INTERNAL PROFILING OF INDUSTRIAL STRUCTURES.

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INTRODUCTION

There is a regular demand for fast inspection of Civil Engineering structures such as caverns, sewers, and tunnels, as well as Mechanical Engineering structures such as car and aircraft body panels or satellite dishes. The measurement of cross sections provides selective information about these structures which can be used for a variety of monitoring and information gathering purposes. Often the process of gathering data concerning cross sections is called "profiling". A number profiling devices and techniques exist, some provide data at the time of measurement while others only after subsequent processing. The most successful systems are limited to: the diode laser or light emitting diode using 'time of flight' methods, optical triangulation, or contact methods. Ideally measurement should be performed with a narrow collimated beam directed to a small unique point on a given surface. However until a fast coaxial laser range finder is produced with data acquisition speeds in MHz then there will continue to be a call for alternative methods and techniques to measure distances with speed and accuracy. One such method is based on optical triangulation using linear sensors which can be realised with current technology and have data recording rates of kHz and reasonable resolution with sub-pixel accuracy. In this paper some background information is given on profiling, followed by a discussion of the design of an optical triangulation transducer Although many of the examples concern large industrial structures such as railway tunnels, there are a vast number of alternative applications.

WHY MEASURE CROSS SECTIONS?

It is often necessary to survey structures to detect changes in geometry or fabric. Observations to collect data appertaining to regularly spaced cross sections is a well known and proven technique to assist the assessment of structural condition and change because of the reduction in the quantity of information gathered to manageable proportions. Frequently these data are supplemented with additional information concerning the spatial position and orientation of the cross sections. This type of information can be used for:

(i) estimation of clearances,
(ii) checking alignments of ducts and lift guide rails,
(iii) monitoring changes which can indicate problems of deformation,
(iv) compilation of inventories and "as built" drawings,
(v) determination of volumes of excavation or lining materials,
(vi) indication of structural failure,
(vii) collection of information for refurbishment,
(viii) checking the driving of tunnels,
(ix) monitoring progress of projects,
(x) measurement of car body panels,
(xi) classification of racing rating for yachts.
(xii) checking accuracy of satellite dishes

The structures and cavities encountered in civil engineering, and the large work pieces produced in mechanical engineering present a growing demand for specialist measurement techniques. The subjects vary in size from a few tens of millimetres to a few tens of metres, often demanding sub-millimetre accuracy with a high data recording and processing rate. In practice, for many applications there are no robust general purpose systems available. Optical triangulation systems have an excellent reputation for being quick, robust, reliable, and accurate in operation, the obvious limitations being occlusion and non-linearity.

METHODOLOGY OF CROSS SECTION MEASUREMENT.

Measurement of cross sections of a structure such as a tube tunnel requires careful consideration. If too few points are measured, then these will not adequately represent the shape of the tunnel. If the position of the cross section that is measured is not referenced to some datum, level, or pre-marks, then subsequent repeat measurements may be invalidated.

Establishing the location of a cross section. When cross sections are used to monitor any structure it is essential that the same section is measured. This can be achieved by having clearly visible permanent targets or identifiable marks in the plane of the cross section. Alternatively some other method of establishing adequate control must be found.

Calculating the number of measured points per cross section. The number of points which should be measured on a surface is a function of the shape of the surface. A surface can be modelled from sampled spatial data provided that sufficient measurements are made. This is analogous to the signal processing situation where Nyquists theorem states that to prevent aliasing a signal must be sampled at least at twice its maximum frequency. The characteristics of the surface undulations can be determined by preliminary tests to calculate the required frequency of point measurements.

PAST AND PRESENT PROFILING TECHNIQUES.

Methods currently employed to measure cross sections may be divided into two groups: contact and non-contact. Non-contact methods may be further subdivided into the automatic and non-automatic.

(1) CONTACT METHODS.

These take a number of forms and are generally used where access to more sophisticated and expensive equipment is limited or not allowed, or where a simple approach can provide quicker results. Three methods are briefly described.

(i) Probe and protractor.
(ii) Finger probes.
(iii) Tape extensometers.

(2) NON-CONTACT METHODS.

Non-contact methods of measurement fall into two categories (i) manual, where human involvement is required during the measurement process, and (ii) automatic, where limited supervision is required.

(i) MANUAL.

- (a) Theodolite, EDM, or Electronic Tacheometer.
- (b) Optical tacheometer.
- (c) Laser tacheometer.
- (d) Photogrammetry.
  - (i) Stereo.
  - (ii) Light sectioning.

(ii) AUTOMATIC.

- (a) Reflectorless EDM.
- (b) Automated theodolites.
- (c) Optical Triangulation.

