AN APPROACH TO DIGITAL PHOTOGRAMMETRY FOR BODY SURFACE MEASUREMENT

H.L. Mitchell
Senior Lecturer
Department of Civil Engineering and Surveying
University of Newcastle
Australia

Commission V

ABSTRACT:

A near-real-time close-range digital photogrammetric measuring system for bio-medical measurement has been assembled, following an approach which uses digital cameras, a cast pattern to provide texture and targets, and PC-based processing for target searching and image matching. The rationale behind this choice is given, but emphasis is given to designing hardware and software to meet criteria for high speed and accuracy, a moderate resolution level, full automation, and low cost in a case study of an instrument which is intended for practical use. So far, the instrumentation has been routinely demonstrated to achieve measurement by fully automated procedures of some areas of the human body with accuracies of surface heights to better than one thousandth of the camera-to-object distance and sub-pixel planimetric precisions in as little as a few minutes.

KEYWORDS: Biostereometrics, close-range photogrammetry, digital photogrammetry

1. INTRODUCTION

The long-held photogrammetric interest in bio-medical measurement has continued unabated in recent years, as digital processes foster fast, automated bio-medical measurement, while still achieving satisfactory levels of resolution and accuracy. Reports of automated non-contact surface measuring systems to fulfil broadly similar aims in terms of human face and body measurement go back at least a decade, e.g. Newman *et al.* (1982), and continue to be reported with some regularity. This paper provides a case study of one particular photogrammetric approach using digital cameras and PC-based processing to automated measurement of parts of the body. As currently configured, the system, which has been under development since about 1988, comprises two digital cameras fixed on a 200mm base, synchronously imaging the subject from about a metre. A slide projector provides texture on the object. Different PC-based image processing options, including least squares image matching, have been tried in a search for the optimum procedure which satisfies the design parameters. To date, the instrumentation has repeatedly accomplished test measurements of certain areas of the human body with sub-pixel precisions, in times ranging from a few minutes for a low resolution description to around half an hour for higher resolution, with reliability, by fully automated operation and at low cost.

2. DESIGN CRITERIA

Much has already been written on the use of digital cameras in close-range photogrammetry, especially for near-real-time uses, and on relevant digital photogrammetric techniques, and is not repeated here. Although there are perceived demands in industry for automated surface measurement and although much can be learnt from such digital measurement systems for non-medical purposes, development of a "universal" measuring system is too demanding, and the design must instead be influenced by specific medical uses.

Apparent demand for medical measurement is indicated by developments in biostereometrics, which go back some tens of years. The number of reports of attempts to apply non-contact measuring methods for medical purposes is now so extensive that even to simply list them would be impractical; the proceedings of various conferences on related areas may be of interest, (e.g. Baumann & Herron, 1989; Neugebauer & Windischbauer, 1990). Most developments for human body surface measurement (to be distinguished from point measurement for motion analysis) are intended to aid medical procedures concerning bone - skull, mandible, spine and limbs - rather than the soft tissue itself, uses primarily being for scoliosis detection and treatment, facial reconstruction and other orthopaedic procedures. (It must be noted that there are complexities in locating the bone from skin surface measurement). Automated back measurement devices have emanated most noticeably from research at Oxford (see e.g. Turner-Smith, 1988) and from Münster (see e.g. Frobin & Hierholzer, 1991). Examples of digital photogrammetric efforts to assist maxillo-facial reconstructive surgery to correct disfigurements, the effects of accidents or masticatory disorders are given by Dowideit *et al.* (1983), Mesqui *et al.* (1986), Grün and Baltsavias (1988), Deacon *et al.*, (1991). In this writer's experience, enthusiasm for surface measurement came primarily from orthopaedic surgeons, for quick recordings of patient's spinal movement capabilities and for reconstruction following fractures. There are also reported prospective applications not involving the bone: measuring the body for prosthesis fitting, (e.g. Rüther & Wildschek, 1989), for studies of changes in female breast form during detection of diseases and for studies of other parts of the body for volume determinations in cases of therapeutical studies, (e.g. Adams *et al.*, 1988; Trinder *et al.*, 1990). A mention of promising uses is given most recently by Deacon *et al.* (1991).

