Laser-based triangulation techniques in optical inspection of industrial structures.

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ABSTRACT.

An optical triangulation technique using a solid state laser diode source and detector, providing sub-pixel resolution on a CCD detector was developed and is discussed. A novel approach to the problem of non-linear accuracy is outlined. Results of extensive research into improving the accuracy of the device with particular reference to configuration, optical components, the laser source, linearity, resolution, calibration and interpolation are presented.

1. GENERAL INTRODUCTION.

There exists a vast number of structures which require measuring to, check manufacturing or construction tolerances, monitor deformation, acquire structure detail for research purposes, assist planning and for long term record. In the past these tasks have been carried out by time-consuming and expensive manual methods or frequently not at all. The demand for spatial information is ever increased by the knowledge of the ability of relatively cheap computer workstations to be programmed to analyse such data. However manufacturers may have to accept working periods of several days to measure a structure such as a car body or to monitor the deformation of engineering structures such as railway tunnels. Many methods are currently applied to data capture such as motorised theodolites, laser based range finders, coordinate measuring machines, ultrasonic techniques, and photogrammetry. Most of these methods do not entirely satisfy the requirement for speed and accuracy to reduce the time taken for the measurement process to be completed.

A technique which has not been generally applied to the measurement of structures in the range 0 - 10 metres is optical triangulation with a laser light source[1]. This technology can easily provide high data rates on a kilohertz to megahertz basis and adequate resolution with "sub-pixel" techniques where the resolution actually achieved is greater than of the fundamental image element itself. The principle of an optical triangulation system is that with the fixed parameters of camera angle, base-line length and a narrow light beam source acting as a pointer to a discrete position on a structure, the camera can be used for angle measurement. The distance of the object from the base line can be determined by calculation using the known parameters or by calibration and interpolation. In this paper, results obtained from the use of such a system are presented, the advantages and disadvantages are discussed and some of the inherent problems in triangulation systems are addressed.

Optical Triangulation.

Mechanical and civil engineering artifacts and structures present a regular and expanding requirement for measurement. The subjects of study in many cases vary in size from a few millimeters to several tens of meters, often demanding sub-millimeter accuracy and high speed data recording. In practice, however, there are often no systems available or suitable to provide a rigorous general purpose solution.

Optical triangulation measurement systems with fast data recording are available, and have a good reputation as being robust, reliable, reasonably fast and acceptably accurate. They are, as is any optical method of measurement, dependent on clear lines of sight and may suffer non-linearity. The present paper offers a partial solution to these problems and discusses the causes of error and reports on trials carried out to test the accuracy of a novel optical triangulation system.

Surveying of structures.

Photogrammetry is a well established and widely used technique which can be used in a variety of ways.[2] To acquire data appertaining to cross-sections of a structure such as a railway tunnel a photograph is taken of a the structure illuminated by a narrow light plane[3]. With the use of metric cameras or adequate control in the scene, cross-sections of a given structure may be obtained, as illustrated by Figure 1.

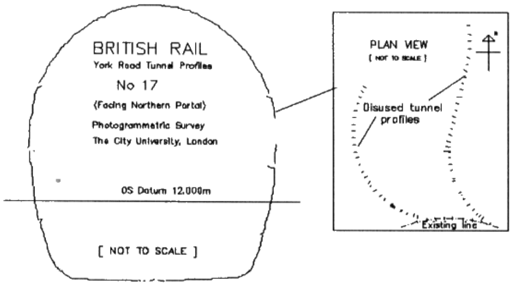


Fig 1. Cross-section of British Rail tunnel obtained by conventional photogrammetry.

The use of optical triangulation, when applied in a suitable configuration, is also able to obtain data of the same nature, but directly, more accurately and with considerable speed advantages over conventional methods such as Electromagnetic Distance Measuring (EDM) theodolites[4] or photogrammetry. Some examples of the type of data that can be collected by an optical triangulation system are shown in Figure 2.

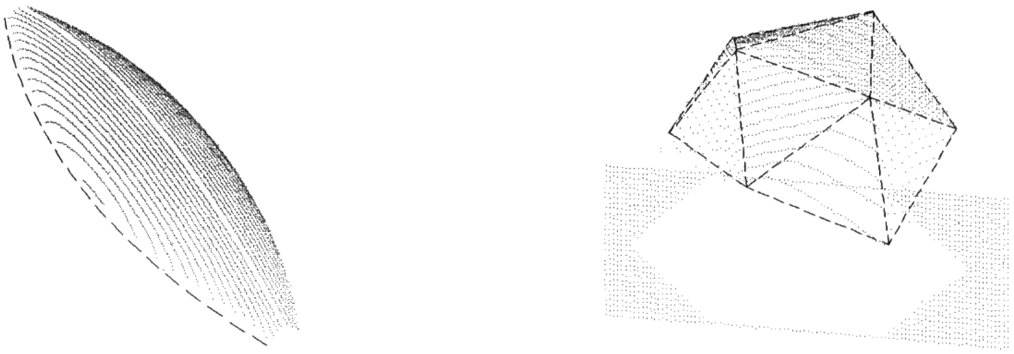


Fig 2. Cross sections of a model boat hull and polyhedron obtained by optical triangulation.