There has been research carried out in the area of profiling the interior shape of industrial structures at City University for over ten years. A light plane is projected by a rotating laser light source. This line is photographed using a metric cameras. Scale is established with surveyed targets or a measured bar. After processing the photographs are measured on an analogue plotter or a mono or stereo comparator.

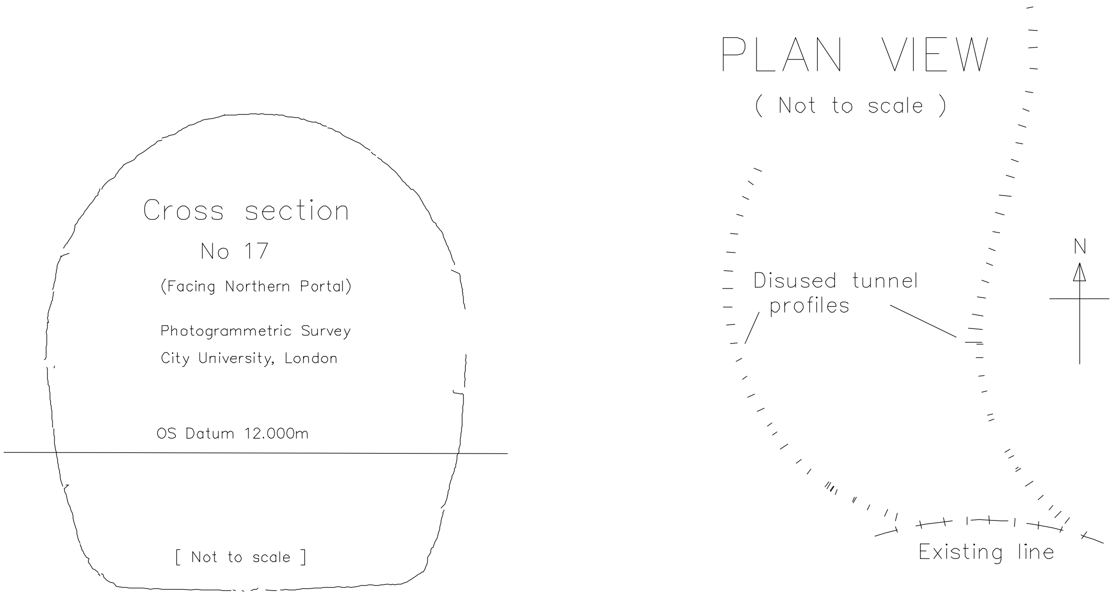

Figure 1. British rail profiles collected in 1985, plan view and profile number 17.

It was the realisation of the inadequacies of the photogrammetric approach that led eventually to the development of an optical triangulation transducer.

OPTICAL TRIANGULATION THEORY.

There are a number of possible configurations for optical triangulation systems, but the principle of operation remains the same, that is, a light source identifies a point on a surface to be measured. The reflections of this light will radiate in a variety of directions, a small proportion of which is collected by a lens and focused on a sensor which provides the means to distinguish the, relatively high intensity, peak from the background illumination and record its position. This position is related to a prior calibration from which a distance can be computed. This system is held together in a fixed configuration so that a multiplicity of such measurements can be made.

An understanding of theory is vitally important for the efficient design of electro-optic systems, a small oversight can have very large consequences. For instance, the filter that is sometimes glued to a standard CCD sensor (to provide a spectral response curve similar to the human eye) will also block out most of the light from a diode laser of a wavelength of 780nm. A typical configuration for optical triangulation measurement is shown in Figure 2. This comprises a laser pointer, lens, sensor and mechanical components to provide a stable configuration.

