A REVIEW OF CLOSE RANGE OPTICAL 3D MEASUREMENT

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ABSTRACT

Close range optical measurement systems have undergone a transformation during recent years, generated primarily by demand from the aerospace and manufacturing industries. The current trends are toward more automation of the measurement process and real time solutions providing three dimensional coordinates in a user defined reference frame. Further, the precision and reliability of the acquired data is steadily improving while the systems which produce the data are requiring less skill to operate. The traditional role of the surveyor in close range three dimensional measurement is therefore no longer seen as a necessity, especially in routine operations such as quality control for industrial applications. Inevitably such systems are seen by users as "off the shelf" tools to produce the desired results for a particular application in the most appropriate and efficient way. Theodolite, photogrammetric and non-conventional systems which fall into the category are described and discussed, and their capabilities and range of applications are assessed. The widespread adoption of these systems will have a considerable impact on the close range industrial measurement, and an attempt is made to predict the implications for the future.

Introduction

Prior to the 1980s, close range optical three dimensional (3D) measurement was a relatively obscure piece of terminology which probably meant little to the average surveyor and nothing to the lay person. However, the elements of this new field of research and development already existed. The use of theodolites for angle intersections at close range was an accepted technique, optical alignment techniques could achieve fine tolerances and close range photogrammetry was often employed as an alternative for various reasons. Intersections are still used by surveyors on a routine basis, but optical alignment and photogrammetric techniques were commonly considered too specialised with respect to both expertise and equipment.

Whilst these techniques may have been adequate for the tasks at hand in the 1960s and 1970s, in hindsight it is easy to recognise some deficiencies. Lack of reliability is one such deficiency, and is particularly applicable to two theodolite intersections and stereophotogrammetry. The absence of check measurements or sufficient redundancy in networks to detect gross errors is a potentially serious problem for any measurement system. In addition, the accuracies of the techniques could also be called into question. Modern methods pay considerable attention to the removal of
systematic errors via equipment design or physical modelling. Inadequate modelling of systematic errors such as camera calibration or theodolite dislevelment is likely to result in poor accuracy.

Perhaps the most important deficiency in the measurement techniques was the long turn around times. Theodolite intersection was initially restricted by the lack of angle encoders to produce digital data, and generally rendered impractical by the lack of on line computing facilities to calculate XYZ coordinates from the angles. Conventional close range photogrammetry still has the problem today that there must be a delay whilst the negatives are photographically processed and observed, as well as the subsequent calculations if an analytical solution is employed.

Even if the problems cited above could have been solved, the remaining difficulty would have been a commercial market for the measurement techniques. Many 3D measurement problems were solved in an ad hoc way which was alien to what we now call technology transfer. In some cases methods were developed which were technically or commercially unrealistic, or simply too far ahead of their time. The best indicator of this initial lack of success was the number of pilot projects reported in the literature which were never taken up on a long term basis. This lack of success was quite apparent for close range photogrammetry, which appeared to be a solution looking for a problem in many instances.

By the 1980s, however, close range optical 3D measurement had emerged as an identifiable discipline. Part of the reason for the change was technological development. Digital theodolites and total stations became more precise, more reliable and within the financial reach of most surveying and mapping organisations. The introduction of versatile semi-metric cameras and automated image measurement systems revived interest in close range photogrammetry. But perhaps the most influential technological advances were large scale integration and the availability of personal computers (PCs). The ability to rapidly transfer field data to a PC, verify the integrity and completeness of the data, and then quickly produce XYZ coordinates or plotted information allowed close range measurement systems to realise their potential for efficiency and productivity.

Of course, close range measurement systems would not have been developed without user demand. Generated primarily by the aerospace and manufacturing industries, the requirement for precise, reliable and accurate XYZ coordinates to be produced quickly within the industrial environment has forced a response from the instrument manufacturers. Although theodolite systems dominate the market, the most recent developments have seen the emergence of competitors in the form of photogrammetric and non-conventional systems.

**Theodolite Systems**

A number of technical advances and market developments came together in the 1980s and resulted in a new area of surveying expertise based on the digital theodolite. The genesis of the development was the introduction of encoded angle circles and electronic data recording for field survey equipment, pioneered by Zeiss Oberkochen with the release of the Reg Elta 14 in 1968 (Leitz, 1970) and quickly followed by the AGA Geodimeter 700 (Rawlinson, 1976). Both of these systems recorded data on a bulky paper tape recorder which was neither convenient nor practical.

