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THE USE OF OPTICAL TRIANGULATION FOR HIGH SPEED ACQUISITION OF CROSS SECTIONS OR PROFILES OF STRUCTURES

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Abstract

Optical triangulation is used in the human visual system and surveying tacheometers to estimate distance. This method is now used in systems with solid state sensors which enable fast measurement of distance with sufficiently high accuracy for many applications. City University has built on past experience to develop the optical triangulation technique to gather data appertaining to cross sections or profiles of structures in the range 0·2 m to 20 m radius from the measurement axis. Results obtained using three prototypes are given.

Introduction

Since 1987, City University has been developing the optical triangulation technique for gathering data about cross sectional profiles of structures. The multidisciplinary project involves personnel from the areas of electro-optics, machine vision and photogrammetry.

Capture of cross sections or profile data is carried out by repeated distance measurements from a known position to an unknown surface, as found in a sewer or railway tunnel. With the measured distance, another parameter can be recorded, such as angular rotation of the measuring system, therefore enabling the reconstruction of the two dimensional surface outline. The range of interest is typically from 0·2 m to 20 m. Provided that measurements to the surface are made as often as demanded by sampling theory, a cross section of the structure can be adequately described. If a number of cross sections are collected with the addition of another parameter, such as the distance moved orthogonal to the two axes of the original plane, a three dimensional representation of a structure is the result (Fig. 1).

Background

City University has been involved in recording cross sections and profiles since about 1962. The techniques of stereophotogrammetry, monophotogrammetry with light flash and rotating laser systems have been used, the latter being the most successful with many tunnels being profiled. Examples include Stanningley (British Rail Eastern Region), Leek (British Waterways, Staffordshire), York Road and Hotel tunnels at King's Cross (BR Eastern Region) and South Crofty Tin Mine shaft (Rio Tinto Zinc, Cornwall). The most comprehensive survey was carried out at King's Cross with over 70 cross sections being measured. The problems of using the rotating laser system with photography are:

(a) long exposure times;
(b) time consuming post-survey processing is required;
(c) no on-site analysis;
(d) the camera is generally some distance from the plane of interest; and
(e) with the low intensity line produced by the laser the site must be dark.