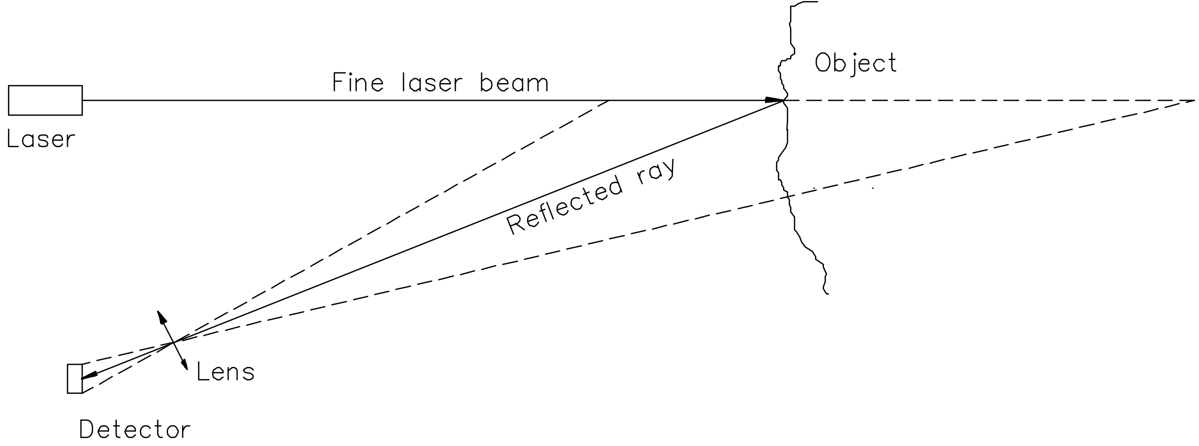

Figure 2. Optical triangulation configuration.

The relationship between the distance from a structure and image position on the sensor is shown graphically in Figure 3.

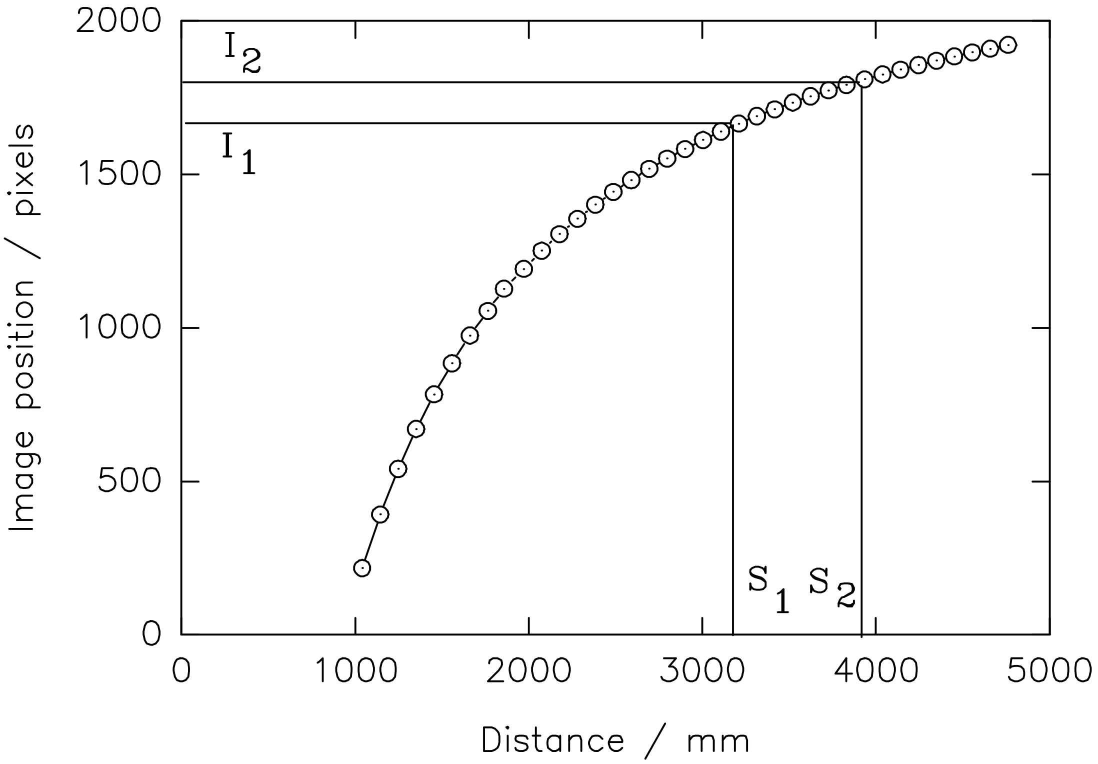

Figure 3. Calibration curve.

The images produced from the reflected laser pointer at surfaces S_1 and S_2 are formed at the points I_1 and I_2. Hence, by using a look up table of previous calibration points, the laser image position can be converted to distance by interpolation. A preferred design places the axis of rotation perpendicular with the laser beam and in a plane with the sensor and lens, so that the beam describes a cross-section of any structure in its path. The laser employed takes into account the spectral sensitivity of the sensor. Silicon has a peak response in the near infra-red part of the spectrum. Hence, 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 much cheaper than the other two and well matched to the detector peak sensitivity.

A number of prototype transducer systems have developed at City University where they have progressed through a number of configurations. These are shown in Figure 4,5,6,&7.

