

11 Medical photogrammetry

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11.1 Introduction

The primary aim of this chapter is to bring medical photogrammetry to the attention of potential users as a means of measurement on living human patients. The scope of medical photogrammetry is outlined, and the advantages and disadvantages of the various photogrammetric options are pointed out, especially when these differ from those in industrial, architectural and other close range applications. Examples of the application of photogrammetry to medical and related health studies are provided. A brief examination of some alternative measurement technologies used for medical measurement is also included.

11.1.1 *Scope of medical photogrammetry*

The history of attempts to apply photogrammetry to the measurement of the human body is almost as long as the history of photogrammetry itself. Over the last century or more, analogue, analytical and digital photogrammetry have been used to record shape and size in studies relating to a wide range of areas of the human body, such as torsos, heads, faces, limbs, breasts, feet, skin, eyes and teeth. Some of the applications have been for the purpose of advancing anatomical studies, while others have related to the detection or treatment of diseases and other conditions.

Opportunities for such measurement relate primarily to:

- the **detection** of medical conditions, by mass screening or examination of individual patients.
- the **treatment** of a disease or condition.
- **studies** into the mechanics, workings and other anatomical aspects of the human body.
- **research** into diseases and/or their treatment.

Although photogrammetric measurement is particularly relevant to orthopaedics and anatomy, it can also contribute to ophthalmology, neurology, dentistry, occupational therapy, ergonomic studies and many other areas related to human health. The users of the results may be involved in health in various ways, as medical researchers, surgeons, clinicians, biomechanical engineers, occupational therapists and so on.

For the purposes of this chapter, all measurements which relate to living human patients, whether applied in a clinic, a surgery, or a biomedical laboratory, will be

regarded as medical measurement. The measurement of inert items, such as prostheses or parts removed from bodies, is not seen as medical photogrammetry as this does not involve a patient, even though the client may be a medical practitioner.

An extensive number of papers has been written on medical measurement, and a bibliography on medical photogrammetry would be very extensive indeed. Papers listed in the bibliography are far from exhaustive on the subject. References have generally been limited to examples only, and preference has been given to studies which have led to practical use of the techniques. Where a choice has been available, references have been selected from those sources which are most accessible.

11.1.2 Special characteristics of medical photogrammetry

Photogrammetry has a distinct value as a medical measurement tool since it uses photography which offers a quick, convenient and safe means of recording a condition at a particular point in time. It is not invasive, and touching the patient, with the risk of hurting or infecting, can be usually avoided. Further, photography does not distort the surface being measured. Photogrammetry can be contrasted with other external measuring techniques, such as those involving electrogoniometers and accelerometers attached to the body for movement analysis, which are not only uncomfortable but can interfere with the free movement of the patient.

Although photogrammetry, along with other optical techniques, appears to have the disadvantage that it is associated with the exterior of the body, rather than the interior which is often seen as so relevant to health, it is found in practice that external studies are valuable in many situations for a number of reasons. Firstly, many internal disorders are apparent through external conditions, a good example being orthopaedic deformities of the face and spine. Secondly, many disorders, such as those which relate to the skin (including ulcers), the teeth and the eye (including the retina) can be examined externally. Thirdly, because of natural concerns about physical appearance, an external manifestation may be under treatment, rather than an underlying condition. Fourthly, internal measuring techniques can have their disadvantages because of some risk (such as the ionizing effect of X-rays) and because they are often cumbersome, inconvenient, expensive or slow. Photogrammetry can be again contrasted with slow and intrusive internal examination techniques, such as ultrasound examination of foetuses, and computed tomography.

The widespread interest in the use of photogrammetry in biomedical applications has led to the use of the word *biostereometrics* to describe medical measurement by means involving stereoscopic principles, but it has also come to be accepted as a general word for optical and related medical measurements. Medically, *biostereometrics* is a more acceptable term than medical photogrammetry as it is more indicative of the link between the medical profession and the measurers.

Medical photogrammetric measurement for the diagnosis and treatment of human conditions, and for biomedical research, creates a class of close range photogrammetry with its own distinctive challenges and constraints. The reasons for this are as follows:

- Medical measurement deals primarily with living human patients. Consequently, it is necessary to be concerned about their convenience, comfort, privacy and dignity. Measurement is typically confined to a clinic or perhaps a surgery,

rather than a photogrammetric laboratory. It is also necessary to consider the patients' safety and health. This can be relevant when using laser beams or even control point markers. More importantly, from a technical aspect, human beings move continuously, even if imperceptibly, over short periods of time, and so quick and finely synchronized imaging can be crucial.