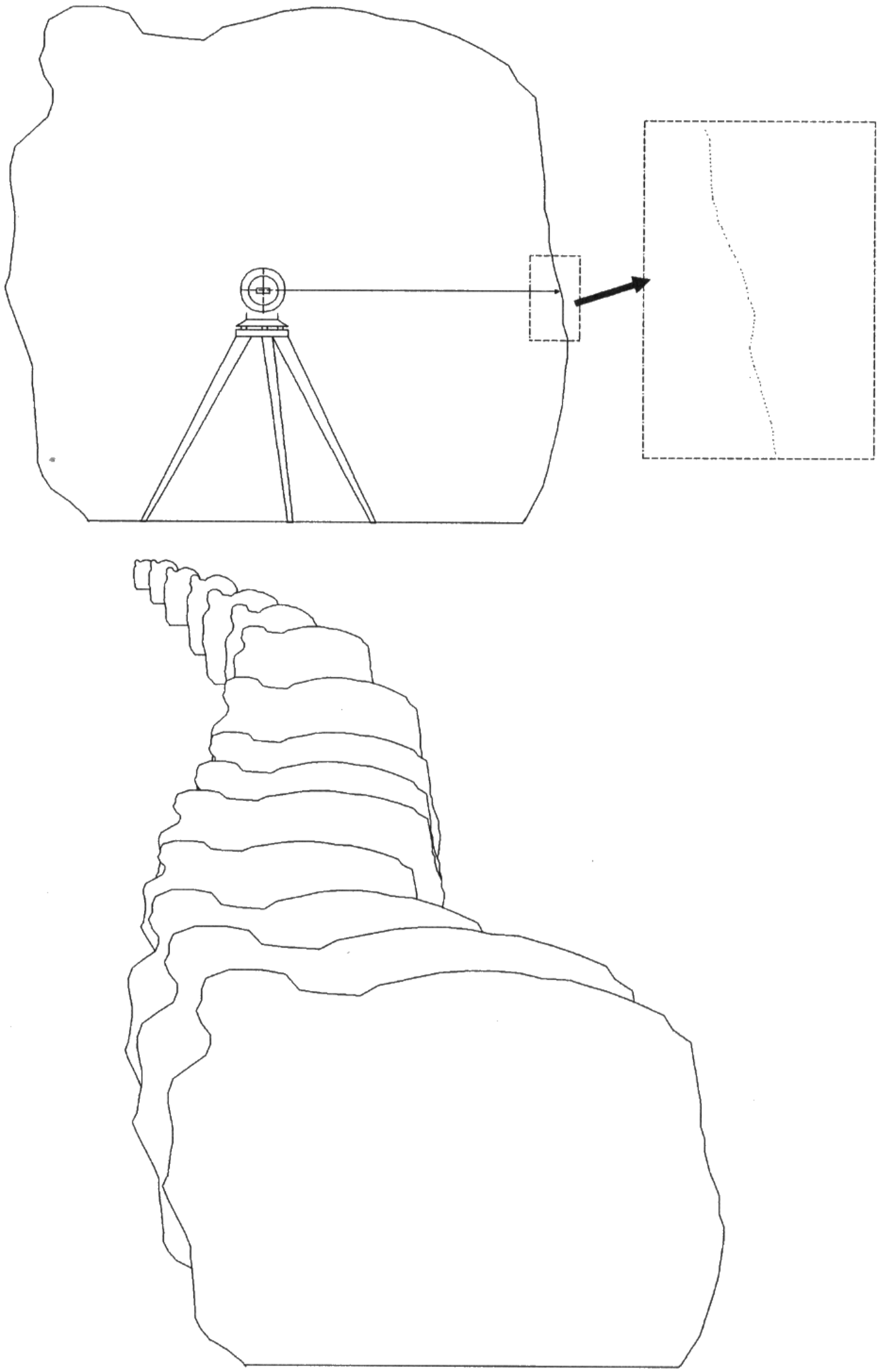

FIG. 1. Acquisition of cross sections.

Fig. 2 shows the type of profile collected. The inset gives a plan view of the position of all of the individual profiles (not to scale). The type of analysis that can be carried out with this information ranges from deformation of a structure with time to wriggle surveys to indicate vehicle clearance. The experience gained in this field has led to a specification for a measuring system for this type of work which should be:

(1) non-contact;
(2) fast (measurement rate >100 measurements per second);
(3) accurate (standard deviation <0·5 mm); and
(4) robust.

There are measuring systems which meet some of these specifications such as:

(1) Amberg Measuring Technique Profiler (Hagedorn, 1986). This is non-contact and robust equipment but does not have the required accuracy and measurement speed; and
(2) Kern Space system (Gottwald and Berner, 1987). This system requires a feature or target, it is slow in operation but it has high accuracy.

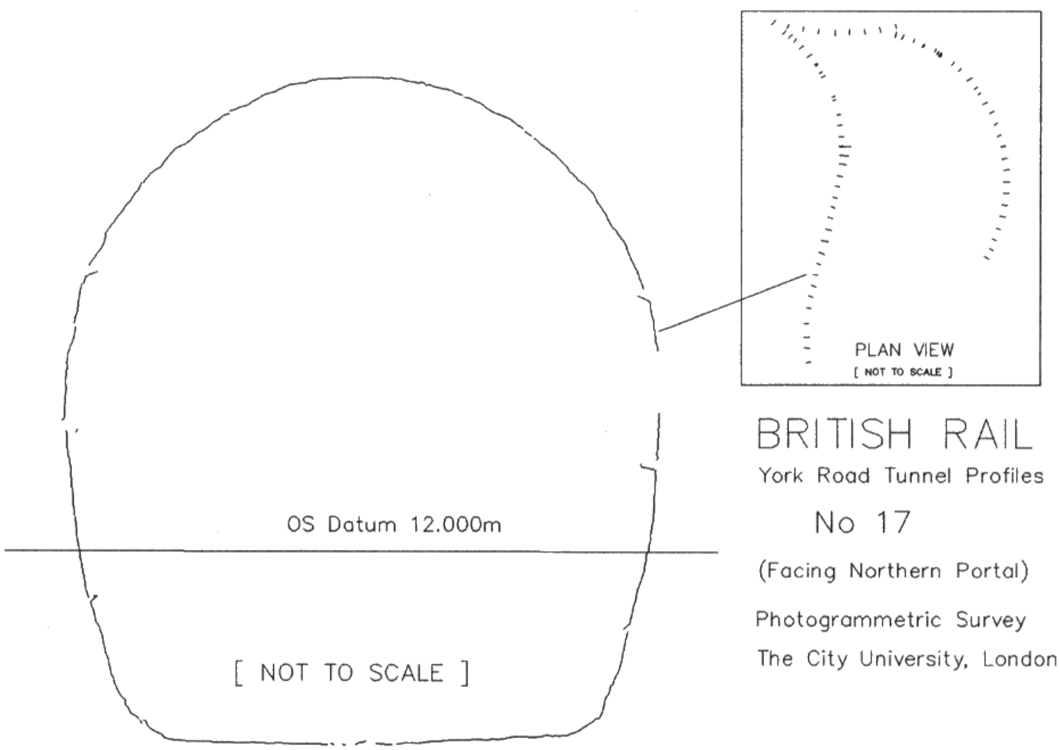

FIG. 2. British Rail cross sections.