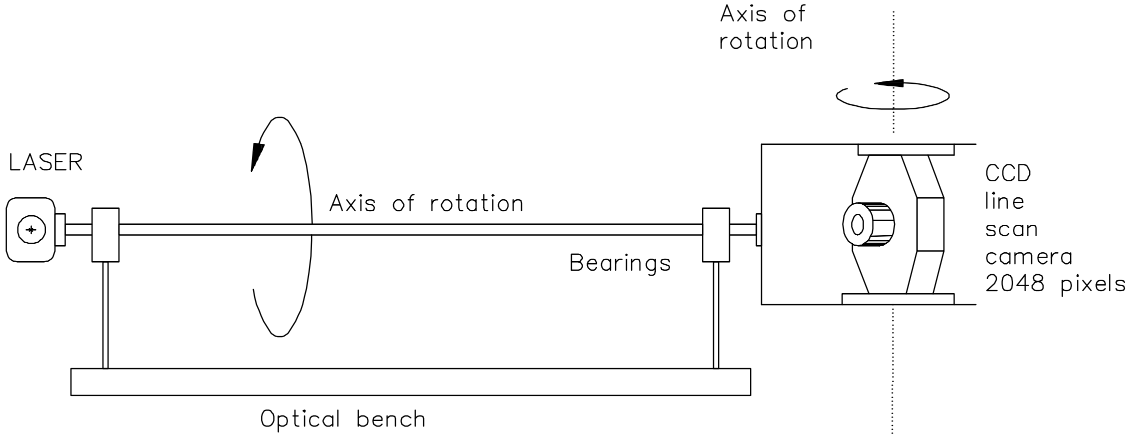

Figure 4. Prototype No 1.

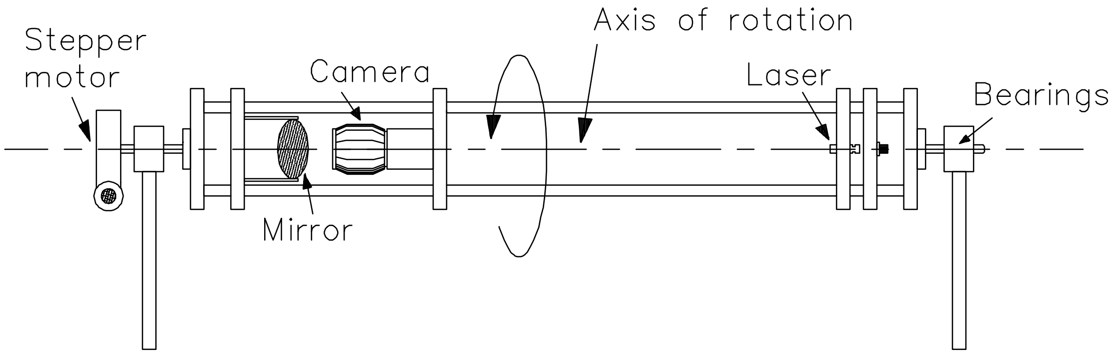

Figure 5. Prototype No 2.

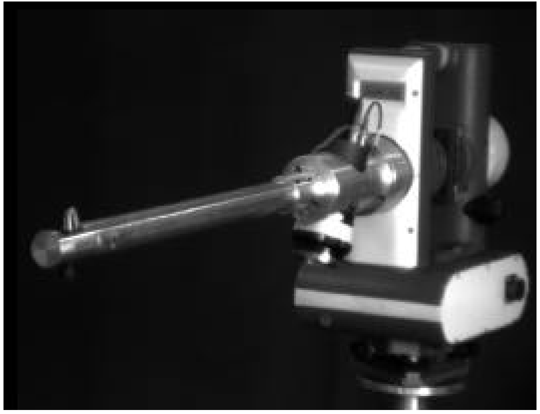

Figure 6. Prototype No 3.