This drawback was remedied in 1977 when the Wild TC1 introduced recording on magnetic cassette tape (Schwendener, 1978). Subsequent developments concentrated on solid state recorders and the "electronic field book". By the end of the decade there were a number of total station systems of this type, such as the Zeiss Elta 2 with the REC module and the Hewlett Packard HP3820 with the HP3851 data collector. The combination of the total station, data recorder and PC software realised the "field to finish" process which is only now being universally adopted by the
surveying profession, despite the fact that field to finish was in commercial use as early as the mid 1970s (Johnston, 1979).

Electronic theodolites were an offshoot of total stations. They first appeared in the late 1970s (Erickson, 1977) and are distinguished by the lack of any integral EDM or recording facility. Initially the new instruments were treated as a novelty and their only perceived advantage was the direct digital readout of angles, which removed potential errors in setting and reading optical micrometers. New models soon appeared which were not only substantially lower in cost when compared to total stations, but more significantly incorporated an RS232 serial communications port for data output. This feature opened the way to real time measurement of angles and therefore XYZ coordinates.

By the early 1980s a number of real time measurement systems based on two or more digital theodolites had been released. One of the earliest systems was the Keuffel and Esser (K&E, now Cubic Precision) AIMS, which made a significant impact on the aerospace industry in North America. The K&E system attracted the attention of the main stream surveying equipment manufacturers, and the Wild RMS, Kern ECDS and Zeiss TOK systems were introduced quickly thereafter. In the last few years real time industrial systems have become more widely available and more generally accepted, again largely due to advances in computer technology which have led to accurate and reliable digital theodolites, as well as more robust and portable PCs.

The use of theodolites for angle intersections is not a new concept, as it was suggested as a method of XYZ coordinate measurement in the aerospace industry as early as 1944 (Hume, 1970). Any pair of theodolites can be used to establish a local, plane coordinate system once they are levelled and the horizontal circles are mutually referenced. The procedures and mathematical algorithms required are well established (Allan, 1988).

Real time systems consist of two or more digital theodolites linked directly to a PC. The pointing direction of the telescope of each theodolite is sensed electronically via one of a number of schemes of encoded glass discs (Brooke, 1988). Horizontal and vertical angle data is transmitted via serial communications to the PC, which has appropriate software to compute XYZ coordinates. The simple angle intersection solution is most commonly used, but a more sophisticated bundle adjustment process borrowed from close range photogrammetry can be employed. The advantage of the photogrammetric network approach is that levelling and mutual referencing of the theodolites is unnecessary. The function of the theodolite is then simply as a pointing device, and this reduced requirement is reflected in the instrument currently under development by Kern (now part of the Leitz group). The next industrial theodolite will probably not have a display, level bubbles or foot screws.

No matter which type of solution is used, the computations require the establishment of at least one distance to scale the network. To avoid the uncertainty of theodolite station locations, scaling is done by introducing a known distance into the network in the form of an accurately calibrated invar rod or glass scale with end targets. Generally the first group of observations taken in any set up procedure is to such a scaling bar. The second group of observations is typically transfer points on the object to be measured. The initial coordinate system has an origin at one of the theodolite stations. Software provided with digital theodolite system must have the ability to transfer the coordinate datum to the object to allow real time measurement within the object coordinate system, usually the original coordinate system chosen for the computer aided design (CAD) model. The third group of observations is the points of interest. All points must be targeted to avoid ambiguity and realise the highest accuracy. Some surfaces are suitable for use with a coaxial laser in one of the theodolites, but most objects require adhesive "bulls eye" targets or spherical offset targets, with either a magnetic base or a standard diameter tooling locator pin.
The software package supplied with such systems generally has a range of integral or optional functions useful in an industrial environment. Good examples of desirable features of the software are such tasks as the "best fit" computation of geometrical elements ranging from simple straight lines to surfaces of revolution, the connection or intersection of such elements, and the display and analysis of deviations from design positions or theoretical surfaces. The hardware and software should also have the ability to accept input from more than two theodolites. Four observed angles and three unknown coordinates produces a single redundancy which has only limited value for error checking. Four theodolites are necessary for effective reliability testing, but few organisations can justify the purchase of more than three instruments. In every case the input angle data should be processed by a rigourous least squares adjustment solution for the XYZ coordinates (Connelly and Afnan, 1989).