OPTICAL TRIANGULATION TECHNIQUES

There are many systems which use optical triangulation as the basis for a measuring device. Many have been used in surveying and are described (Irvine, 1986) under the heading of *tacheometry,* meaning rapid measurement.

The use of optical triangulation with modern electronics is well known in the areas of industrial metrology (Goh, 1986) and robotics (Tiziani, 1989). Both have adapted and improved the techniques for their own purposes: in robotics very fast data rates are required for object recognition and inspection; in metrology, higher accuracy is required. However in the field of surveying and civil engineering there has been relatively little research on the subject, leaving much to be done to adapt to the particular requirements of surveying and industrial measurement of structures over the 0·2 m to 20 m range.

Theory

A lens, sensor and laser configured as in Fig. 3(a) can be used to measure relative or absolute displacement. The relationship between object and image is:

$$\delta = \frac{iD}{o}.$$

There is a linear relationship between object and image. A simple calibration will allow this system to be used to measure distance or, alternatively, relative measurement may be performed by comparison with an object of known dimension.

If the camera and laser are configured as in Fig. 3(b), where the camera and light source axes are no longer perpendicular to each other, then provided that D is small and θ is constant, the equation is modified to:

$$\delta = \frac{iD}{o} \sin \theta.$$

However, the limitation to a relatively small range may not always be convenient. Additionally this configuration is not designed to keep the image in focus over the range. If a larger range of measurement is required then Ji and Leu (1989) have derived an exact relationship between the object and image displacements which incorporates the Scheimpflug condition (Wolf, 1983) to ensure perfect focus throughout the range (Fig. 3(c)) and in which

$$\delta = \frac{Di\sin \theta}{D\sin (\theta + \phi) + o\sin \phi}.$$

This equation shows the inherent non-linearity of triangulation systems which, for the same range, is increased as the distance between the sensor optics and light source is decreased. In spite of this, it is still possible to construct a range finder, but it is necessary to calibrate the system initially and then to interpolate for distance measurement. The measuring system will now have a non-linear resolution over its range. An example of how onerous this variable resolution can be in a triangulation based measuring system is given in Fig. 4. Half of the available resolution is used over the first 0·75 m leaving the rest for the remaining 4·3 m of the range.

Advantages

The advantages of such a triangulation measuring system are speed (data rates up to 10 000 measurements per second are possible) and accuracy (the system can resolve 2000 to 20 000 points over the range). 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.

Limitations

A disadvantage of triangulation systems is that the measurement does not take place coaxially with the light source, leading to problems of occlusion and in the physical size of the measuring instrument. If the distance between sensor and light probe is reduced to minimise these problems then the non-linearity inherent in the simple triangulation geometry becomes a serious limitation. In metrology and robotics it is possible to accommodate a large base length but, in surveying, the size of the instrument and its characteristics are important. A solution has been identified to the linearity problem which is the subject of a patent application. 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.

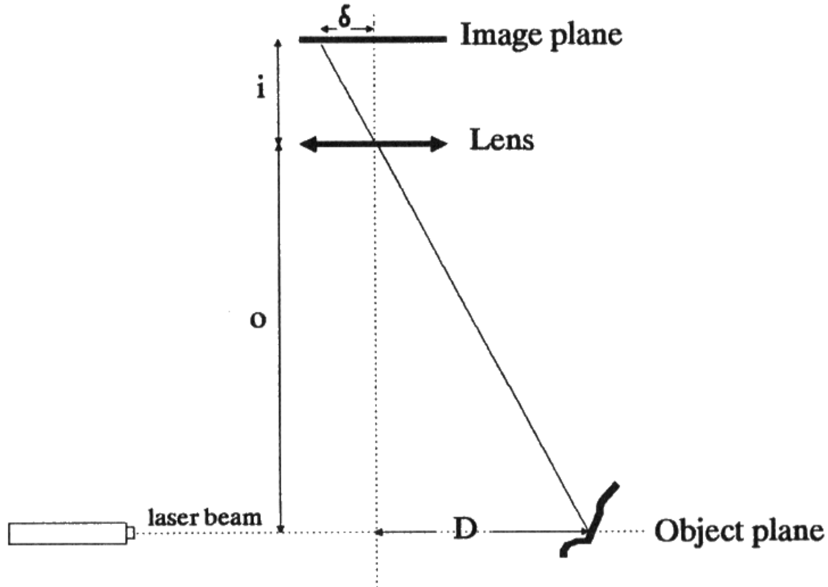

Fig.3(a)