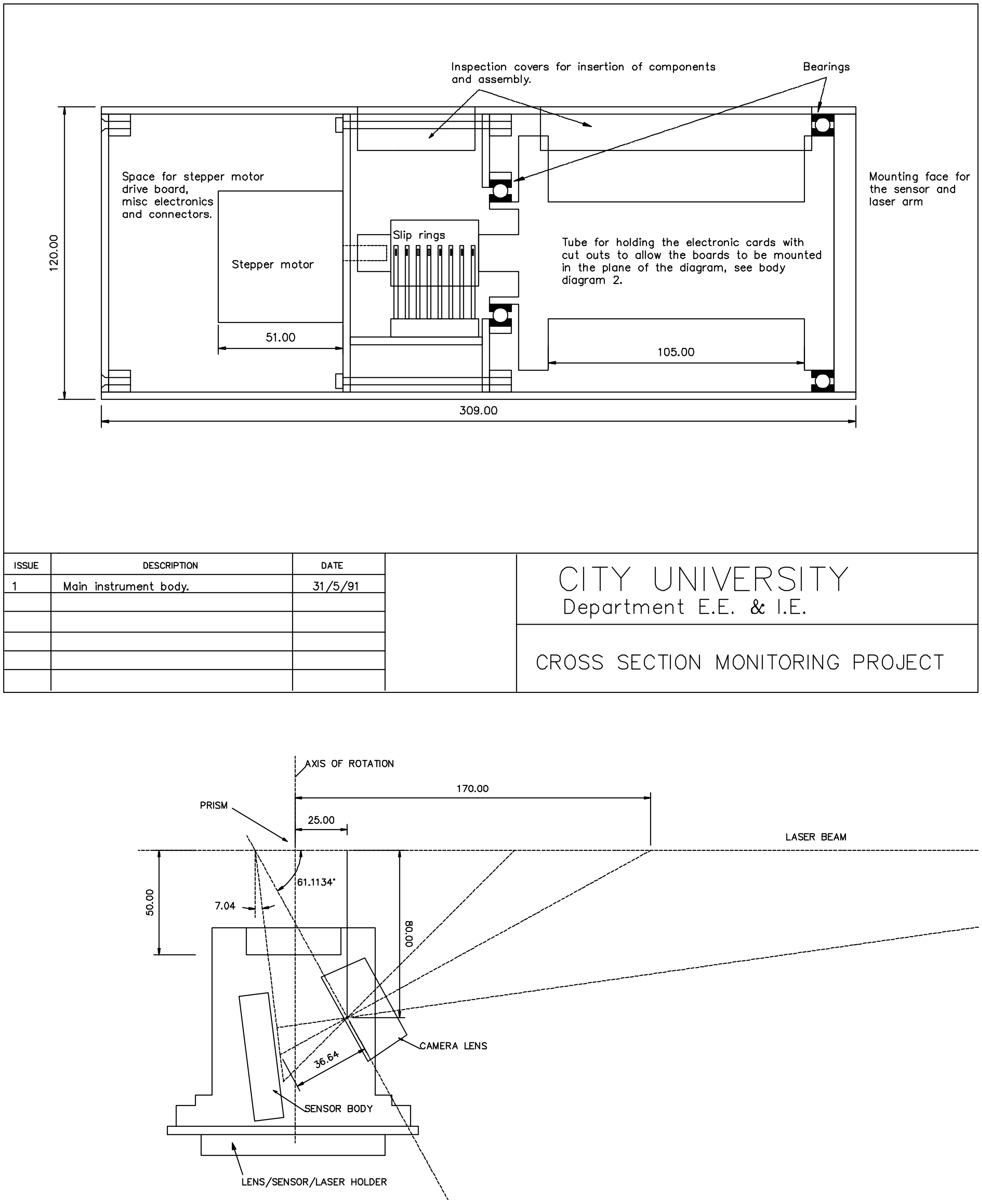

Figure 7. Prototype No 4.

All of the systems have been able to gather 2D, and 3D, spatial information about structures such as road, rail and tube tunnels, mine-shafts and sewers etc. For example, Figure 8. shows a profile of the laboratory.