Many orthopaedic uses require low accuracy, quick recording, quick computations, and low resolution. Facial recording is clearly more difficult than limb and back measurement and may best be served by high resolution systems. It is considered that the greatest demand for near-real-time-photogrammetry and close-range-photogrammetry systems in medicine lies with user-friendliness and simplicity, even with low accuracy and low resolution. Such applications are closer to robotics and machine vision than to precise photogrammetry. This instrumentation has been developed in an effort to meet these specifications, having an orientation toward the recording of soft tissue surfaces on backs, limbs and perhaps faces.

Acceptance by users was seen as crucial to the success of a digital measuring system, and careful assessment of design criteria has been seen as an important element. The perceived requirements for effective back, limb and even facial recording are enumerated below in a perceived order of significance to the design.

A) The first and most essential consideration is quick data capture, since the live, human subjects are continually moving, even if slightly, dictating a data recording time of less than about 0.3 seconds.

B) It is essential also that the system's output must be that sought by the practitioner, presented in the most appropriate and easily comprehended format. For the applications mentioned earlier, the results will typically be used for comparative analysis involving another, similar set of results; comparisons may detect existing conditions or deteriorating conditions or may be employed to monitor progress of treatment; a left limb may be matched with the right during the treatment of fractures. Seldom will the practitioner wish to examine a single surface presented as a digital model. Consequently, this study assumes that results in the form of digital surface models will be used, following digital surface model matching techniques as outlined by Pilgrim (1991), who does not use control points on the surface but matches the surface shapes in a least squares procedure not dissimilar to image matching. Furthermore, Pilgrim detects surface differences simultaneously with the surface aligning.

C) Most importantly, operation must be reliable since the operator may be a clinician, not a technician and not an expert with the instrument. Operator intervention is probably unacceptable.

D) For the instrument to be acceptable for clinical use, it must be convenient to operate. Again, this can be a difficult criterion to satisfy.

E) Accuracy requirements are rarely specified exactly. Frobin & Hierholzer (1991) measure backs with an accuracy of 0.5 mm in the direction perpendicular to the surface, and reduce this error to 0.2 mm by interpolation and smoothing. Sub-millimetre accuracies are obtained on facial measurements by Deacon *et al.* (1991). For this project, sub-millimetre accuracies are being sought. However, it must be noted that what is important here is not absolute accuracy, but relative accuracy - and not only relative accuracy across one model, but relative accuracy between digital models.

F) The requirement for resolution are as uncertain as accuracies. Active methods give a typically high point density; Frobin & Hierholzer provide around 8000 for subsequent back surface shape analysis; Deacon *et al.* seek a similar order of magnitude of points for facial representation. For this work, a lower level of resolution will initially be accepted: around 10 mm spacing over a surface area of about 250 mm by 250 mm.

G) Meeting competitive developments will require that the instrumentation be inexpensive. Back, limb and facial observations are currently made using the human eye/brain combination or simple callipers. Although they have the advantages that of being readily accessible, simple, working in real time, being easy to use, and very effective, and being acceptable to clinician and patient, photogrammetric measurement has advantages in precision and accuracy and in the ability to store volumes of quantified data.

H) The question of what delay can be tolerated in the provision of results seems to depend on the application. There are definite advantages in some cases for the clinician to be able to analyse the results, even by way of digital model matching, while the patient is still in the clinic. Other cases, such as scoliosis screening and monitoring changes over time, clearly do not require real-time results. The provision of output quickly does not seem to be a barrier to amenity, but even so rapid results will be sought here.