A comparison of performance for measurement to 5000 points on a surface at a range of 1-4 metres from the measuring system to a grossly irregular surface is made. The number of points required will depend strongly on the nature of the irregularities on the surface and what importance is attached to them. Clearly if too few points are taken then this can present a distorted representation of the surface, and care must be taken to avoid this. Table 1 shows the parameters of importance for three surveying techniques introduced, for surveying a similar scene.

Method	Data acquisition time	Post processing	Accuracy / std dev
EDM	33 mins	No	3 mm
Photogrammetry	15 sec	Yes	2 mm
Triangulation	5 sec	No	1 mm

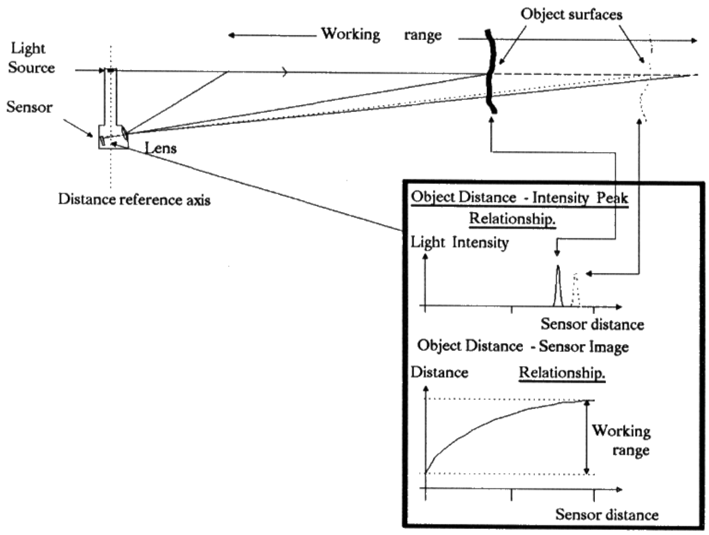
Table 1. Comparison of parameters of importance for three surveying techniques.

The work described in this paper concentrates on an analysis of the theoretical errors experienced in triangulation systems as the basis of developing an understanding of the basic physics of these systems and to compare predicted errors with those obtained in practice.

2. THE OPERATION OF THE TRIANGULATION SYSTEM.

Introduction.

A typical configuration for optical triangulation measurement is shown in Figure 3(a). This comprises a laser pointer, lens, sensor and mechanical components to provide a stable configuration. The relationship between distance from a structure and image position on the sensor is shown graphically. Figure 3(b) illustrates the operation of the image processing of the laser image in use as a distance measuring sensor. A feature of this design is that the laser pointer beam is perpendicular to the axis of the system which allows for rotation about that axis, so allowing the beam to describe a cross-section of any structure in the path of the beam. The laser employed takes into account the spectral sensitivity of the sensor and if this is silicon, the peak response is in the near infra-red part of the spectrum. A diode laser source, such as one of those emitting at wavelength 670,750 or 780 nm is a suitable choice, the first being highly visible to the naked eye, the latter being only just visible in the dark but is much cheaper than the other two and well matched to the detector peak sensitivity. If another type of laser is used, such as He Ne (632.8nm) then its physical size is an important consideration as the diode laser offers not only the advantages of small size but low voltage operation.



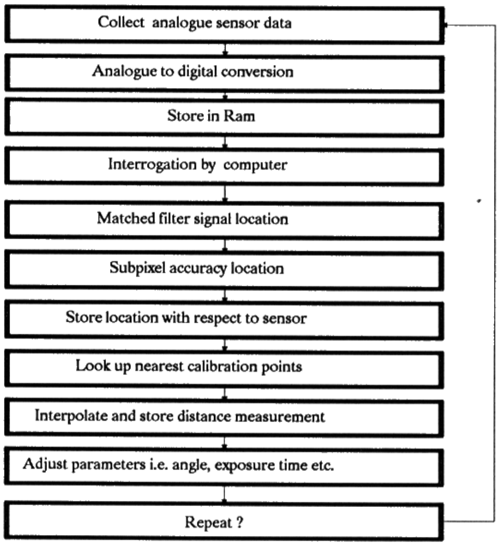


Fig 3(a) Configuration and operation of triangulation. Fig 3(b) Flow diagram of distance measurement control.

The configuration of one of the prototype systems developed for testing in tunnels is illustrated in Figure 4(a). The components were: a 750 nm diode laser and collimator, a 2048 pixel CCD line scan sensor and camera with a 50mm lens, and a stepper-motor-driven rotation stage with a resolution of 0.01 degrees. The calibration was performed with an interferometer capable of measuring displacements of several meters to a resolution of microns, and a typical calibration curve is shown in Figure 4(b).