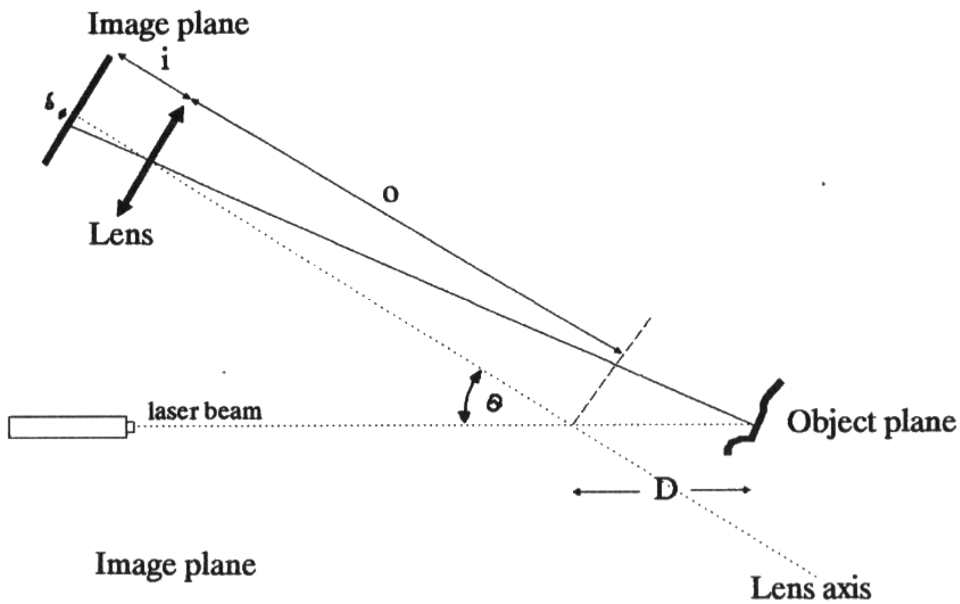

Fig.3(b)

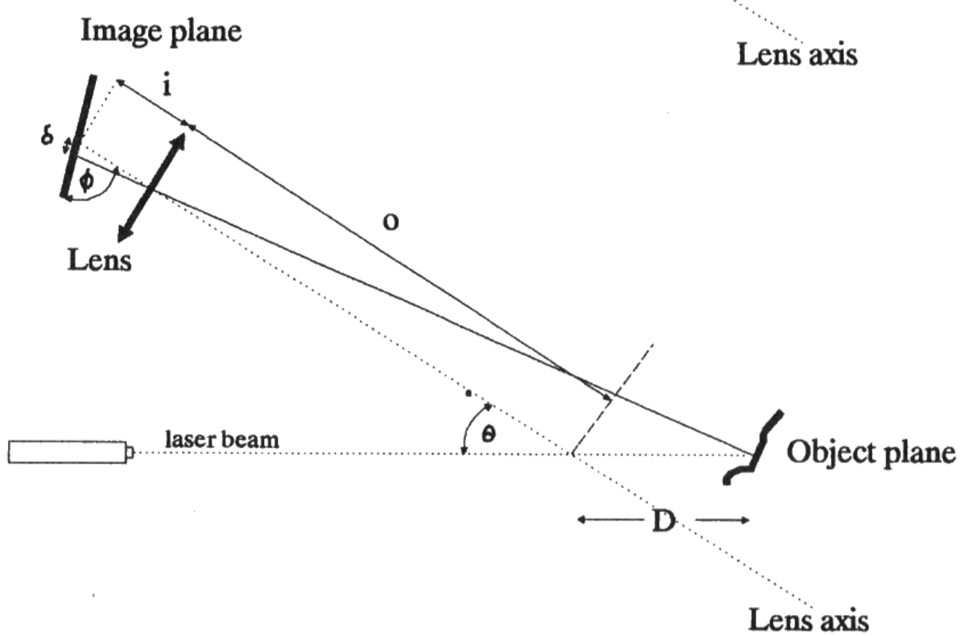

Fig.3(c)

FIG. 3. Triangulation configuration diagrams.