I) Safety is important, especially with the use of lasers, but it seems rarely to be a problem otherwise.

3. DESIGN CONCEPTS

3.1 Basic Configuration

Assuming a spatial ray intersection approach is to be employed, one popular option for automated close-range measurement is the active approach, requiring only one camera, co-ordination of points then being made possible by the controlled projection of a light spot, of lines or of a number of points or lines. This approach typically provides a large number of surface points; computations can be simple and easily near real-time. If a moving spot or line is used, complications lie in mechanically moving and accurately controlling the projection, while simultaneously having a short data collection duration. If a projected pattern is used, points in the pattern need to be identified and the projecting device must be calibrated; see e.g. Baj & Bozzolato (1986), Frobin and Hierholzer (1991), Ng & Alexander (1991).

The alternative is conventional photogrammetry, with projected texture by a light spot, a line or pattern. Again there are mechanical complications inherent with the mechanical movement of a single spot or line. To satisfy criteria (A) and (G), the passive approach with a projected pattern was selected here, software solutions being seen as preferable to mechanical complications.

3.2 Hardware

Two Philips inter-line-transfer image sensors with 604 pixel columns by 588 pixel rows over a sensor area of 6.0 mm x 4.5 mm, (a pixel size of 9.9 microns x 7.7 microns), operating in a CCIR interlaced mode, are each fitted with Fujinon-TV 25 mm focal length f/1.4 lenses. The cast texture is provided by a modified slide projector, housed with the cameras in a specially fabricated casing, providing a fixed base of 200 mm and a convergence angle such that the camera axes intersect at a distance of a metre. A PC Vision Plus brand frame-grabber is used, operating at 30 frames per second, and digitising the video signal to 8 bits (i.e. 256 grey-levels). It can store two 512 x 512 images in frame memory, but only 500 x 500 images are currently employed in the subsequent processing. The cameras are programmed to image within 0.1 seconds of each other.

The object's location at about a metre from the cameras is fixed by a plate which has a rectangular aperture corresponding to the field of view of the cameras. For a sensor area of 6 microns x 4.5 microns and a 25 mm lens, the field of view of the cameras is about 240 mm x 180 mm at a distance of a metre. Thus a pixel corresponds to about 0.4 mm x 0.3 mm on the subject.

For a base-to-height ratio of 1:5 and a expected depth range on the object of up to 50mm, the anticipated parallax range is, in the terms of the scale of the object, 10mm. For an object dimension of 250mm, this suggests that 25 target points across the object in each direction (or about 600 targets across the surface of an object which fills the entire view of the cameras), would ensure that all conjugate targets and only conjugate targets fell within the expected parallax ranges. This figure corresponds to a target every 20 pixels in each direction on an image of 500 pixel dimension. Projected grid lines are usually at about this spacing and are about 1.5 mm wide on the object.

In order to meet the cost and simplicity criteria, all image processing is carried out on an ordinary IBM-compatible PC with maths co-processor and a VGA monitor.

3.3. Computational Stages

A suite of programs, written in FORTRAN, has been prepared to carry out the various stages of the computations:

i) to display the camera moving images before adopting them;

ii) to grab and store the images at the chosen moment within 0.1 seconds of each other;

iii) to detect targets on each image, in order to produce a finite list of points at which precise matching should be successful;

iv) to classify the targets, thereby providing information to facilitate subsequent matching;

v) to pair possible conjugate target points;

vi) for stereoscopic image correlation to provide image co-ordinates; and

vii) for surface reconstruction and display.

3.4 Target Detection Classification.

Various procedures which search for features suitable for stereo matching within the pattern have been explored, including the use of template matching and the interest operator described by Förstner & Gülch (1987).