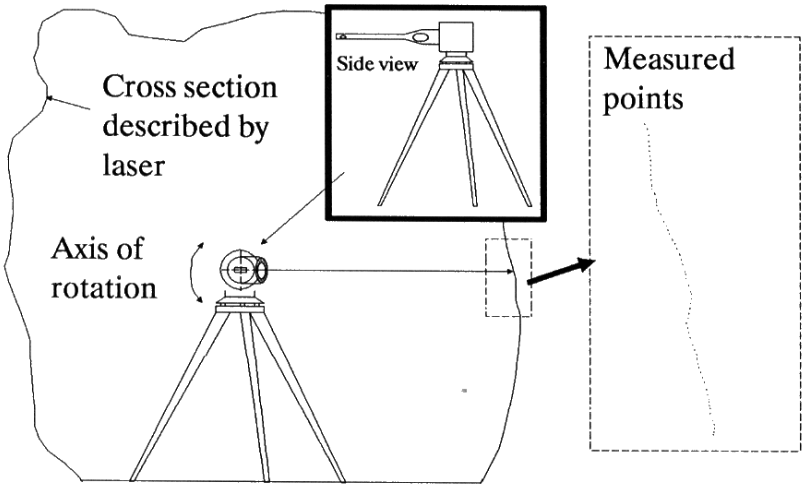


Fig 4(a). Cross section measuring configuration.

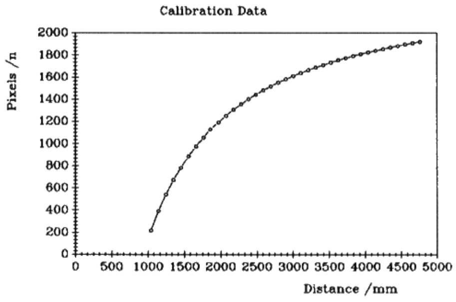


Fig 4(b). Calibration curve.

Theory of operation.

The equation relating δ to 'D' is shown in (1) for a camera and light source configured as shown in Figure 5, provided that 'D' is small and 'Θ' is constant.

$$\delta = \frac{idSin(\Theta)}{o} \qquad (1)$$

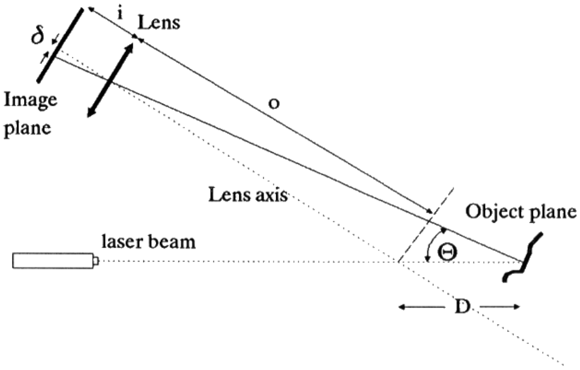


Fig 5. Simple triangulation configuration.

Over a small range the system is linear and in some circumstances it may be useful to use it over that range, but often a larger range is required, in this case the configuration has the additional problem of requiring a large depth of field to keep the image in focus. It is apparent from the geometry of the situation that, with the same base length, the resolution will decrease with an increased measuring distance from the base-line of the system. Unfortunately, with an extended range, the camera will be out of focus at certain part of the range, or a large depth of field will be required (this is not always possible as it is achieved by a small aperture which reduces the amount of light able to reach the sensor from the object). To overcome the focus problem the sensor, lens and light source can be arranged to fulfil Scheimpflug's condition which states that 'for perfect focus, the image plane, the object plane and lens plane all must intersect along a common line',[5] as shown in Figure 6. Ji and Leu[6] have derived an exact relationship between the object and image displacements which incorporates the Scheimpflug condition as shown in (2).

$$\delta = \frac{DiSin(\Theta)}{DSin(\Theta + \Phi) + OSin(\Phi)} \qquad (2)$$

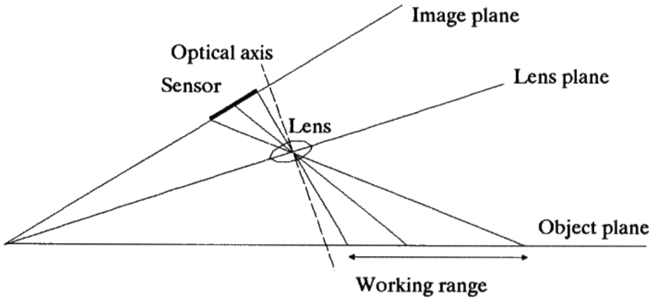


Fig 6. Geometry of the Scheimpflug condition.

This equation is plotted in Figure 7(a), for a set of values of D,i,Θ and Φ, defined as shown in Figure 7(b). It is evident that a basic triangulation system is inherently non-linear in accuracy and resolution, if a uniform resolution sensor is used.

