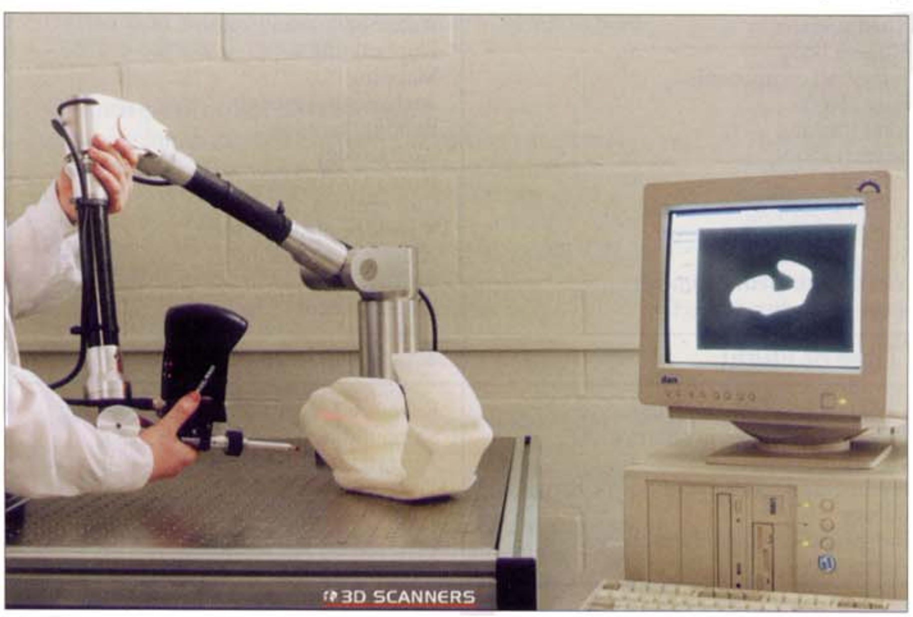


Figure 4. Example instrument - 3D Scanners
Modelmaker with FARO portable CMM
Range: 100 mm Stand off: 50 mm. Resolution:50 microns in line with the laser stripe, 200 microns along the stripe.
Measurement frequency: 50 Hz

Figure 7. Ultrasonic device configuration

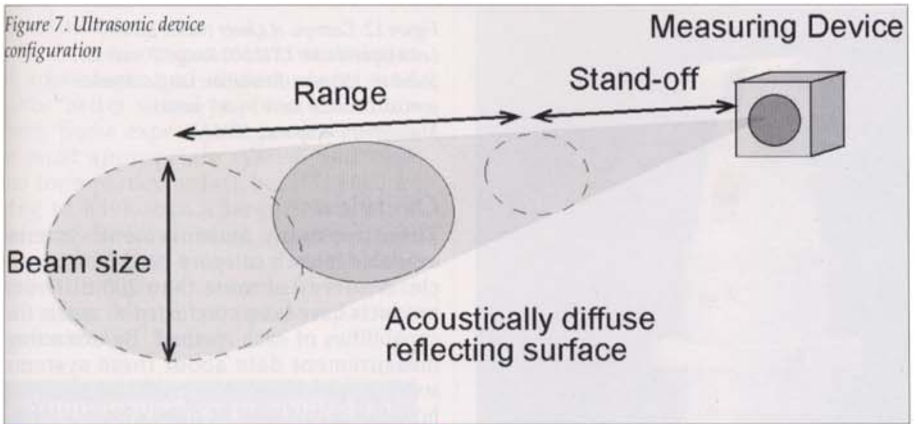


Figure 8. (Above) Example ultrasound system - Migatron
Range: 1.8 meters; Stand off 200 mm. Resolution: 1.7 mm Measurement frequency: 28 Hz

Figure 10. (Below) Example time-of-flight system - LASAR
Range: 38.5 metres Stand off: 1.5 metres
Resolution: 2-500 mm depending on range
Measurement frequency:190 scanned lines per second