A regular pattern is commonly supposed to cause confusion and erroneous matching, although it has been used in other medical and close-range measuring devices, e.g. Rüther (1989), Rüther & Wildschek (1989), Trinder *et al.* (1990), Deacon *et al.* (1991). The grid has been used successfully here to provide distinct target points, with known characteristics, at a pre-selected spacing. Areas within the grid pattern possesses a symmetry, which is obvious at the grid intersection points, but which is also apparent at the centres of the areas between intersections and at the centres of the lines between intersections. This is so even when the pattern is distorted by the perspective, and this property can therefore be utilised for target point selection. Indeed, tests showed that around 2000 target points could typically be detected in the image by finding symmetry, but the image processing is laborious.

For a coarser resolution, the peaks in intensity across the pattern in the filtered image provide a very simple means of detecting the grid intersections. Such a procedure permits very fast target detection but usually gathers only around 400 targets.

3.5 Target Classification

The interest operator referred to in Section 3.4 is subsequently used for classification of features detected by the symmetry of the pattern. The target types are distinguishable by the characteristics of the "error ellipses" derived from the image intensity gradients in the vicinity of the targets. Grid intersections can also be differentiated from the points at the centres of the grid squares on the basis of their reflectance intensity.

3.6 Pairing of Points

Pairing of prospective match points on both images of the stereo-pair is based on parallax limits defined by epipolar geometry, within some bounds governed by the expected variations in depth across the object surface and with some small tolerance (typically a couple of pixels) to allow for error in locating the same target in each image and any imprecision in the relative orientation. If a large number of targets have been detected, a number of targets in the right hand image may be paired with any one target in the left hand image, this number depending on the pre-set parallax limits. These limits can be varied according to the degree of convolution of the object surface. The multiple target matches than have to be contended with in the precise matching - see Section 3.7

3.7 Image Matching

To correlate conjugate targets, least squares signal-based matching was chosen in preference to feature-based matching because of the former's superior precision. Tests of least squares image matching with the regularly patterned surfaces showed that it works reliably; sub-pixel precision matching can be undertaken not only at the grid intersections but also at other types of target points. The incidence of poor matches, blunders and mismatches of like features can be limited if run-time parameters are carefully selected. Moreover, the statistics of the least squares match, particularly the variance factor, can be used to distinguish mis-matches from correct matches, in which case the grid spacing can be reduced to improve resolution. The pull-in range of the least squares matching was found by tests to not be an obstacle to the least squares matching in this case.

The established 8-parameter least squares matching as given by, for example, Albertz and Kreiling (1989, p260), is used but with modifications to accelerate processing. Geometric constraints are not incorporated on the assumption that this requires that the target point co-ordinates detected in an earlier stage already satisfy the geometric constraint by lying exactly on the epipolar lines. Internal match precision on the images of the grid on skin varies, but rarely exceeds 0.3 to 0.5 pixels, or about one part per thousand of the image dimension on skin surfaces. For an object at one metre, this is about 0.2 mm. In fact, if the precision exceeds a certain pre-selected tolerance level, the matched point is rejected.

A number of strategies which have improved the reliability and/or precision of the least squares matching in recent years, have been published since the early exposition of the least squares matching theory (e.g. Ackermann, 1984), but they have not been incorporated into this work because of their perceived detrimental effect on the speed of computation. These include combined object surface and radiometric modelling (see Weisensee & Wrobel, 1991, Heipke (1990,1992), Wrobel (1991), among others); "back matching", i.e. the matching of the right hand image target points against those of the left as well as the matching of the left image points against the right, (see Hannah, 1989); adaptive matching; using filtered images for faster convergence (e.g. Li, 1991); pre-processing of the images for contrast stretching and thresholding images; re-sampling to epipolar geometry to simplify matching (and viewing); and the use of a hierarchy of images in scale space to progressively refine estimates of parallaxes. Robust estimation is not included in the least squares procedures, but may yet be useable.

3.8 Three-dimensional Surface Reconstruction

Surface co-ordinates in the object co-ordinate system are calculated by space intersection based on a relative orientation and a scaling from a calibration phase on a suitable model. Absolute orientation is not necessary with digital model matching, so, significantly, control points and devices to constrain the position of the body are not necessary.