- The measurement also involves interaction with the medical practitioner. This may require careful communication about the constraints and requirements of the measurement, and the form of the output. Indeed, one of the major challenges of medical photogrammetry is to provide information which is appropriate, usable and medically meaningful. Simple measurement of the object is generally not sufficient to fulfil the requirements of the medical client. Furthermore, diagrams, whether contoured plans or perspective wire frame models, are rarely of direct use to the medical practitioner as they are not likely to present any extra quantitative information beyond that which an examination of the patient would provide. Also they are difficult to interpret without some familiarity with them. In some cases, other forms of output are needed such as areas, volumes, and medical parameters. Measurement without appropriate presentation can result in a waste of the information that the photogrammetrist has extracted.
- Surprisingly perhaps, the cost of photogrammetric measurement usually needs to be kept low because the measurements are not normally crucial to saving life. Measurement can sometimes be dispensed with altogether, and replaced by a skilled surgeon with a good eye, or with simple callipers. Measurements intended for mass screening or anthropometric data collection need to have a low cost per measurement if they are to see widespread implementation.
- In comparison with many other uses of photogrammetry, the requirements of medical measurement in terms of accuracy, precision and resolution are generally low.
- The urgency with which the results need to be supplied to the client is very variable. For some clinical, and even surgical, applications it is clear that immediate results are desirable. In other cases, a slow turnaround is acceptable.

11.1.3 Development of medical photogrammetry

Throughout history, body form has been described using measurements estimated by eye or taken with tapes and callipers. Egyptian artists of 40 centuries ago developed a system of proportions, using the width of the hand as a unit, for representing human body form. These efforts at quantification were frustrated, however, because of the difficulty of obtaining direct measurements on a living human body and to the lack of a convenient three dimensional measuring system. The work of the American physician Holmes in 1863, who used stereopairs of photographs to study gait, is often quoted as the earliest application of photogrammetry in medical measurement. The measurements led to an improvement in the design of artificial limbs for amputees maimed during the American Civil War. With the turn of the century, the number of applications began to increase and diversify into many areas of medicine, but progress was slow because of the interruption of two world wars and also because the major effort was being directed into developing aerial photogrammetry which had a far greater potential.

Since the 1950s there has been more extensive development and diversification. Medical measurement has been assisted by the introduction of other imaging systems such as moiré fringe interferometry and structured light. More recently, the increasing availability of computers has enabled the introduction of analytical methods of analysis and of digital imagery. The need for photogrammetric procedures to be at the cheaper end of the cost scale demands a high level of automation. To-day, digital techniques are being increasingly utilized in a quest to increase automation, but their impact in routine work cannot yet be described as widespread.

11.2 Photogrammetry in medicine

Basic theory of close range photogrammetry has been discussed in preceding chapters. This section discusses how photogrammetric principles and practice can be utilized in medicine and outlines some of the associated problems. The primary technical concerns are the same as for other close range photogrammetric applications, but the solutions may need to be different.

11.2.1 Data acquisition

Photography

The fundamental choice in any close range application is the camera type. When this choice is being made, it must be remembered that medical photogrammetry almost invariably requires synchronized photography, because the state being measured is a dynamic one, and this increases the number of cameras that are needed. There are few static situations when a single camera can be moved to different exposure stations to obtain stereophotography. The major decision in camera selection is between film and digital cameras. However, the use of film cameras does not preclude digital data reduction because photographs can be scanned into a digital form (see section 11.2.3).

- **Film cameras** are familiar to most people and are seen as easy to use. When fine detail is required, film has few peers. Film processing can cause delays, but these can be tolerated in many applications. Usable film cameras range from the expensive metric cameras, produced specifically for photogrammetric purposes, to cheaper amateur (non-metric) types. The availability of non-metric cameras may be appealing for low accuracy, low cost applications, and in cases where photography at a high repetition rate is required, but they invariably require calibration to provide interior orientation elements. The metric cameras, which are suited to precise work, may require glass plates. They may also have fixed focusing which makes them unsuitable for very close-up photography. On the other hand, metric cameras have the advantages of small lens distortions (the parameters for which may well be provided by the manufacturer anyway), of being fitted by the manufacturer with fiducial marks, and of holding the film flat during exposure.
- **Digital cameras**, which produce images suitable for use with appropriate software on a personal computer, are now cheaply and easily obtainable. They are available in two forms. Firstly, those used in conjunction with a computer which has

been fitted with a frame-grabber board and allow direct output of a digital image file to the computer. Secondly, the so-called still video cameras which have on-board storage capacity for a number of images which can be down-loaded to a computer some time after the imaging. Cameras of the latter group are as convenient as film cameras in terms of their portability and handling characteristics. However, for medical applications with a living patient, digital cameras of the former type have the advantage that the images can be viewed immediately, before the patient moves. Accuracy requirements in medical imaging are not high by typical photogrammetric standards, and the low resolution of many digital cameras is not a handicap. Overall, digital cameras require some computer skills when handling the images. The merits and limitations of the various forms of digital cameras are covered in Chapters 3 and 5.

Once the camera type has been selected, attention must be given to various photographic matters, which depend on object size, the precision of measurement required, constraints on the camera and/or the object position, and camera availability.