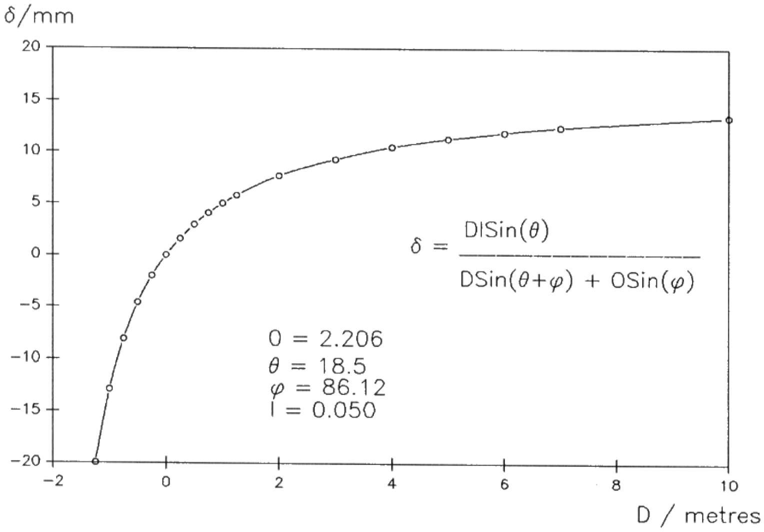


Fig 7(a). Graph of δ against D.

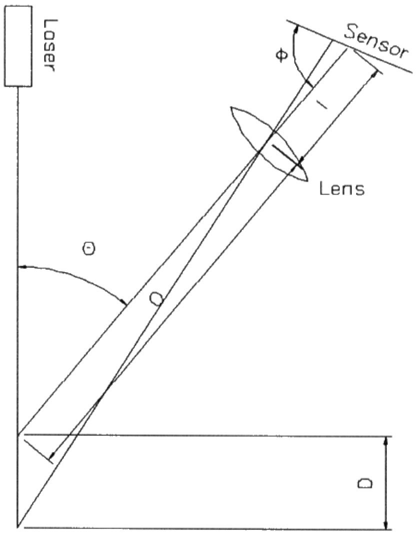


Fig 7(b). Configuration for perfect focus.

To use a triangulation system there must be an initial calibration, and subsequent interpolation between calibration points for a distance measurement. The implications of the inherent non-linearity are that linear systems can be constructed that are highly accurate over a small range, or non-linear systems designed for a relatively larger range.

Non-linearity.

Because ready-made components such as cameras come 'off the shelf', fundamental thinking about the appropriateness of the configuration is not often considered. However in the case of optical triangulation, a detailed appraisal is required to gain optimum performance. An example is the solution to the depth of focus problem when measuring over a long range, say 1-5 metres. Conventionally, sufficient depth of focus is required to enable correct focussing at each end of the desired range, however, a small aperture is then required and consequently the system may not be able to collect enough light to operate at full speed. By adjusting the image plane with respect to the lens to conform to the Schleimpflug condition, perfect focus may be obtained throughout the range with beneficial results.

In the case of non-linear resolution a solution is to use some form of correction to oppose its effect so that over a certain range a more linear variation in accuracy would result. The counteraction of the non-linearity is performed in a similar way to that of a fish eye lens which changes the normally linear relationship between object and image so that the image is distorted. This type of correction of the characteristics is well known in the design of linear instrumentation[7] where non-linear elements are put in opposition, so modifying the overall relationship one to the other.

The results of simulation and bench testing are encouraging with certain configurations showing a linear relationship between object distance and image location with respect to imaging chip. For example, Figure 8, schematically illustrates the relationship between the image on the sensor and distance measured using the same base length (1.0m), starting distance (1.0m), focal length of lens (50mm) and CCD chip length (26.62mm). The dotted line is the corrected curve and the continuous line represents the uncorrected data.

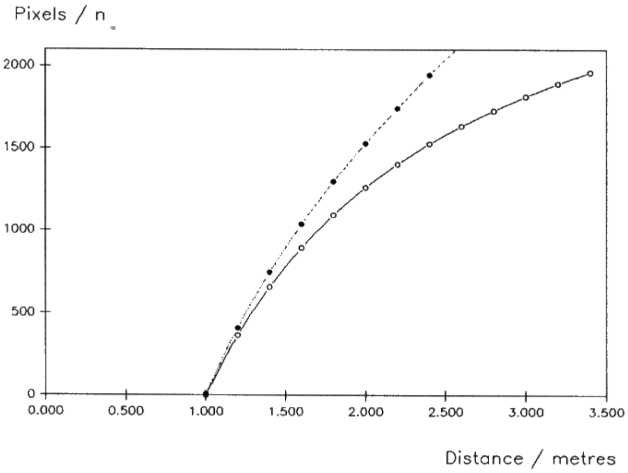


Fig 8. Correction of optical triangulation non-linearity.