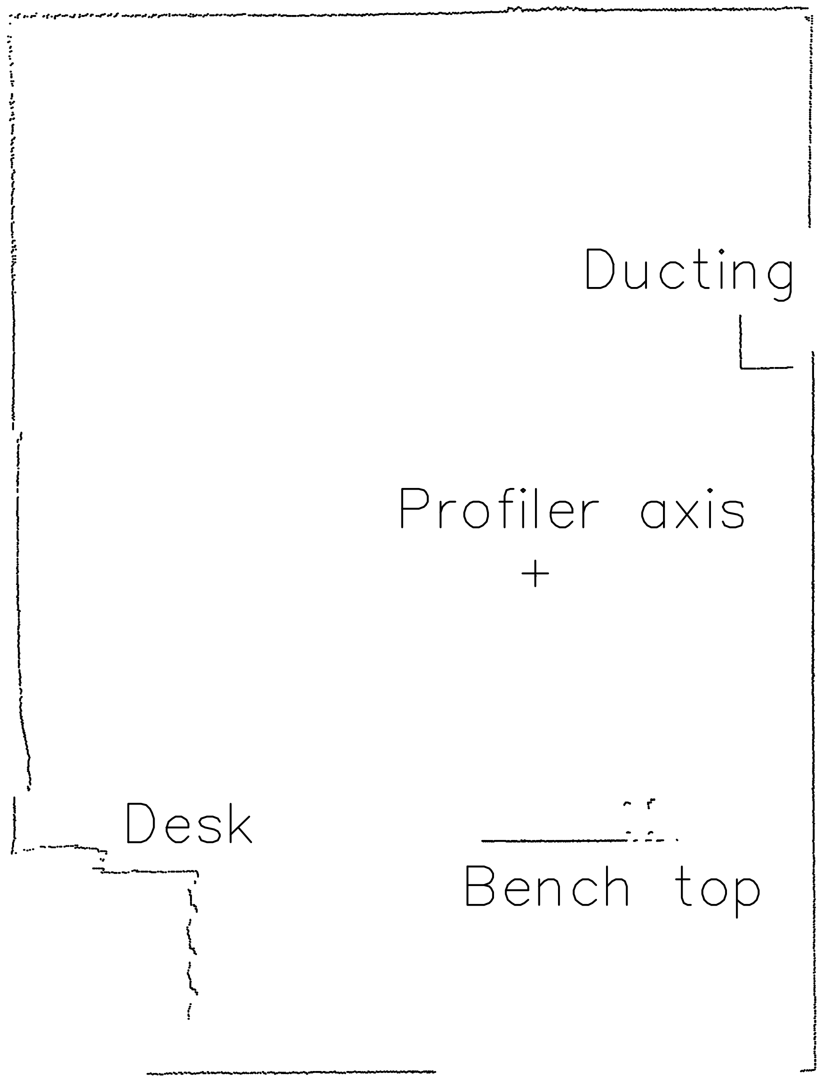

Figure 8. Profile of laboratory using Prototype 3.

The collection of data appertaining to a cross section of a structure is effected by the measuring arm being rotated about the distance measuring axis, thereby describing a cross-section as the light source is perpendicular to the measuring axis. Further measurements, at new positions of the measuring axis, will result in the spatial co-ordinates of cross-sections of a given structure in 3D space.

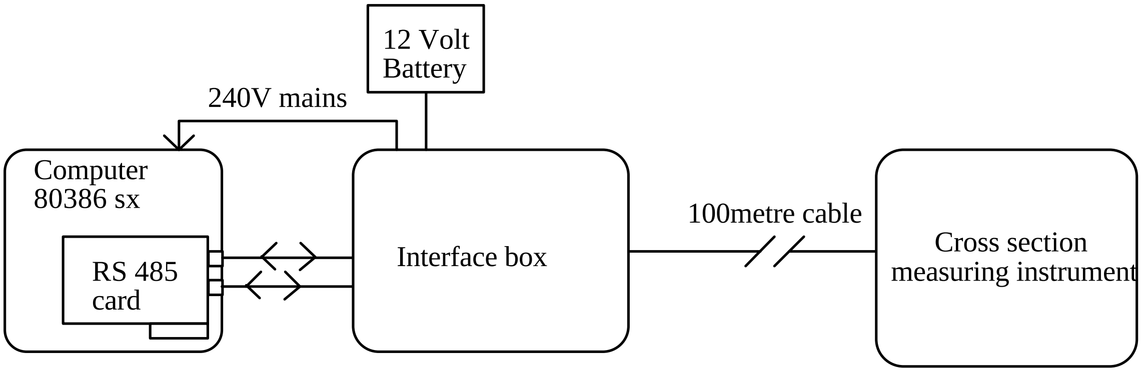

Figure 9. Block diagram of electronic design for prototype.

The instrument has a number of discrete sections, the general interface, stepper interface, sensor interface, power supply, A-D conversion, and prototype interface. These sections are shown in Figure 10.