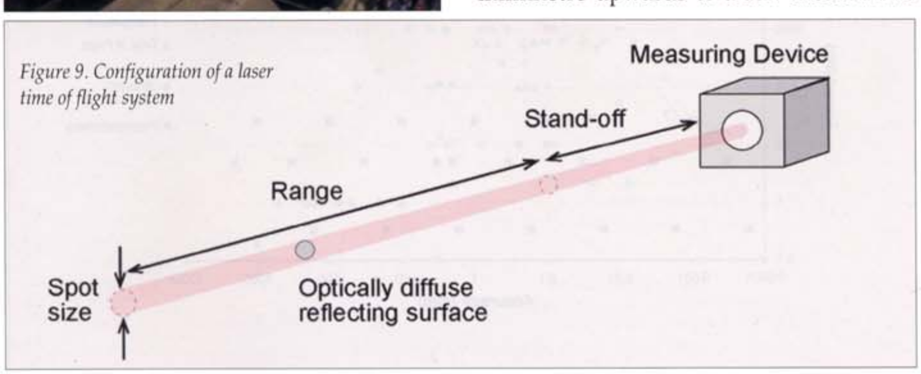


Figure 9. Configuration of a laser time of flight system

tems over triangulation systems is the sent and returned light rays are usually co-axial.

Ultrasonic rangefinders use sound to measure. Distance is measured with an accuracy of a few centimetres, over a range of a few metres, at a rate of milliseconds to several seconds per sample. Sound waves propagate from the transmitter and bounce off objects, returning an echo to the receiver. If the speed of sound is known, the distance to an object can be calculated from the time delay between the emitted and reflected sounds.

Benefits of the system include;

- Measurement over distances of up to 10 metres
- Works with almost any surface type - especially good for liquids where optical methods fail
- Resistant to vibration, radiation, background light and noise
- Largely unaffected by dust or dirt
- Cheap

Some disadvantages are;

- Moderate accuracy: 0.1 to 2% of the range
- Large beam fan angle hence poor object resolution
- Affected by temperature and humidity
- Limited speed for high accuracy measurement due to averaging
- Restricted object surface angle: requires a near-perpendicular surface

Laser time-of-flight instruments can offer very long-range distance measurement. They can measure the distance to a single small point at a distance of up to 50 metres without requiring a special target, or measure several kilometres with a retro-reflecting target. Instruments can be compact, and are often combined with a sighting device, such as a theodolite or binoculars. Distance is measured with accuracy from around a millimetre upwards to a few metres. The range can be from a few hundred millimetres to several kilometres. A typical speed of operation would be one sample per second but some devices can operate at 1000 Hz with lower accuracy.

Time-of-flight systems generally use one of two methods to determine distance: a short pulse of light is emitted and the delay until it returns is timed, or the phase difference between an emitted modulated light beam and the reflected waves is measured. Each method has advantages and disadvantages.

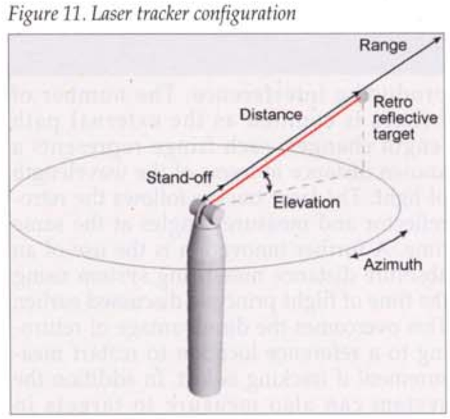
The benefits of time of flight include

- Long distance measurement, up to 10 kilometres with a retro-reflecting target
- Range of up to 1km without target, depending on surface type
- High relative accuracy, i.e. a few centimetres over several kilometres
- Simple to use 'point and shoot'
- May be combined with a theodolite for range and bearing
- Relatively low accuracy over short distances
- Improved accuracy requires a long sampling time, up to several seconds per point
- The surface characteristics of the target object limit the maximum range

Interference

Distance measuring methods that use interference usually provide relative measurements rather than absolute. The distance to an object can only be known relative to another by zeroing the counter to a reference position.