3.9 Calibration

Full calibration is one component of the project, but although lens calibrations and other calibrations have commenced, (see Fryer and Mason, 1989, for calibration of the lenses used), this facet is not complete and is not reported here. However, calibration of optical and other hardware components has not been seen as crucial. Provided that the device is used to generate surface models which are to be matched with other digital surface models created by the same instrument, then systematic effects due to erroneous principal distances, inaccurate sensor dimensions, uncertain principal point positions, systematic sensor geometry error and even lens distortion effects, will essentially cancel. The accuracy level possible for this instrument is conditional upon its use in that manner. In addition, with 100% overlap in the case of convergent cameras, lens distortion effects on depth measurement will tend to cancel, following theory similar to that given by Fryer and Mitchell (1987). It is recognised that errors such as transient sensor warm-up effects and random sensor geometry faults cannot be cancelled in this way and must yet be accounted for.

3.10 Algorithmic and Programming Considerations

Considerable effort has been spent on devising procedures to accelerate all stages of the image processing. Indeed, although much of this cannot be satisfactorily described here, it represents a substantial amount of work. Since development commenced, the run time of many component programs used in this project have been cut by at least an order of magnitude. In fact, time from imaging to depiction of the surface by contours on a monitor can now be as low as a few minutes to around half an hour for higher resolution.

3.11 Run-Time Parameters

In order to achieve accuracy, reliability and speed of all procedures (especially the least squares matching), comprehensive trials continue in order to choose optimum values for the large number of run-time parameters, relating to the target detection, classification, pairing, matching and use for surface reconstruction. Like the programming mentioned in Section 3.10, this matter represents extensive effort and perhaps the bulk of the work of the project.

4. RESULTS

4.1 Accuracy Assessment

Tests for accuracy of the least squares matching and of the orientation have been carried out on plane, cylindrical and conical timber and metal surfaces; see Figure 1 for an example of one contoured surface. The accuracy was assessed by least squares fitting of surface results to the pertinent geometric shape using theory outlined by Fryer and Parbery (1992), and was typically ±0.5 mm on the different models. Allowing a depth error of 1 mm on more uneven body surfaces, the depth accuracy is about 1/1000 of the camera-to-object distance.

4.2 Operational Tests of Speed and Reliability

The apparatus has been in use reliably for recording back and limb morphology and occasionally faces as part of continual demonstrations, as well as trials for assessing speed, reliability and resolution in realistic cases. Figures quoted below refer to processing on a Zenith brand 486 PC operating at 33 MHz.

From part of an abdomen, 472 points were abstracted to produce the contours shown in Figure 2, by detecting symmetry in the images and later using least squares matching taking a total of 20 minutes. A comparison of surface measurement results on part of a human back in terms of processing times and resolutions yields the following figures. Detecting target by their symmetry provided a surface defined by 947 points, the time for target detection being 15.3 minutes, the time for least squares matching of all points being 19.1 minutes, the total computing time being 35.5 minutes. Detecting the grid intersections yielded 207 surface points but with corresponding times of only 80 seconds, 44 seconds and 127 seconds respectively. This speed is superior not only because of the fewer points detected but also because of the lack of multiple target matching to be resolved.

Computation times depend on the run-time parameters chosen in each case, and on the projected grid spacing which influences the number of targets.

An example of a face portrayed by 736 successfully matched points, but with 8 erroneous points edited out, is shown in Figure 3, and suggests some potential for facial measurement.