3. FEATURES OF TRIANGULATION SYSTEMS.

Advantages.

The advantages of a triangulation measuring system are speed (data rates up to 10,000 measurements per second are possible) and accuracy (resolution of 2,000:1 to 20,000:1). When such a system is rotated about a central axis, it is possible to measure structures which are relatively large with reasonable speed and accuracy for most practical purposes. In many situations this speed of measurement is an important consideration for economic reasons and the measurement itself is usually only one step in an overall engineering problem.

The typical working environment for a measurement system can vary enormously from the clean research environment to that encountered in a mine shaft where there are draughts, local temperature and humidity variations, surface wetness, occluded surfaces, and an environment hazardous to the operator. Any measurement system may be required to cope with this very wide range. The triangulation scheme discussed herein is robust to the extent that all electronic components are solid state and operate at relatively low power. The mechanical requirements for the triangulation system are amenable to a design optimised for the particular measurement requirements.

Disadvantages.

A disadvantage of the use of triangulation systems is that the measurement does not take place coaxial with the light source, leading to problems of occlusion and in the physical size of the measuring instrument. If the distance between the sensor and the light probe is reduced to minimise these problems then, the non-linearity inherent in the simple triangulation geometry becomes a serious limitation. The light source used has to maintain a high signal to noise ratio at the detector compared to the ambient light reflection in the area of interest, and this can lead to problems of eye safety. The system has a finite resolution and so is suitable for bounded situations where it is known that all objects of interest will fall within the range of the measuring equipment. However such situations are numerous. e.g rail, sewer, and road tunnels. Speed of measurement is limited by the time it takes (a) to collect enough light and (b) the time taken to clock the data from the array and process it. This implies a maximum data rate of 10kHz for a 2048 pixel CCD chip typical of what is available commercially . However there are alternatives such as "tapped" arrays which overcome some of these problems. The lens system and laser launching system may present problems in dirty environments with ensuring clear optical surfaces.

4. ERRORS.

The errors in measurement may be split into two groups, distance measuring errors and the errors in determining the spatial coordinates of the measured points. In both categories there are systematic and random errors. The systematic errors can be estimated and, in many cases, a correction can be made. The random errors are best treated statistically.

4.1. DISTANCE MEASURING ERRORS.

There are many sources of errors in triangulation systems which reduce the maximum resolution available for a given configuration. In many instances a solution can be found which is a result of compromises of cost and convenience. However a full understanding of all the contributing sources of error is necessary for a given design to be 'optimised'. An optical triangulation system is made up of mechanical and optical components, some of which are amenable to design considerations such as choice of laser, sensor or materials and others which are beyond the capabilities of the designer to adjust, such as reflectivity of the surface to be measured and nature of the medium through which light is transmitted and received, e.g. air. The errors that relate to the camera are considered followed by the errors external to the camera.

4.1.1. CAMERA ERRORS.

The measuring system uses a lens and sensor as an angle measurer, this camera will produce errors of measurement due to temperature changes, image processing and modelling limitations, these errors are illustrated in Figure 9. The effect of each of these errors is analysed in this section.

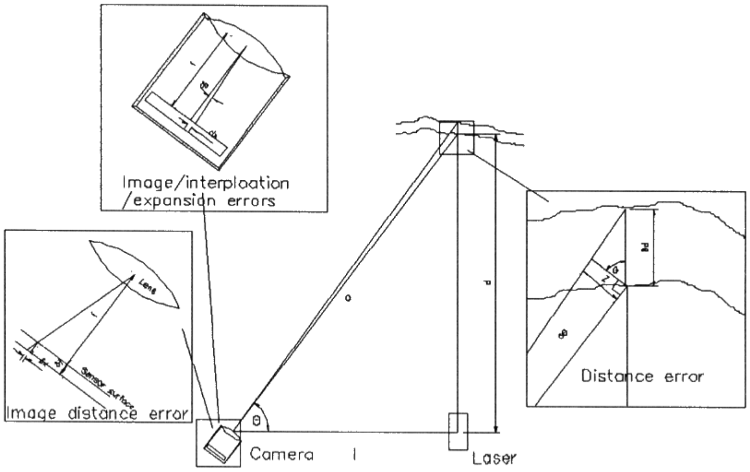


Fig 9. Sources of camera errors.

The errors which originate within the camera, essentially angle measuring errors, can be related to distance measuring errors. If the error in locating the image is 'δx' and 'f' is the focal length of the lens used, then the angle '$\delta\theta$' is given by $\mathrm{Tan}^{-1}(\delta x/f)$, 'O' the distance between the Object and the camera lens is given by $O = l/\mathrm{Cos}(\theta)$ the intermediate distance error $Z = O\mathrm{Tan}(\delta\theta)$ and the actual distance error $\delta d = Z/\mathrm{Cos}(\theta)$. By co~~n~~mbining these equations the total distance error is given by (3).

$$\delta d = f\, l\, \delta x/\mathrm{Cos}^2(\theta) \qquad (3)$$

By determining δx for each of the sources of error the total distance measuring error can be evaluated.