The applications of theodolite systems in industry, engineering and manufacturing are numerous and beyond the scope of this paper, but all of the tasks have a common aim of producing XYZ coordinates quickly and accurately. Surface measurement, tooling inspection (quality assurance) and reverse engineering (as built surveys) are the primary categories of application. The interested reader is referred to the literature produced by the instrument manufacturers and various published articles (Woodward, 1987). A measure of the success of theodolite systems is their penetration into a market which is dominated by coordinate measuring machines (CMMs). It is estimated that there is in excess of 200 systems currently in use in the aerospace industry in North America (Fraser, 1989b) and perhaps more than 300 world wide. In Australasia there is certainly no more than several in total, and only three modern systems in use for industrial measurement. The vast majority of these systems use the minimum of two theodolites, although there are three theodolite systems in use (Shortis and Adams, 1990).

Photogrammetric Systems

Close range photogrammetry was first employed soon after the development of the camera in the mid 19th century, at first for large scale topographic mapping (von Gruber, 1932). It was not until the 1960s and 1970s that non-topographic applications became widespread, particularly for architectural and heritage recording (Atkinson, 1969). Engineering and industrial applications were also expanding at this time (Case, 1976), however most users were employing simple stereopairs in conjunction with stereoplotters or stereocomparators. By the 1980s, multistation convergent photography and free network adjustment had been accepted as the technique which realises the highest levels of versatility and reliability with the optimum levels of accuracy (Granshaw, 1980).

The initial impetus to industrial photogrammetry was provided by improvements in close range cameras. Prior to the 1970s, close range cameras were metric (fixed interior orientation), fixed focus and could only accept glass plates as the emulsion medium. These restrictions were lifted in the 1970s as cameras like the Zeiss Jena UMK appeared with the facilities for step settings in focus and the option of roll film. Applications in the fields of structural monitoring, deformation surveys and engineering surveillance abounded, but most were still using stereopairs (Shortis, 1986). Changes in camera design have continued, resulting in the current generation of semi-metric cameras which incorporate continuous focus, reseau grids and standard size roll film. Examples of large (230mm) format cameras are the Geodetic Services CRC-1 and the Rollei LFC, whilst there are several offerings in the smaller 70mm format size such as the Rollei 6006, Hasselblad MK70 and Pentax 645 (Karara, 1989). These cameras are used in a wide variety of industrial applications with the emphasis on multistation convergent photography, self calibration and stringent tolerances (Fraser and Brown, 1986).

The second factor in the rise of industrial photogrammetric systems was the development of sophisticated algorithms for the optimization and adjustment of close range networks. When
implemented effectively, a non-specialist can be trained to design the network (Gustafson and Brown, 1985) and reduce the image observations (Brown, 1982). Self calibration via additional parameters can be used to compensate for systematic errors, whilst free network solutions can be used to simplify the field procedures by eliminating the requirement for coordinated control targets. The only remaining non-deterministic error, image plane unflatness (Brown, 1984), can be largely eliminated by an efficient film flattening device in the camera or by piece-wise correction to a dense reseau grid in the camera. All of these processes can be made somewhat transparent to the user.

Stereophotogrammetry is still utilised for various close range applications, but with a few exceptions it has been universally rejected in the industrial and manufacturing industries. The main reasons for this rejection are inflexibility, lack of reliability and the requirement for the specialised skills associated with the operation and use of stereoplotters and stereocomparators. Indeed, the introduction of automated image comparators was the third factor in the increased use of close range photogrammetry as an industrial measurement tool. Automated systems require no physiological skills on the part of the operator, and therefore can be used by a non-specialist. Further, automated systems are considerably faster than manual measurement, which reduces the turn around time to a level which is more acceptable to industry (Fraser, 1989b).

Automatic image measurement systems have their roots in both manual comparators and analytical stereoplotters. Automatic comparators such as the AutoSet-1 (Brown, 1987) and the Rollei RS1 (Luhmann, 1986) are similar to manual comparators only in the sense that both types of device measure precise x-y image coordinates on photographs. An automatic comparator, like an analytical stereoplotter, is back driven so that it can be directed to the target images, but the precise target image location is determined by image processing to obviate the need for manual measurement. The image of a small patch of the photographic negative is scanned by a charge coupled device (CCD) sensor and captured by a frame grabber board. The image location within the CCD frame is then computed using a centroiding algorithm to find the centre of the target. The location within the full frame of the photograph is computed by adding the CCD centroid location to that of a precise x-y positioning table upon which the photograph is mounted.