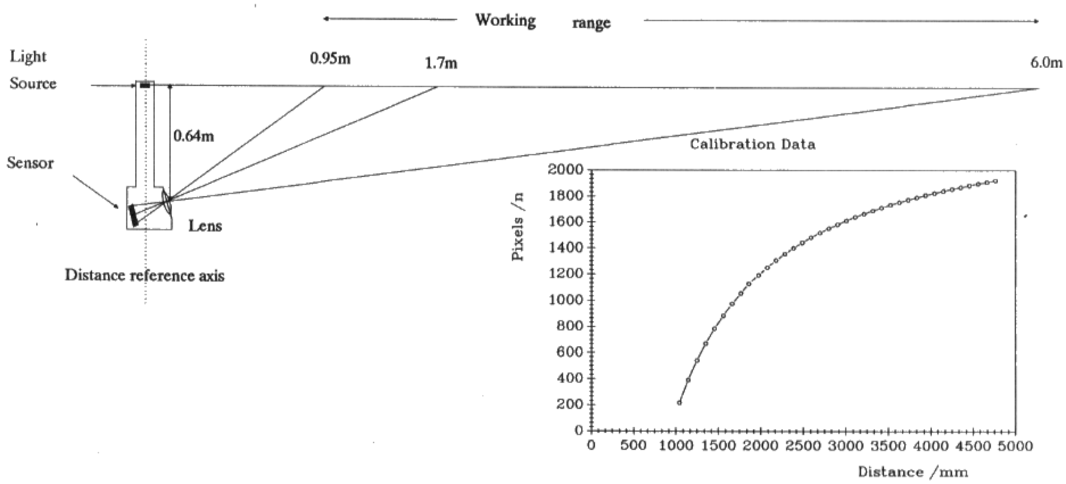

FIG. 4. Non-linearity.

Prototypes

Three prototypes have been built and tested.

Prototype I. This was used to establish that the triangulation technique was promising enough to pursue. Fig. 5 shows the results of collecting a profile in a corridor in the University (approximately 200 points).

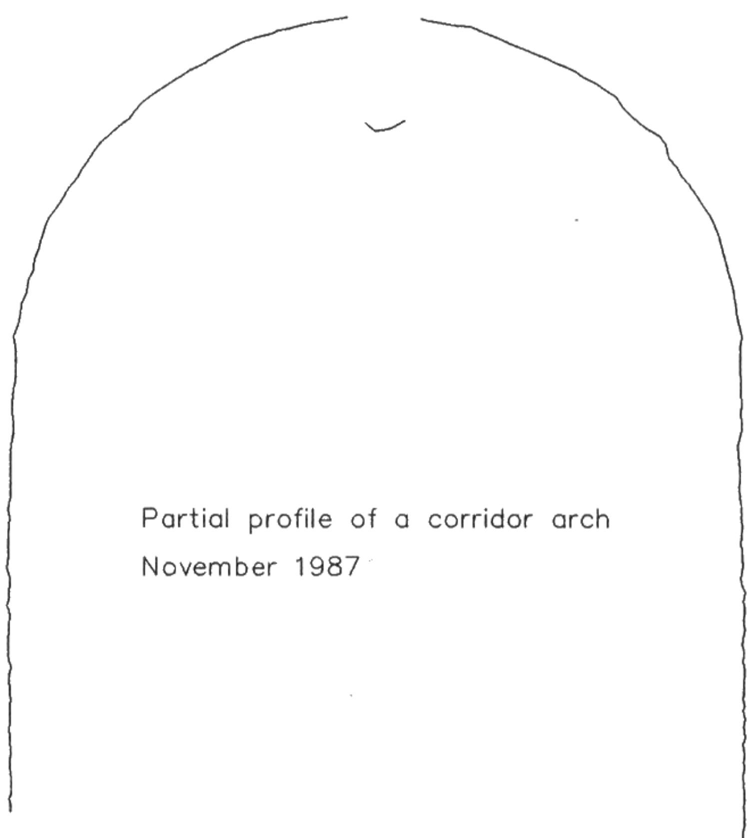

FIG. 5. Profile from prototype I.

Prototype II. This was intended to be faster, more reliable and robust than the first model. A data rate of 800 measurements per second was standard. Fig. 6 shows another section of corridor with 2000 measurement points per profile, 13 complete profiles and 50 mm spacing between cross sections. Artifacts in the profile that can be identified are a light switch on the left hand wall and various pipes and conduits.

Sections that are missing from the diagram were caused by occlusion or extraneous light at certain angles.