(1) Location of image with respect to CCD linear array.

The precision with which the Gaussian peak of the laser spot can be identified with respect to the sensor determines one of the fundamental limitations of the resolution of the system as a whole. It may appear that the resolution will be determined by the number of pixels in the camera and their size and distribution, this is a general guide but with sub-pixel interpolation algorithms, it is possible to locate the image with an improvement of resolution of 3 to 20 times depending on the nature of the surface to be measured. Improving the system resolution can be achieved by decreasing the size of the pixels used, increasing the accuracy of image location or by narrowing the field of view. The error in location, δx_1, is defined in (4) where L is the sensor length, n the number of pixels and δs is the sub-pixel interpolation estimation.

$$\delta x_1 = (L/s)\delta s \qquad (4)$$

(2) Sensor position changes with temperature.

The sensor is mounted on a printed circuit board which is held in the camera/lens housing. It is assumed that the camera unit cannot move in relation to the laser, but that it is possible for the CCD sensor itself to expand with temperature. As the sensor is constructed on a silicon substrate, the chip package is designed to expand at the same rate so that unwanted stresses are not allowed to build up within the package. The coefficient of expansion of silicon (α') is $2.6\text{x}10^{-6}K^{-1}$ at 293 K (20°C) and the possible external temperature range over which the sensor is likely to be operated is 0 to 30°C, however the chip itself will warm up during use. For a symmetrically held package the expansion δx_2 will be given by the relationship (5), where L is the length of the chip, T is the temperature rise and it can be seen that the maximum change is at either end of the sensor. This can be related to a distance error by the angle measuring error equation (3). A means of reducing the effect of temperature on a CCD array is to use a Peltier cooler too keep the chip at a constant temperature in use.

$$\delta x_2 = (L/2)\alpha' T \qquad (5)$$

(3) Change in camera image distance with temperature.

The lens camera system will expand or contract with temperature changes, this will affect the focus on axis, but off axis it will alter the position of the image with respect to the sensor chip and hence alter the accuracy of distance measurement as shown by Figure 9. The error introduced is $\delta x_3 = \delta f\mathrm{Tan}(\theta_2)$ where $\delta f = \alpha' Tf$, and f = focal length of the lens, α' = coefficient of expansivity of the camera body material, T is the temperature change, and θ_2 is the angle between the camera axis and the sensor. Hence the effect on the image is given by (6).

$$\delta x_3 = \alpha' TL/2 \qquad (6)$$

(4) Interpolation errors from calibration data.

To use the system for distance measurement data are collected from the image location algorithms and related to distance from the measuring system axis by means of an interferometer or other high accuracy measuring system. As there are 'n' pixels and with a sub-pixel interpolation limit of 'p' then there are 'np' possible positions of calibration points which can be measured. However as n is typically 1000 and p may be 10 then there may be a very large number of measured data points to be collected. It is preferable either to characterise the data by a function such a polynomial or to interpolate with a reduced data set. Both of these methods will cause errors if the model of the system characteristic does not perfectly match the true data.

The numerical methods[8] which may be used to interpolate between calibration points, assuming that there are too many points to store for direct look up methods, are piecewise linear, polynomial and cubic spline interpolation, and direct evaluation of an equation which describes the calibration curve such as a least squares best fit of a polynomial of appropriate degree. For the simple case of piecewise linear interpolation, the error will be the difference between the calibration curve C and the straight line S between calibration points. The error curve will oscillate between the correct value at the calibration points to a maximum error at some point between the calibration points. Again this error can be related to a distance measuring error by use of equation (3).

4.1.2. EXTERNAL ERRORS.

The remaining analysis of errors concentrates on the factors which are outside of the camera angle measuring system such as the transmission medium, laser pointing error, base line expansion and image distortion. Again these errors are both random and systematic in nature and each will be analysed with reference to its effect on distance measuring accuracy, as shown by Figure 10.

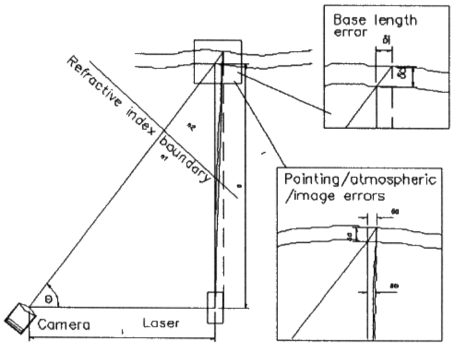


Fig 10. External error sources.

(1) Base line length changes with temperature.