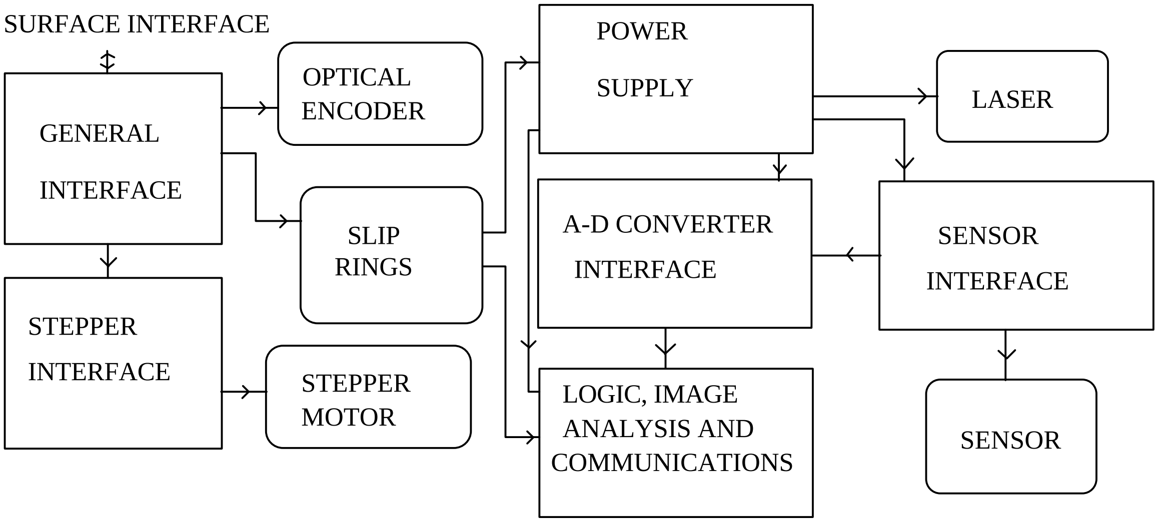

Figure 10. Block diagram of electronic circuits inside the prototype instrument.

The electronic circuits inside the instrument were all produced on Printed Circuit Board (PCB) with the exception of the logic, image analysis and communications board. Because of the number of chips required on this board and the prototyping nature of the project this board was produced with wire wrap which allows a high component density and rapid changes to be made if required. Furthermore, wire wrap is very reliable. The individual components of the electronic circuits are described in the next section.

TRIANGULATION ERRORS

It is apparent from the geometry of an optical triangulation scheme that the sensor resolution and chosen measurement range will define the accuracy of measurement. This accuracy will be inversely proportional to the range of measurement, however, the desired range may be obtained with a number of differing configuration parameters which affect the accuracy or range of measurement. Hence, for a given accuracy, sensor or range of measurement, the remaining parameters must be carefully chosen to minimise the gross error in distance measurement. There are further errors which are beyond the designers control but which must also be identified and understood before a full theoretical analysis of distance measurement errors is completed.

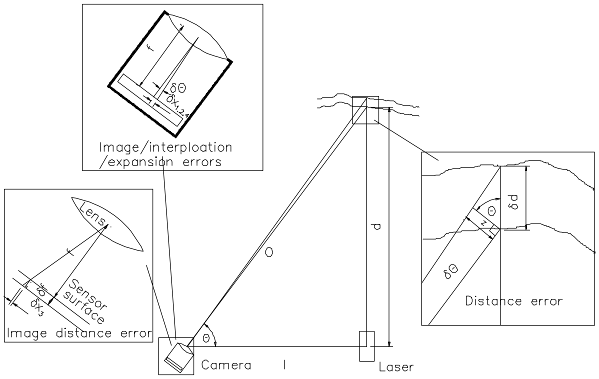

Figure 11(a). Camera errors.

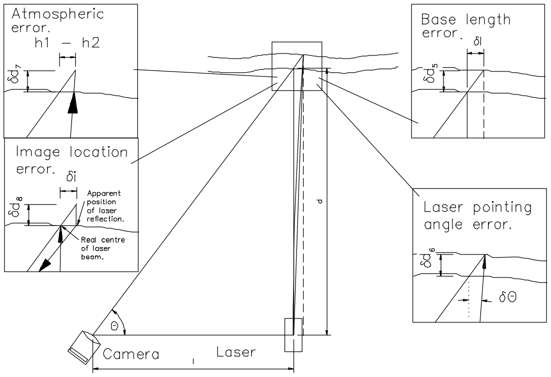

Figure 11(b). External errors.

(i) Triangulation base length changes with temperature. The components, light source and camera, are held in a fixed orientation with respect to each other, see Figure 11(b), and the measurement axis. This configuration is maintained mechanically thus, there is always the possibility of change from the calibration state due to temperature or stress, a major source of error will be in changes to the triangulation base line. The temperature range over which the system may operate could be as much as 20^{o}C. The thermal expansion properties of materials are well known so two solutions are possible, first, to use a material of low thermal expansivity such as Invar, or second to enter corrections to the calibration for the ambient temperature.

(ii) Sensor position changes with temperature. Change of position and expansion of optical components with temperature also causes errors. The sensor, which is mounted on a Printed Circuit Board (P.C.B.), is held in the camera/lens housing and will move with temperature. The expansion coefficient will be that of silicon, as the sensor is constructed on a silicon substrate and the chip package is designed to expand at the same rate, so that unwanted stresses are not allowed to build up.

(iii) Change in image distance with temperature. The last error due to temperature change is that of the camera lens system expanding or contracting, this affects the focus on axis, but, off axis will alter the position of the image with respect to the sensor chip and hence introduce an error due to the changed configuration.