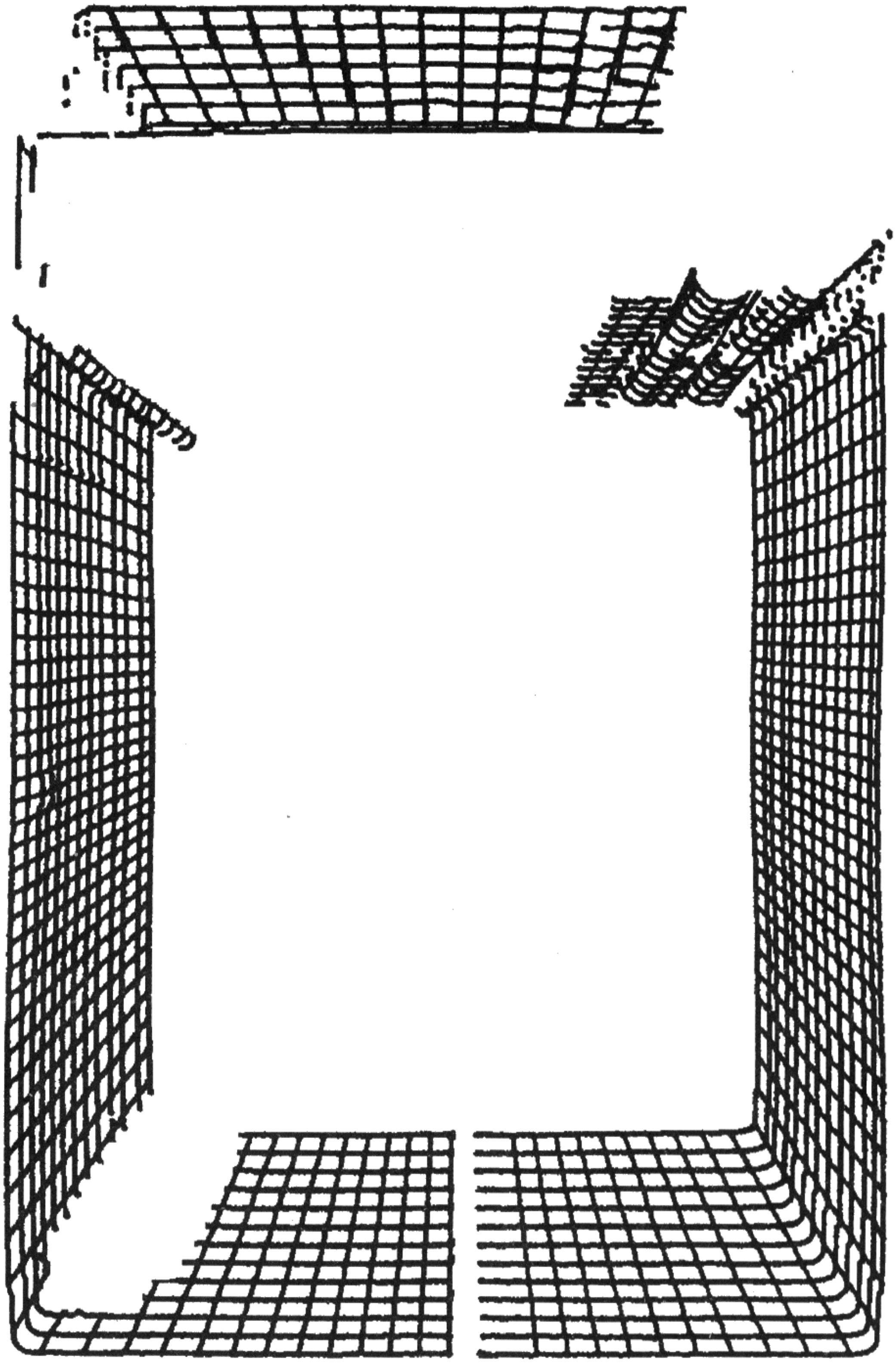

FIG. 6. Cross sections from prototype II.

Prototype III. This prototype was set up on an optical bench to measure to the back of a retroreflector used by a Hewlett-Packard interferometer. The interferometer is interrogated as the target is moved over the range of the device. The