The optical triangulation system is constructed from a laser, sensor and lens mechanically held in a fixed configuration. The system is operated via calibration at a specific time and subsequent interpolation. There is an implicit assumption that the system is still in the same configuration as it was at the time of calibration which may not be the case, due to temperature changes etc. The main resulting cause of error is the variation of base line length due to the thermal expansion of the material over its operating temperature range. It is assumed that the design is such that the camera and the laser are not able to change in orientation with respect to each other. The expansion of a material is equal to $L\alpha''T$, where 'α''' is the coefficient of linear expansivity. The coefficients 'α''' for steel, aluminium and invar are 23,15 and 0.9 x $10^{-6}K^{-1}$ respectively.

In the case of the test system aluminium was used for strength, cheapness and lightness, however, invar would reduce the length error but at the cost of weight and expense. The variation in temperature can be compensated for, as the expansion of the material is known. This is not an unreasonable solution as many high precision devices allow the input of correction data for temperature and pressure such as EDM[5] and Interferometer systems[8]. The error δd introduced by linear expansion of the base line will depend upon the angle of camera view θ, linear expansivity α'' of the material used, the temperature range and the length, 'l', of the base line, as shown in Figure 10. The error is given by (5) where δl is the difference in the length of the base of the system.

$$\delta d = \delta l \mathrm{Sin}(\theta) \qquad (7)$$

(2) Laser pointing stability.

A laser provides a source of well collimated light which is able to illuminate a small portion of the object. This is what makes this method an active, as opposed to passive, sensor system. The successful use of this light spot depends critically upon the pointing stability of the source. Lasers have very low pointing angle variations, but they do exist and as such have to be taken into account. Both diode and gas lasers could be used in this application as both provide a highly collimated light source. The sensor used in the system has a peak sensitivity and quantum efficiency in the near infra-red. Hence only HeNe lasers (632 nm) and visible wavelength laser diodes (670 nm) were considered. Both of these are well developed technologies providing reliability and cheapness. For the optical triangulation scheme to operate successfully the light source must be able to accurately illuminate the point of measurement on the structure to be measured. This requires, of the laser, the following:

(1) Low beam divergence. This is required because with a small spot size there is maximum signal to noise ratio.

(2) High directional pointing stability. The system is calibrated once and then based on this an interpolation takes place, errors will result from a lack of reproducibility.

(3) Power output variability and stability. This requirement allows measurement to a greater range of surface reflectances and allows prediction of the exposure level based on the past exposure level, this would not be possible if the power output changed between exposures.

(4) High reliability. The system will be used in a range of temperatures, humidity and pressure, and also for long periods of time. The laser must be reliable if the system is to be trustworthy.

(5) Low cost. Each component in an optical system will contribute to the overall cost and the laser is likely to be a significant cost in the development of the system.

A comparison of performance of a HeNe laser and a typical diode laser is made in Table 2.[9,10]

Parameter	He Ne	Diode	Units
Divergence	0.7 - 2	1.2	mrad
Pointing stability	< 0.1	< 0.1	mrad
Lifetime	> 10,000	> 50,000	hours

Table 2. Laser performance comparison.

As in the case of the systematic errors, the pointing error can be translated into a distance measurement error. The error introduced through pointing error is given by equation (8), where $\delta\theta$ = pointing error of the laser.

$$\delta d = L\mathrm{Tan}(\theta)\mathrm{Sin}(\theta)\mathrm{Tan}(\delta\theta) \qquad (8)$$

(3) Ambient temperature, pressure and humidity.

The laser beam and the reflected light all pass through the medium of air before entering the camera. During this period it is possible for the light to encounter temperature, pressure or humidity gradients which can affect the direct path of the light to the camera, so giving a false reading. The sight of a ship sailing along the horizon some distance from the perceived water / sky boundary may be recalled to understand the significance of this. A commonly used formula[11] for the calculation of the refractive index of air is:

$$(n - 1) \times 10^{-6} = 103.49(P - E)/T + (86.26/T)(1 + 5748/T)E$$

Where n = refractive index, P = pressure (mmHg), E = water vapour pressure (mmHg) and T is the temperature in Kelvin and the carbon dioxide content of air has been ignored. This formula is accurate to better than 1 part in 10^{-6} which is satisfactory for this work. To use this equation it is desirable to compute the relative change in refractive index with respect to temperature, pressure and humidity. Typical input parameters are P = 760 mmHg, T = 293K, E = 7.6 mmHg, and the rate of change of each of these is $\delta N/\delta P = +0.35$ units/mm Hg, $\delta N/\delta T = -1.22$ units/mm Hg, $\delta N/\delta E = +5.72$ units/mm Hg. It is now possible to calculate the change due to each of these parameters over a given range. With these values the variation in position of the laser beam and hence a distance error due to non homogeneity of the transmission medium can be computed. To estimate an approximate order of magnitude for this error an imaginary boundary can be postulated between the object and measuring system which, for simplicity is the plane which is the perpendicular bisector to the ray traced from the laser to the structure surface. The refractive index is n_1 on one side of this plane and n_2 on the other. The error δd can be calculated by consideration of the geometry and Snell's Law and is then given by Equation (8).

$$\delta d = (l\mathrm{Tan}(\theta)/2)\mathrm{Tan}[(90 - \theta) - \mathrm{Sin}^{-1}((n_1/n_2)\mathrm{Sin}(90 - \theta))]\mathrm{Tan}(90 - \theta) \qquad (9)$$

(4) Surface irregularities.