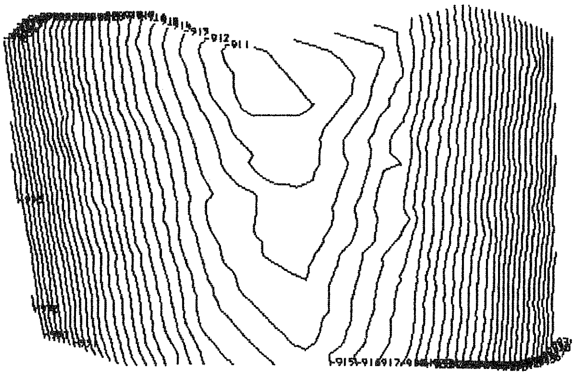

Figure 1: 1 mm contours of a conical metal surface, based on 474 surface points.

4.3 How Well Does the Instrument Meet Design Criteria?

A) Time to record: Cameras are easily timed to record in less than 0.1 seconds. This criterion is easily satisfied with the conventional two camera approach.

B) Output of results: Results are presently displayed using contours. Digital surface model matching has not yet been incorporated into the software.

C) Reliability: The reliability of matching obtained in the test was surprisingly high by both approaches, largely due to the robustness of the least squares matching procedure, using the selected run-time parameters. If the method fails it will usually be only in the vicinity of areas in the vicinity of hair, eyebrows, eyes, and so on, which are not relevant to the practitioner nor to surface model matching. It may fail in the vicinity of steep slopes around the nose, or at eyebrows or eyes, but again what is relevant to the practitioner is the soft tissue around the cheeks, chin and forehead and as such disruptions to the smooth skin and steep slopes need not be a problem, especially if digital surface matching is to be used. A surface measuring system must be capable of coping with different skin types and colours, a matter which remains undetermined in this case.

D) Convenience: The operation has so far been fully automatic in all modes, owing largely to the selection of parameters appropriate to the surface in question. The instrument will operate in a normally lit room.

E) Accuracy: Current accuracy as estimated from the tests as described above is adequate for the particular uses expected to generate significant demand.

F) Resolution: The levels of resolution which have been achieved - see Table 1 - are adequate for the anticipated uses.

G) Cost: The hardware required for the current instrumentation comprises the cameras, the illumination and texturisation apparatus (specially fabricated), a typically-configured PC with VGA screen for image display, frame-grabbers boards and a separate monitor for the cameras. Proprietary software is used for surface contouring and display.

H) Computation Speed: Considerable programming effort has been devoted to ensuring a short and probably acceptable computation time, although not strictly real time.

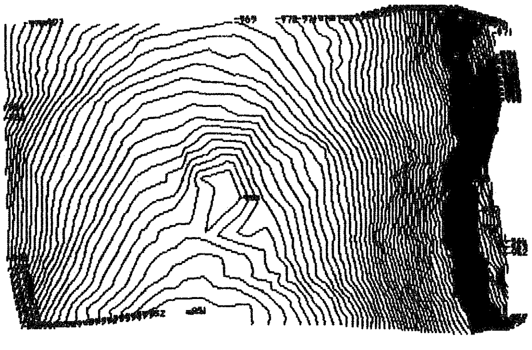

Figure 2: 1 mm contours of part of abdomen, based on 421 points, as determined using symmetry detection followed by least squares matching.

I) Safety: The procedure is safe, and moreover, using digital surface model matching avoids the need for control points or fixing the patient with respect to cephelostats, for example, and makes the method comfortable for the patient.

This instrument may be compared to recent similar, digital photogrammetric approaches to bio-medical measurement, e.g. by Grün & Baltsavias (1988), Trinder *et al.* (1990), and Deacon *et al.* (1991), and to active triangulation approaches, e.g. Frobin & Hierholzer (1991). However, these approaches all differ in the way they meet the criteria mentioned above, and the task of the comparison becomes difficult and is perhaps not constructive. As no body surface measuring devices are used in the health services of the local region at present, it seems reasonable to foresee use by the medical practitioners with whom the writer has been in contact.