Automatic measurement of target images is only practical if the signal to noise ratio of the negative is kept at an acceptable level. In the industrial environment this aim can be achieved when retro-reflective targets are used. The retro-reflectors are illuminated by a flash or strobe attached to the camera and produce a high contrast target image under a wide range of ambient lighting conditions.

The entire process consists of a series of steps which can be carried out by non-specialists under the supervision of a photogrammetrist or industrial measurement expert. The network design, or verification of a previous design, is carried out using a CAD-like graphical optimization package. The initial coordinates for the points of interest would most probably come from the original CAD model of the object to be photographed. Fictitious image measurements are generated by the simulation. This data is then processed by the adjustment package to predict the accuracies of the point positions and ensure compliance with specified tolerances. If the specifications are not met, or the accuracies are non-uniform, the network design can be altered and the simulation repeated until the results are acceptable. Camera positions, orientations and focus settings are then extracted for the actual photography.

The field work commences with the targetting of the object. Tools and jigs commonly have locator holes for offset targets, whilst most other objects require adhesive targets to signal points of interest. Additional targets may be placed to define local coordinate systems or augment the network adjustment, if necessary. At least one accurate distance is measured to fix the scale of the object. The photographs are then taken, perhaps using hard copies of views from the network simulation as a guide to the positioning and orientation of the camera. The negatives are processed,
preferably on site using local facilities or a portable dark room, to verify the photographic coverage and the target exposures.

The operation of the comparator commences with a set-up phase which is controlled by an operator using a digitising tablet. The set-up phase establishes a resection of the photograph in 3D space using targets with known or adopted XYZ coordinates. A drive list of other targets can then be compiled, as any point with approximate 3D coordinates can be located in terms of 2D coordinates within the photograph. Once the set-up phase is complete, the comparator then automatically acquires the image observations using digital image processing. Any image which is not present or fails a set of quality criteria is logged and brought to the attention of the operator at the end of the automatic observations.

Additional points or points with unknown coordinates can be located coarsely by the operator for centroiding until there are sufficient observations to compute an approximate XYZ location via a simple intersection. As each point is coordinated it can be added to the drive list. Alternatively, strips of retro-reflective targets can be suitably positioned on the object to facilitate measurement when the shape or design is unknown. A simple "line following" technique can be employed which relies on equally spaced targets along the strip. Deviations from straightness of the strip of images on the negative can be accommodated by adjusting the active window within the CCD patch. This entire process is controlled by a series of prompts and menus.

The measured image data is then processed by the network adjustment to produce XYZ coordinates of the targets with estimates of accuracy. Sophisticated software packages incorporate automatic gross error detection and significance testing of additional parameters. Post processing of the target coordinates can be implemented to carry out datum transformations and best fit calculations in a similar fashion to the on line functions in theodolite systems. In addition, off line data compiled from photogrammetric measurement can be subjected to network tests which are inappropriate for on line measurements. Principal amongst the uses for network testing are deformation analyses and epoch comparisons for quality assurance (Fraser, 1988a).

Fraser (1988b) gives a comprehensive review of industrial photogrammetry, including digital photogrammetric systems based stereo correlation and real time processing of CCD images, which are beyond the scope of this paper. In any case the main stream photogrammetric systems using conventional cameras and automated comparators have made the greatest impression on industrial measurement, but to date these systems are a relatively minor participant in the overall field of close range optical measurement for industry. There are, at most, approximately 30-40 systems in use throughout the world (Fraser, 1989b). There are no full systems in Australasia, although various organisations have semi-metric cameras and software for the simulation, adjustment and analysis of close range photogrammetric networks.

Automated Theodolite Systems

Theodolite systems are currently under further development. Like the influence of automatic comparators on photogrammetric systems, theodolite measurement can be enhanced in productivity and response time by automating the observation of the targets. Again like automatic comparators, most attempts at automation have concentrated on the combination of back driving the instrument and the inclusion of digital image processing using CCD arrays and high contrast (retro-reflective or laser spot) targets. The elimination of theodolite operators reduces the possibility of gross errors, quickens the observations and probably improves accuracy.

A logical extension of the encoded circles with facility for output of angle data is the inclusion of stepping motors and facility for input of angle data. There are a number of motorised theodolites
currently available, such as the Wild TM series, Zeiss ETh3 and Geodimeter 460, all of which will accept azimuth and vertical angle input and drive to the new pointing direction. If a target is within the field of view then the direction can be located precisely by centroiding a CCD image. Any bias in the CCD array can be effectively eliminated by centring the target within the field of view using the stepping motors. The final direction to the centroid is a combination of the angle readings and the offset between the optical axis and the target centre.