(iv) Laser pointing stability. The operation of the triangulation scheme depends critically on the light source providing a well collimated beam to illuminate a measurement position on the object, and upon the pointing stability of the source. The pointing stability of lasers sources is poor with variations of as much as 0.1mrad. However, it is now possible to purchase laser diode collimators with dramatically improved laser pointing stability.

(v) Ambient temperature, pressure and humidity. The laser beam and the reflected light all pass through the medium, air, before entering the camera, thus 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, giving an error. Large temperatures differences can exist e.g. deep gold mines in South Africa have rock temperatures as high as 63^{o}C.

(vi) Surface irregularities. Image location errors can cause distance measuring 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.

(vii) Location of image with respect to sensor. The precision with which the Gaussian laser spot can be identified with respect to the sensor determines one of the fundamental limitations to the resolution of the system as a whole. This precision will depend in the size, number and distribution of the pixel sites and upon the sub-pixel interpolation algorithms. The size of the pixels sites on the prototype are 13μm square, with 2048 pixel sites, the sub-pixel accuracy improvement for co-operative surfaces extends from 1:1 to 100:1. The size of sensors currently available have a maximum of 6000 pixels.

(viii) Interpolation errors from calibration data. To use the system for distance measurement, data is 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. If there are 'n' pixels and a sub-pixel interpolation of 'x' then there are n*x possible calibration points which can be measured. However as 'n' is typically 2000 and 'x' may be greater than 5, then there may be a very large number of measured points to be collected. It is preferable to either characterise the data by a function such a polynomial or to interpolate with a reduced number of points. Both of these methods will cause an error if the model of the system characteristic does not perfectly match the true data.

SUMMARY.

The eight errors described from i...viii, can be sub-divided into random and systematic errors, the random errors are best treated statistically and are unavoidable, the systematic errors can be estimated and corrections made. The error types are shown in Table 1, and are those estimated for the configuration of prototype 3.

		Error type		Distance error ranges / mm		
Error name		Random	Systematic	Min distance	Camera axis	Max distance
Sensor expansion	δd_2		✓	0.03	–	0.7
Camera expansion	δd_3		✓	0.07	–	1.9
Base expansion	δd_5		✓	0.14	0.25	0.9
Image location	δd_1	✓		0.05	0.12	1.3
Interpolation	δd_4	✓		0.02	0.04	0.45
Laser pointing	δd_6	✓		0.02	0.45	5.1
Atmospheric	δd_7	✓		0.00001	0.0003	0.0013
Surface problems	δd_8	✓		0.13	0.24	0.85
Statistical standard deviation of random error.				0.14	0.525	5.35

Table 1. Summary of errors.

The standard deviation of a random variable is the positive root of the square root of the sum of squares of the random errors, using the values computed above, the standard deviation is 0.31mm. This can be compared to the actual standard deviations obtained experimentally.
To design an optical triangulation measuring system with minimum errors over a given range, the variable parameters require careful consideration as several configurations are possible. For a comprehensive analysis of a given design a computer simulation of the results is desirable where errors can be assessed and "trade offs" made between the competing parameters.

FUTURE TRENDS.

There are two essential requirement for greater efficiency of profile measurement, faster speed of measurement, and higher accuracy. It is likely that both of these requirements will be met in the near future, with a high speed, coaxial optical beam approach. This will enable a great number of alternative uses for distance measurement which are not currently feasible. There appears to be a move towards further automation which is likely to increase in the future. In some circumstances, especially where human access is difficult, intelligent, autonomous robotic solutions are likely to be developed.

It is possible that in the short term the development of a commercial Optical Triangulation measuring system could fill the accuracy and speed gap, this has already happened with very short range devices where optical triangulation systems with a range of 50-100 mm are being regularly used in manufacturing industry. This could ultimately be replaced by a high accuracy and fast short range EDM.

Over the next few years there are likely to be further improvements in the close range measurement area with techniques from metrology, photogrammetry and machine vision merging to provide fast and accurate spatial data collection on a scale not yet contemplated. This will allow the 3-D mapping of structures and surfaces providing data for the next generation of computers to manipulate for a large variety of purposes. This close range information will compliment that gathered by large scale surveying methods such as remote sensing, satellite positioning systems and traditional surveys.

CONCLUSIONS.

There exists a number of methods, some of which are regularly used, which are able to measure cross sections of structures. Most of these methods have been reviewed here. Cross section data can serve a variety of purposes such as deformation monitoring or providing valuable information about structures and surfaces.

PAPER REFERENCE

Clarke, T.A., 1993. Internal profiling of industrial structures, New developments in tranducers colloquium, March 30th.