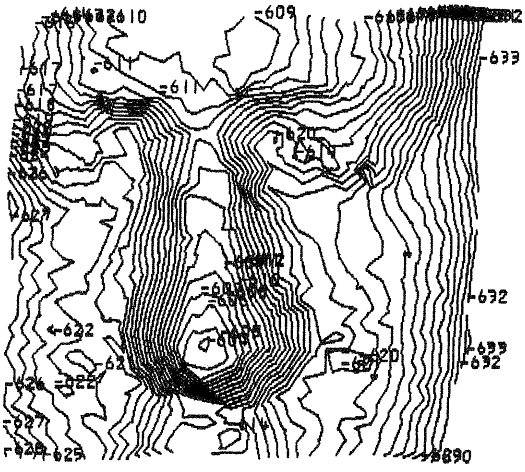

Figure 3: 1 mm contours of a human face, derived from 736 points.

5. CONCLUSIONS

The paper provides a brief case-study of a device which is capable of determining bio-medical soft tissue surface shapes, which operates reliably and without operator intervention, and which has been brought to operating level. A feature of the system may be its simplicity: it has been surprising what could be achieved with a ordinary PC, although with extensive programming effort in image processing and with carefully chosen run-time parameters. The difficult facets of the development have not been seen as achieving precision from the least squares matching but achieving reliability and an acceptable speed.

The projected texturising grid pattern facilitates target searching, and least squares image matching does not suffer. However, target detection can be a slow procedure because of the volume of image processing and judicious selection of an appropriate strategy can be crucial. Different levels of resolution have been found possible: speed can be achieved at the expense of resolution. Low resolution is seen to be suited to a number of medical applications, especially as it provides a surface model little different from the high resolution models for limbs and backs.

Hardware and software development will continue, to advance accuracy, reliability, resolution, coverage and speed. All hardware components must be thoroughly calibrated. Digital surface model matching must become an integral part of the device.

6. ACKNOWLEDGMENTS

The innumerable contributions of colleagues at the University of Newcastle, including Mr M.H. Elfick, Prof. J.G. Fryer and Dr H.T. Kniest cannot go unthanked. Dr S. Robson of City University, London, made extensive contributions to programming. Financial support for the purchase of hardware was provided by the University of Newcastle. ADAM Technology of Perth, Western Australia, provided valuable material assistance and travel support to permit the writer to attend informative meetings and conferences. Early work on this project was facilitated by the writer's visit to the Department of Photogrammetry at the Royal Institute of Technology, Stockholm.

7. REFERENCES

Ackermann, F., 1984. Digital image correlation: performance and potential application in photogrammetry. Photogrammetric Record, 11(64):429-439.

Adams, L.P., H. Rüther, & M. Klein, 1988. Development of a PC-based near real Time Photogrammetry System for Evaluating Regional Body Surface During Breathing. Biostereometrics '88, 5th. International Meeting, SPIE 1030:352-360.

Albertz, J. & W. Kreiling, (1989). Photogrammetric Handbook. Herbert Wichmann, Karlsruhe: 292 pages.

Baj, E.A. & G. Bozzolato, 1986. On line restitution in biostereometrics using one photogram and a metric projector. In: International Archives of Photogrammetry & Remote Sensing, 26(5):271-278.

Baumann, J.U. & R.E. Herron (eds.), 1989. Biostereometrics '88, 5th. International Meeting, SPIE 1030.

Deacon, A.T., A.G. Anthony, S.N. Bhatia, J-P. Muller, 1991. Evaluation of a CCD-based facial measurement system. Medical Information, 16(2):213-228.

Dowideit, G.R., D.G. Newman, & C.M. Young, 1983. A new automated approach to high-density facial measurement. Part 1: the image capturing and processing hardware. International Journal of Bio-Medical Computing, 14:403-409

Förstner, W. & E. Gülch, 1987. A fast operator for detection and precise location of distinct points, corners and centres of circular features. In: Proceedings International Conference on Fast Processing of Photogrammetric Data: 24pp.