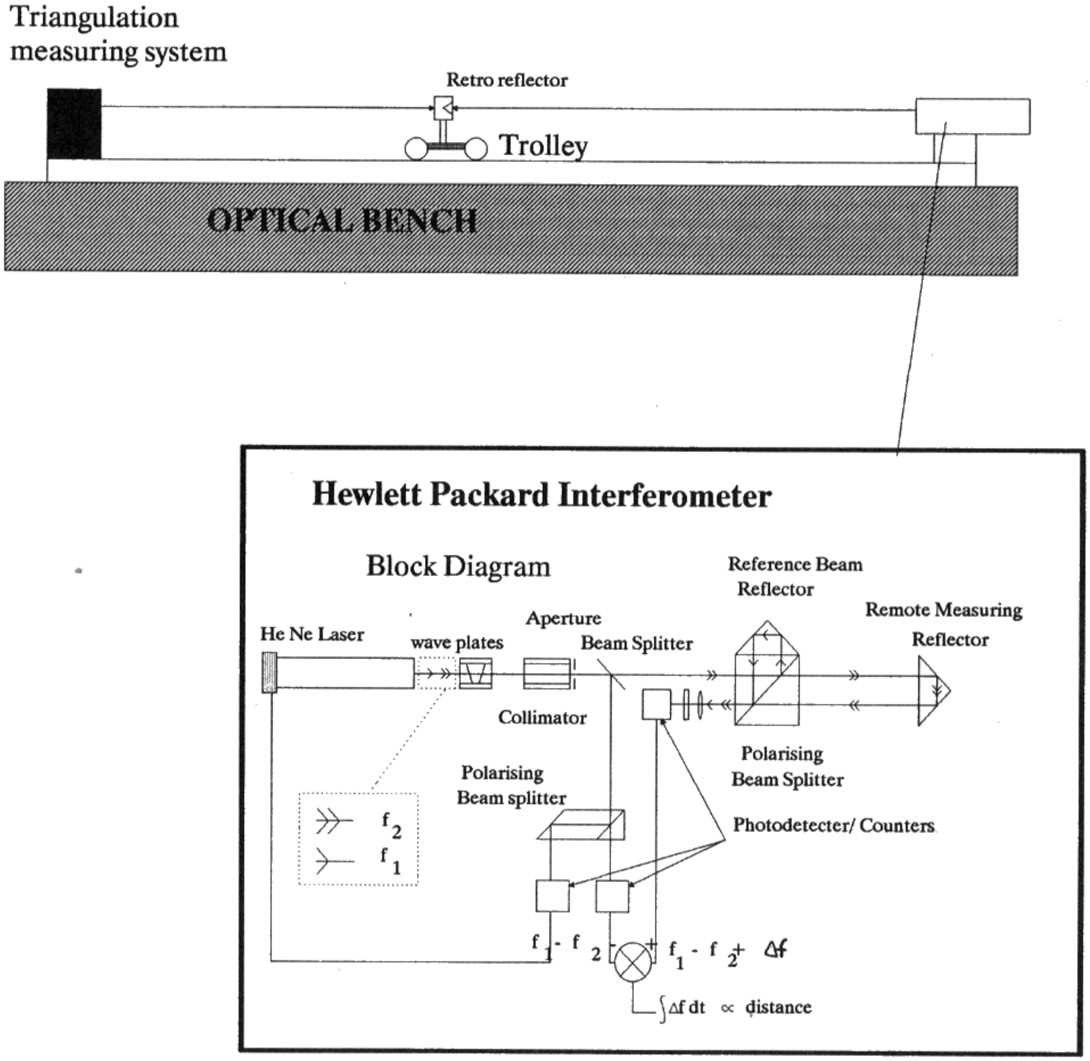

FIG. 7. Calibration set up.

measurement data are placed into a calibration file. Subsequent interpolation between calibration points allows a comparison between the interferometer reading and the profiler (Fig. 7).

The error data were collected at random positions over the 5 m range with up to 100 samples. The standard deviation was then computed from these data. The results of more than 20 sets of error measurements when averaged show that a standard deviation of ±0·36 mm was achieved. A normal distribution was experienced and so a prediction of 99 per cent of measurements to within ± 1 mm is not unreasonable.

The profiler collects data by rotation about an appropriate axis. The angular rotation and distance are recorded. This information can easily be converted into a format suitable for a computer aided design software program to display and analyse the two or three dimensional data. Fig. 8 shows a single cross section of the laboratory constructed from 3600 measured points. The axis of the profiler is shown and some of the artifacts are labelled. Future work will involve field tests and more stringent testing of all the parameters which contribute to errors in measurement.

CONCLUSION

The conclusions reached by research in this area are that the use of optical triangulation provides a technique which is fast, accurate, robust and non-contact. The research at City University has resulted in an enhanced optical triangulation