This type of system can be constructed by simply attaching a CCD camera to a motorised theodolite and paying due attention to the alignment of the optical axes (Wester-Ebbinghaus, 1988). General Dynamics have developed a proprietry system to cater to a variety of 3D measurement problems within a single object (Schwartz, 1989). Both of these systems use focussable zoom lenses, which requires internally illuminated reference marks (fiducials) to compensate for the changes in calibration inherent in the optics of the cameras. In both cases the theodolite is essentially a platform for the camera and the philosophy of the system is principally photogrammetric.

The major instrument manufacturers have approached the same type of system with a surveying philosophy. CCD arrays have been incorporated into the optics of the theodolite telescope, which avoids the issue of continuous camera calibration. The digital images of the field of view of the telescope are used as an adjunct to pointing so that the theodolite can be automatically centred on the target. The Kern SPACE (Gottwald and Berner, 1987) and Wild ATMS (Katowski, 1987) systems appeared at approximately the same time and have similar features and applications. Recently the emphasis has shifted so that the SPACE system is associated with industrial measurement and retro-reflective targets whilst the ATMS system is associated with engineering monitoring and laser spot targetting.

The initial set up of an automated theodolite system closely parallels that of a manual system. The theodolites must be mutually referenced, a standard scale measured and targets defining the object coordinate system observed. The measurement of the points of interest is somewhat different, as the stepping motors can be used to point each theodolite in the direction of each target in turn, assuming that approximate target coordinates are known. This ability would be a bonus even if operators then had to then make a fine pointing to each target. Of course the fine pointing can be automatic using the CCD and the whole process efficiently overseen by a single operator, regardless of the number of theodolites in use. In situations where there are no known points there is the option of video monitors so that a single operator can control the entire measurement process. Other possibilities are line following on strips of retro-reflective targets, trilateration to mini-prisms and surface measurement using one theodolite with a coaxial laser and one or more theodolites with CCD arrays.

**Non-Conventional Systems**

Over the past few years a number of new optical triangulation and radiation systems have appeared to challenge the more conventional systems. These systems are all based on laser technology and can be categorised as multiple or single beam systems. Multiple beam systems are based on two or more laser interferometers which constitute a short range trilateration unit. Single beam systems combine coherent laser radar or a laser interferometer with an optical head and angle encoders. In essence, a single beam system is a short range total station with an ultra-precise distance meter.

Laser systems are restricted in range, but this may not be a severe disadvantage in an industrial environment. Interferometric systems generally require prism reflectors which is a disadvantage. Single beam systems can suffer from poor geometry and have no statistical reliability without
multiple set ups. Both types of system are only marginally portable, but are capable of dynamic measurement at rates exceeding tens of samples per second.

The measurement processes are again controlled by on line PCs or similar computers. The associated software packages are necessarily aimed at guiding the non-specialist via prompts and menus. Once more there are the usual functions of coordinate transformations, geometry computations, and the display and analysis of deviations.

There are a number of other non-conventional techniques which are used as optical measurement systems, such as holography and moire fringes. However these techniques have enjoyed little long term success in the field of industrial measurement due to restrictions on object size or lighting conditions. Applications of these systems are documented elsewhere (Karara, 1989).

Roles of the Systems

The various systems described above are all designed to measure 3D coordinates in the industrial environment. There is a reasonable amount of rivalry between the individual systems, as well as competition with non-optical techniques such as CMMs. However each system has an identifiable specialisation which, to some degree at least, makes the systems complementary.

Manual theodolite systems are particularly applicable to measurement tasks requiring on line feed back of positions or deviations. Tasks which require the measurement or set out of small numbers of targets for remedial work or axis alignment are ideal. Automated theodolite systems are particularly suitable for production line environments where the measurements are repetitive and at predictable locations. Automated theodolites can also be used for real time monitoring of single targets and rapid monitoring of small numbers of multiple targets.

Applications which require the coordination of more than, say, 100 targets are the province of photogrammetry on the grounds of efficiency and cost-effectiveness. Conventional photogrammetry will always suffer from the delay required to photographically process the negatives, observe the target images and adjust the network, but the turn around times have decreased dramatically due to the influence of automatic comparators and PCs. This disadvantage is redeemed by tasks which require the measurement of thousands of points, fast data acquisition to avoid production delays, strobe synchronization with vibrating structures or flash synchronization to freeze dynamic deformation. At present only photogrammetry can provide an effective solution to these types of measurement problems.