Figure 11. Laser tracker configuration



Laser trackers provide a relatively fast, precise and intuitive method of measuring large objects in industrial environments. They measure to a target which can be moved almost anywhere within line-of-sight of the base unit with an accuracy of a few microns, over a range of tens of metres. Laser trackers are based on the combination of two techniques: a laser interferometer to measure relative distance, and optical encoders to measure azimuth and elevation of a beam-steering mirror. Interferometers work on the principle of light interference. The Laser beam is split into two, one beam is used as a reference while the other beam is reflected back from a mirror or retro-reflector at some distance and the returned beam is merged with the reference beam,

Figure 12. Example of a laser tracker system Leica Laser tracker LTD 500 Range: 70 metres. Stand off: 150 mm. Resolution: (angle, distance + 5 ppm) (0.07",1.26 µm + 5 µm / metre) Measurement frequency:1000 Hz

producing interference. The number of fringes is counted as the external path length changes; each fringe represents a known distance in terms of the wavelength of light. The laser tracker follows the retroreflector and measures angles at the same time. A further innovation is the use of an absolute distance measuring system using the time of flight principle discussed earlier. This overcomes the disadvantage of returning to a reference location to restart measurement if tracking is lost. In addition the system can also measure to targets in approximately known positions without an operator.

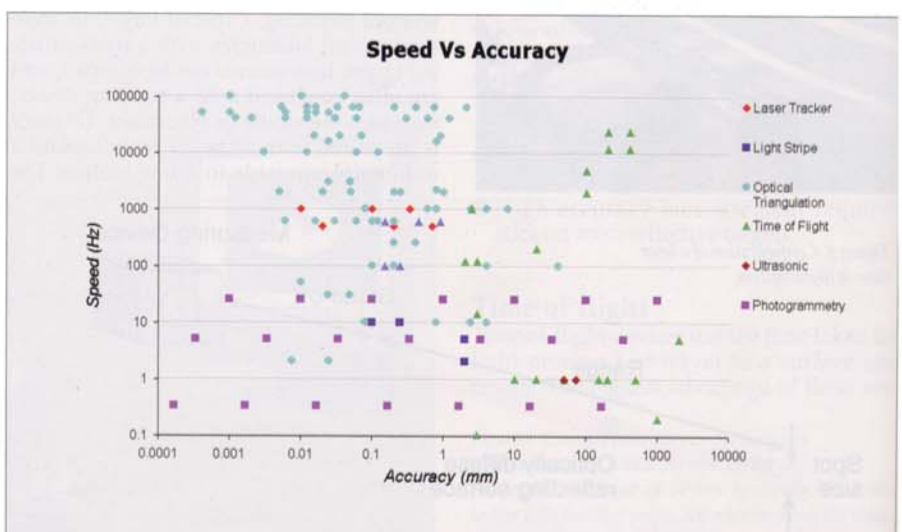
Benefits of this technique include;

- Intuitive: operator places the target anywhere a measurement is required
- Fast: each data point can be recorded in a few seconds
- Single user: one device and an operator can record points working alone
- Range: typically tens of metres, creating a large working volume
- Dynamic measurement of moving targets such as robots

Limitations include such elements as;

- Can only operate in line of sight - breaking the beam requires relocation of the reflector
- A retroreflective target must physically touch the measured point
- Recorded co-ordinates are usually offset from the actual surface
- The size of the retro-reflector limits the minimum radius of curvature measurable
- Changes in air temperature, pressure and humidity affect measurement accuracy

Figure 13



Overview

There are many measurement systems available in each category cited in this article. A survey of more than 200 different products have been conducted to assess the capabilities of each method. By extracting measurement data about these systems some graphs have been produced showing how the capabilities of these systems relate to each other. The first of these graphs (figure 13) illustrates how the speed of these devices varies with the measurement accuracy.