Frobin, W. & E. Hierholzer, 1991. Video rasterstereography: a method for on-line measurement of body surfaces. Photogrammetric Engineering & Remote Sensing, 57 (10): 1341-1345.

Fryer, J.G. & S.O. Mason, 1989. Rapid Lens Calibration of a Video Camera. Photogrammetric Engineering & Remote Sensing, 55(4):437-442.

Fryer, J.G. & Mitchell, H.L., 1987. Radial distortion and close-range stereophotogrammetry. Australian Journal of Geodesy Photogrammetry & Surveying, 46:123-138.

Fryer, J.G. & Parbery, 1992. Monitoring as-built shapes. Submitted to: Australian Journal of Geodesy Photogrammetry & Surveying: 10 pages.

Grün, A. & E. Baltsavias, 1988. Automatic 3-D measurement of human faces with CCD-cameras. Biostereometrics '88, 5th. International Meeting, SPIE 1030:106-116.

Hannah, M.J., 1989. A system for digital stereo image matching. Photogrammetric Engineering & Remote Sensing, 55(12):1765-1770.

Heipke, C., 1990. An integral approach to digital image matching and object surface reconstruction. Optical 3D Measurement Techniques, Herbert Wichmann, Karlsruhe: 347-359.

Heipke, C., 1992. A global approach for least-squares image matching and surface reconstruction in object space. Photogrammetric Engineering & Remote Sensing, 58(3):317-323.

Li, M., 1991. Hierarchical multi-point matching with simultaneous detection and location of breaklines. Photogrammetric Report, No. 55, Department of Photogrammetry, Royal Institute of Technology, Stockholm: 184 pages.

Mesqui, F., F. Kaeser, & P. Fischer, 1986. On-line three-dimensional light spot tracker and its application to clinical dentistry. In: International Archives of Photogrammetry & Remote Sensing, 26(5):310-317.

Neugebauer, H. & G. Windischbauer (eds.), 1990. Surface Topography and Body Deformity. Gustav Fischer Verlag, Stuttgart.

Newman, D.G., G.R. Dowideit, & C.M. Young, 1982. High density facial measurement: a new automated approach. International Journal of Bio-Medical Computing, 13:175-187.

Ng K.C. and B. Alexander, 1991. 3D shape measurement by active triangulation and structured lighting. Proc. 1st. Australian Photogrammetric Conference, Sydney: paper 33.

Pilgrim, L.J., 1991. Simultaneous three dimensional object matching and surface difference detection in a minimally restrained environment. Research Report 066.08.1991, Dept. Civil Engineering and Surveying, University of Newcastle, Australia: 215 pages.

Rüther, H., 1989. Near-Real-Time Photogrammetry in a Personal Computer - PHOENICS. Proc. Conference, Southern African Surveyors, Paper 3-2.

Rüther, H., & R. Wildschek, 1989. Digital photogrammetry for the acquisition of surface data for automatic milling processes. Optical 3D Measurement Techniques, Herbert Wichmann, Karlsruhe: 347-359.

Trinder, J.C., T. Tjugiarto & B.E. Donnelly, 1990b. A close-range digital photogrammetric system. Close-Range Photogrammetry meets Machine Vision, (Grün & Baltsavias, eds.) Proc. SPIE Vol. 1395: 28(5/1):440-447.

Turner-Smith, A. R., 1988. A television/computer three-dimensional surface shape measurement system. Journal of Biomechanics 21(6):515-529.

Weisensee, M. & B.P. Wrobel, 1991. State-of-the-art of digital image matching for object reconstruction. Digital Photogrammetric Systems (Ebner, Fritsch & Heipke, eds.), Herbert Wichmann, Karlsruhe:135-151.

Wrobel, B., 1991. Least-squares methods for surface reconstruction from images. ISPRS Journal of Photogrammetry and Remote Sensing, 46:67-84.