Laser systems are still seeking a particular niche in the field of close range optical measurement. The likely area of application is high accuracy, dynamic tracking of single points. Examples of tasks requiring such systems are the control and calibration of manufacturing robots, CMMs and numerical milling machines.

Role of the Surveyor

The rapid expansion of close range optical 3D measurement in the manufacturing industry and in particular the aerospace sector has been largely equipment only. Over the last several years more than 300 systems with an average cost in excess of $100,000 have been installed world wide. Yet there has been no commensurate increase in involvement by surveyors and photogrammetrists (Fraser, 1989a). Many of the larger organisations do employ optical measurement specialists, who often have a background in surveying or close range photogrammetry, but their involvement is typically at a supervisory or managerial level.
The are several reasons for this apparent contradiction. The most important is perhaps the perception by industry that close range optical measurement is simply another tool at the disposal of shop floor technicians. Whether this perception is valid or not is academic, as measurement tools in the industrial environment must be workable by non-specialists after a short training course. If this is not the case then the industry will simply not use them. Survey technicians are excluded from this environment because they are too specialised and generally lack industrial or union certification.

The response by instrument manufacturers has, not surprisingly, been to tailor their products to this situation by developing "turn key" systems. Automation and good software are the primary devices at the disposal of manufacturers to simplify measurement hardware and methods. Given the influx of turn key systems, the traditional skills of the professional surveyor are no longer required at the data acquisition stage. The industrial measurement circumstance is perhaps a reflection of the changes to the surveying profession as a whole. The impact of total station and satellite positioning technology has been to erode reliance on professional surveyors for skilled field observations. Black box technology such as GPS requires virtually no skill to operate.

This gloomy scenario has one ameliorating factor: the field data has to be designed, processed and analysed. It is in these areas that the specialist skills of the professional surveyor and photogrammetrist can be used to advantage. A thorough understanding of field measurement processes, the influence of gross, systematic and random errors, and the adjustment of the observables can only be gained by fundamental training and experience in measurement science.

Conclusions

On the whole, close range optical 3D measurement is an exciting and expanding field which does have opportunities for the surveyor and photogrammetrist. The development of new equipment and techniques will reinforce the involvement of measurement specialists, whilst automation and turn key systems will tend to reduce dependence on those same specialists. The discipline has been and will continue to be driven by the requirements of the aerospace and manufacturing industries because of the demand to meet stringent measurement accuracies.

However, professional measurement specialists are likely to continue to have a relatively small involvement, and only in the supervisory or team leader role. The industrial environment will continue to use close range systems as off the shelf tools which are to be used on the shop floor by non-specialists. The surveyor and photogrammetrist will only excel in this field if advantage is taken of their unique ability to design, process and analyse observed data.

Close range optical 3D measurement is still a young science. During the next decade of maturation the surveyor and photogrammetrist may become involved or not. The opportunity to exploit the requirement from industry for accurate XYZ coordinate data may not come again.

References


Biographical Summaries

Mark Shortis

Mark completed the Bachelor of Surveying degree at the University of Melbourne in 1975 and continued there to complete a Masters degree in analytical photogrammetry in 1977. He then moved to London to complete a Ph.D., also in analytical photogrammetry, at the The City University. Whilst there he participated in many close range measurement projects with the Terrestrial Photogrammetric Unit. In 1981 he returned to the University of Melbourne, first as a Research Fellow and more recently as a Lecturer, to continue his involvement with close range photogrammetry. In 1988 he spent a year of sabbatical leave at NASA Langley Research Center in Virginia, developing software and procedures for the calibration and use of both conventional semi-metric cameras and digital CCD cameras.

Clive Fraser

Clive completed a Bachelor of Applied Science at WAIT in 1975, followed by a Masters degree at the University of New South Wales in the field of meteorological effects on EDM in 1977. He then changed his research speciality to analytical photogrammetry, completing a Ph.D. on the subject of self calibration at the University of Washington at Seattle in 1979. He then held two academic positions, first as a Post-Doctoral Research Fellow at the University of Canterbury in New Zealand and then as an Associate Professor at the University of Calgary in Canada. Clive is currently the Vice-President in charge of research at Geodetic Services Inc. in Florida. He has continued his work in close range photogrammetry throughout this period, specialising in high accuracy applications in the aerospace and manufacturing industries.