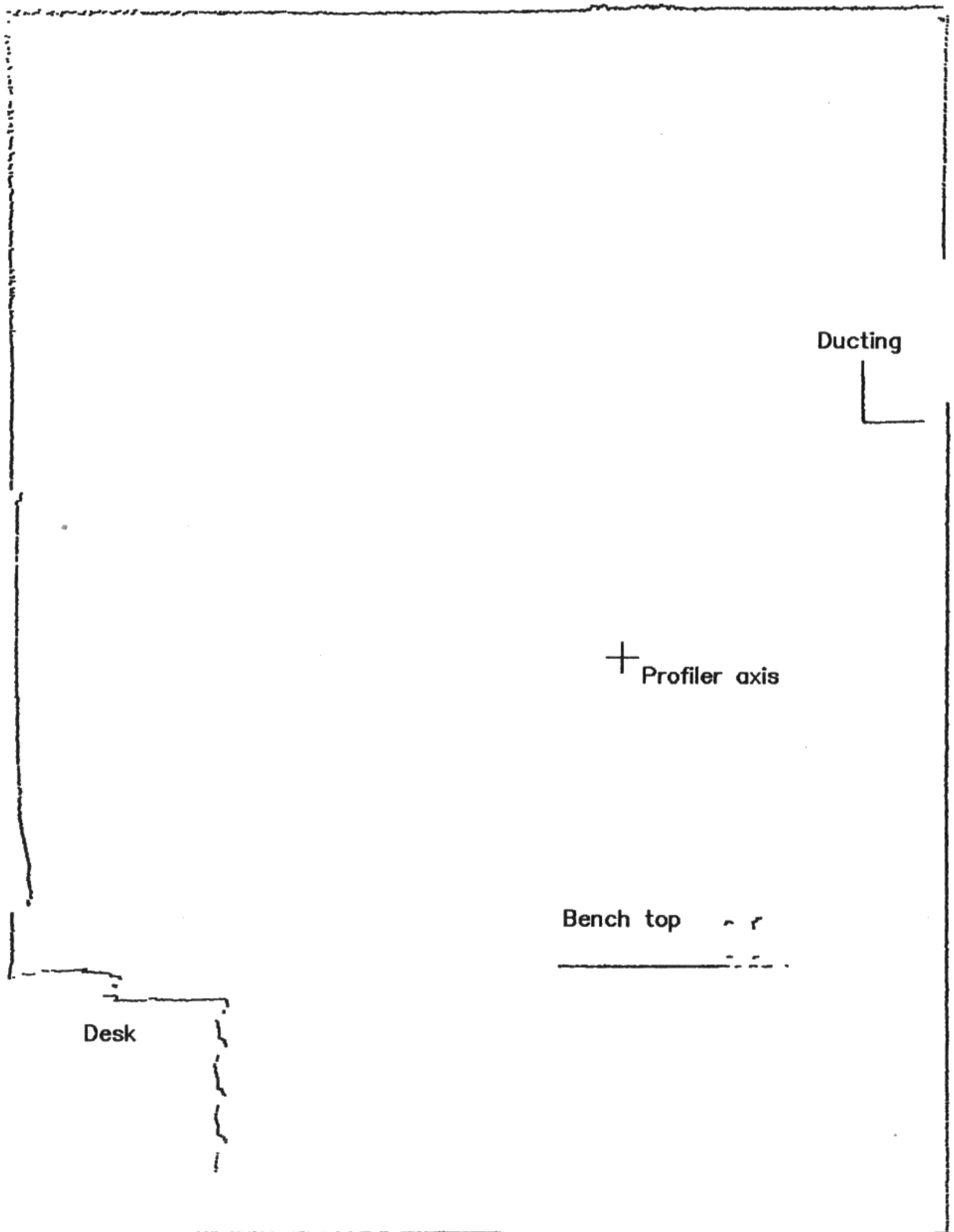

FIG. 8. Cross section from prototype III.

technique for constructing a compact measuring system which has essentially linear resolution over the range of measurement and is the subject of a patent application.

ACKNOWLEDGEMENT

British Technology Group specialises in protecting inventions that arise from academic sources and has filed a patent application to protect City University's ideas on 31st October, 1989.

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Résumé

On recourt à la triangulation optique pour évaluer les distances, aussi bien dans des systèmes à estimation visuelle que dans les levés tachéométriques. On utilise désormais cette méthode avec des systèmes munis de capteurs à semi-conducteurs, que l'on apprécie, dans de nombreuses applications, pour la rapidité des mesures des distances jointe à une précision suffisamment grande. La City University a acquis une solide expérience lui permettant d'appliquer la technique de triangulation optique pour recueillir des données relatives aux coupes en travers ou aux profils des structures, pour une gamme de distances à l'axe de la station comprises entre 0·2 m et 20 m. Les résultats obtenus avec 3 prototypes sont fournis.

Zusammenfassung

Die optische Triangulation wird beim menschlichen Sehprozeß und bei Vermessungstachymetern zur Entfernungsschätzung genutzt. Dieses Verfahren wird jetzt in Systemen mit CCD-Sensoren genutzt, die die schnelle Streckenmessung mit genügend hoher Genauigkeit für viele Anwendungen ermöglichen. Die City University hat auf Erfahrungen aufbauend das Verfahren der optischen Triangulation zur Datenerfassung in Querschnitten oder Profilen von Konstruktionen im Bereich von 0,2 bis 20 m von der Meßachse aus entwickelt.