The image location with respect to the CCD array can cause errors if the surface to be measured has sharp discontinuities either in form or contrast, is aligned at unfavourable angles or is outside the optimum range of reflectivity required by the sensing system. This error can be partially eliminated by the *a priori* knowledge of what the image should look like at a given distance. If this is not the case then the sub-pixel algorithm will record the position of the image distorted by this factor.

4.1.3 SUMMARY.

It is helpful initially to look at the source of errors, e, and in this case there are camera errors and configuration errors. The former are given by:

$$e_{\text{image location}} + e_{\text{sensor expansion}} + e_{\text{image distance change}} + e_{\text{interpolation}}$$

and the latter by:

$$e_{\text{pointing}} + e_{\text{base expansion}} + e_{\text{atmospheric}} + e_{\text{surface}}$$

For a full analysis of the errors it is better to consider the two type of error, the systematic and the random. The systematic errors can be allowed for either in the use or estimation of overall accuracy, whereas the random errors must be statistically analysed to provide the fundamental errors in the error analysis. The standard deviation[12] of a random variable is the positive root of the square root of the sum of the squares of : $e_{\text{image location}}$, $e_{\text{interpolation}}$, e_{pointing}, $e_{\text{atmospheric}}$, e_{surface}. The value of these error cannot be known in advance, whereas the remaining errors are able to be computed and corrections entered if the temperature is known. For a set of parameters the value of errors is shown in Table 3.

	Random errors				
	Image Location	Interpolation	Laser Pointing	Atmosphere	Surface
$\delta x/\mu m$	1.3	0.13	-	-	-
$\delta d/mm$	0.172	0.017	0.192	0.0043	0.17
	Standard deviation = 0.31 mm				

	Systematic errors		
	Base length	Sensor length	Image distance
$\delta d/mm$	-	0.031	0.18
$\delta d/mm$	0.284	0	0
$\delta d/mm$	-	1.9	10.96
	Max errors :- @ Min distance - 0.2mm, @ camera axis distance - 0.284, @ max distance - 12.8 mm.		

Table 3. Theoretical errors in distance measurement.

For a number of calibration and interpolation tests carried out over a variety of distances, and a configuration with parameters approximately the same as used for the analysis in Table 3. an average standard deviation of 0.361mm was obtained which compares favourably with the predicted value.

4.2 SPATIAL POSITION MEASURING ERRORS.

Measuring the distance from an optical triangulation system to a structure is effected by means of mechanically holding the measuring system while a measurement is made. If in addition a number of measurements are required to a multiplicity of positions on the structure surface and these measurements are required to a number of areas on the given structure then additional errors will be accumulated to the individual measurement points. A configuration favoured in the development of a general surveying system incorporating optical triangulation is for rotation about the camera laser axis so that the laser pointer describes a cross section when viewed from a position perpendicular to this measurement plane. The type of structure which benefits from this type of analysis is shown in Figure 1. i.e. a railway tunnel where local deformation and global "wriggle surveys"can be carried out. The errors additional to the measuring errors fall into two categories, those concerning the cross section and those involving the location of those cross sections with respect to a datum or to each other.

The cross section measuring errors are: (a) Eccentricity in the rotation axis due to the measuring and rotation axes not being coaxial, (b) Angular measuring errors caused by the rotation system or angle measuring system, (c) Bearing errors caused by lack of fit of the bearing used to provide the rotation of the measuring system and (d) Deviation from plane errors if the laser does not describe a true plane. The survey measuring errors are: (a) Angle of orientation errors with respect to verticality, (b) Position errors with respect to tunnel or structure locally, and (c) Positional errors with respect to the method of surveying used to coordinate cross sections or to relate to the surveying datum.

A typical use of this type of system is to collect cross sections of railway tunnels to monitor deformation or perform "wriggle surveys". In the former case a accuracy of 3mm/std dev is required to surfaces which are often non-cooperative being caked with soot, in the latter case a lower accuracy is demanded. An optical triangulation system as described in this paper is able to meet the requirements of such surveys. The advantage to the user is that large quantities of data are collected very quickly with high accuracy and repeatability. Structures which would benefit from this measurement technology are numerous and range over: boat hulls, car bodies, building interiors, tunnels, silos, mine shafts, ship structures, in fact any structure to which fast and accurate measurements need to be made.

5. CONCLUSIONS.

An analysis of the errors inherent in optical triangulation systems has been carried out. This analysis highlights the importance of understanding the fundamental physics of the system when designing for a particular application.

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