It is clear from this graph that some of the fastest devices are the optical triangulation devices which also have good accuracy. However, these devices also have relatively small ranges. Time of flight systems can measure relatively quickly but with poor accuracy. Light stripe systems appear to be relatively slow but each stripe may contain several hundred measured points. Another way of analysing these devices is to look at their range versus accuracy characteristics.

The graph is able to clearly illustrate the general trends with these measurement systems, for instance, illustrating that photogrammetry is scaleable to many tasks with approximately the same measurement range/accuracy characteristic depending on how it is used. An issue of concern in the data presented from the specifications of manufacturers data sheets is the lack of consistency in terminology, especially concerning the accuracy of systems. In many cases only precision is quoted but the difference between precision and accuracy varies considerably from technique to technique. These graphs therefore indicate the trends for these devices but it is impossible to compile a true comparison between products while no standard terminology is used by manufacturers.

Conclusion

Each of the six measurement techniques has advantages and disadvantages, and will be better suited to some tasks than others. Some expertise in needed to pick the most appropriate system and supplier for a particular task but it is encouraging to have such a large selection of systems. Several other measurement techniques also exist for specialised applications, for instance, fibre-optic, inductive, Moiré, or speckle pattern interferometry.

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The benefits of using non-contact measurement systems are numerous and are likely to give: lower inspection costs; better quality control; faster production; smaller tolerances; fewer defects; and the ability to reverse engineer. It is likely that whether you wish to measure objects with sub-micron accuracy over a range of a few microns, or large-scale objects of many metres in size with millimetre accuracy an appropriate measurement technique is available for your task. □

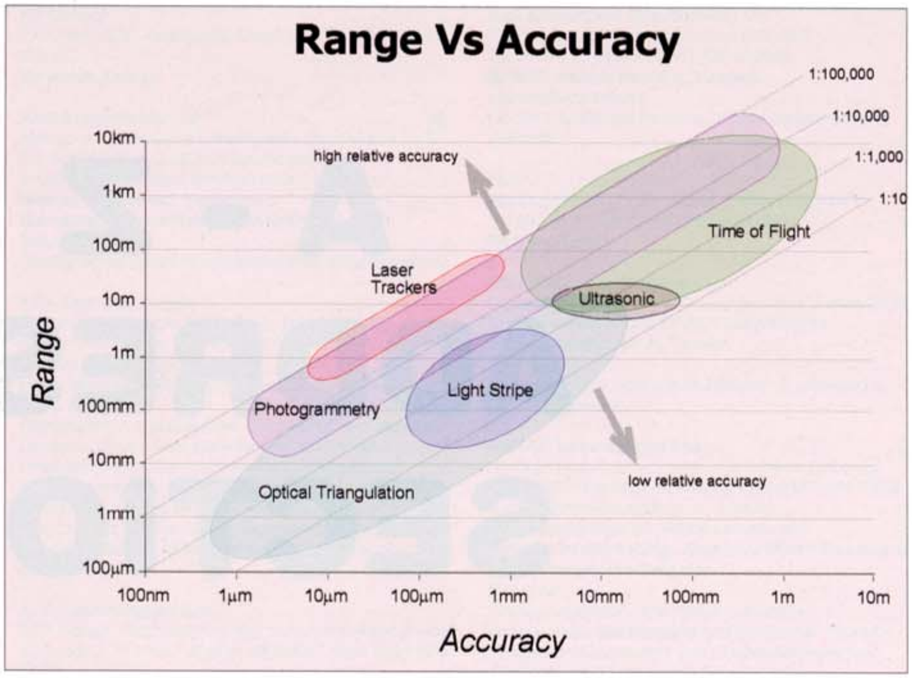

Figure 14. Range versus Accuracy for the six measurement systems.

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