- **Camera synchronization** deserves special mention for medical applications. It is usually accepted that synchronization to about 1/30 s is needed to ensure that the body does not move between images. The shutters of stereometric cameras are already synchronized to this precision. Where electronic flash is used to supplement normal room lighting, this provides a simple and precise means of synchronizing the exposures of film cameras. The shutters are opened manually, the flash fired and the shutters closed again. In some cases, however, a flash can startle patients enough to cause them to adopt a different pose to normal. The acquisition of imaging by digital cameras which are connected to a computer is usually achieved under software control, the achievable level of synchronization usually being dependent on the frame-grabber capacity.
- **Full object coverage** requires a consideration of the camera's focal length and image frame size, in conjunction with considerations of adequate stereoscopic overlap, appropriate camera-to-object distance and suitable base-to-object distance ratio (all of which influence the achievable accuracy and precision). In most cases, the camera-to-object distance will be between 0.25 m and 5 m. Stereometric cameras, provided on a fixed base by photogrammetric instrument manufacturers, will often be found to be very suitable. Those with stable geometry simulating the 'normal' case of photography allow for simplicity in later analysis, but those with a variable geometry are rather more versatile. The all-round coverage required in some studies, such as for the entire torso or the head, may require that images be obtained in several directions, using an array of synchronized cameras. Alternatively, coverage may be achieved in some cases through the use of mirrors, which simplifies synchronization. Medical imaging will generally not be done at infinity focus settings. Consequently, obtaining a suitable depth of field can be difficult, and the principal distance of the lens used during data reduction will not be equal to the focal length.
- **Image resolution**, which is basically a function of emulsion grain size, or pixel

size in digital images, has an influence on the achievable accuracy and precision. Image resolution should be kept as high as possible, therefore, when high accuracies are required.

Control

Control serves the same purpose in medical photogrammetry as in other close range applications, that is to assist with absolute orientation of the three dimensional model. However, orienting the model to a particular co-ordinate system is often not needed in medical work and scale is usually the only absolute quantity needed. Accordingly, control points can be avoided in many applications.

There are nevertheless some cases where a patient co-ordinate system is necessary, notably when comparative measurements over a period of time are needed, or when comparison between a number of patients is desired. These arise, for example, when collecting anthropometric data on the distribution of shapes, in the scrutiny of deteriorating conditions, and in monitoring the progress of treatment. Absolute orientation methods used in individual applications are mentioned in section 11.3, but it should be noted that frequently there are medical constraints to control placement. In particular, there are few natural detail points on the body to serve as control. Furthermore, the placement of permanent control points on patients is rarely feasible. Not only can the patient grow and otherwise move, so that the entire point of having the control is lost, but, more importantly, permanent markings, by tattoos or other skin markings, are normally unacceptable. In just a few cases, some permanent features of the body, such as the eye-base, can be utilized to ensure consistent scaling for comparisons of a patient at different times. In other cases, a framework of control points around the patient has been resorted to, with a fixed relationship between the patient and the frame being provided by connections, such as rods into the ears. Use can sometimes be made of blemishes on the skin, such as moles and warts.

Some photogrammetrists have tried to avoid the need for control altogether where comparative measurements are to be made. To assess changes in the shape brought about by facial surgery, Coombes *et al.* (1990) have matched facial shape parameters. Of greater interest is the matching of surface shapes via a least squares solution. Karras and Petsa (1993) have successfully applied surface shape matching to a number of comparative studies including the changing shape of the abdomen during pregnancy.

No matter whether control is used or not, or whether equipment is calibrated or not, it is crucial that the accuracy of the photogrammetric output be carefully assessed, so that accuracy levels can be quoted with confidence. Results provided to the client, even without a specific accuracy level, will have an implied accuracy, which may not be realistic. It is also important to remember that the internal precision of results is not a true indicator of accuracy.

11.2.2 Object preparation

Object preparation is as necessary for medical photogrammetry as it is for other close range applications. There are two cases to consider:

- those applications for which targets are needed, i.e. when specific body points are to be located.

- those applications involving general surface shape measurement based on a random network of points.

Targets may be utilized when anatomically relevant points are to be located, as is often the case in spinal shape detection. Generally, however, target placement requires the involvement of surgeons or other medically trained personnel, and this raises logistical and cost considerations. The selection of suitable targets is an important consideration for the photogrammetrist. Targets may be either passive (reflective) or active (light emitting). Highly reflective targets (usually retro-reflectors) are popular in medical photogrammetry since active targets, which require wiring, can constrain the poses adopted by the patient. Dynamic studies create additional targeting problems which are mentioned again below.

Skin, especially that of younger children and babies, often appears on an image with a uniform, low contrast, and hence it usually needs artificial texturization. This is commonly achieved by the projection of patterns on to the skin. On darker skin, laser light may be necessary. Powder has also been used to add texture. Waldhäusl *et al.* (1990) have used ultraviolet filters to obtain contrasting texture from areas of skin high in melanin, in conjunction with a double flash to avoid shadows. Although placing an extensive array of targets can compensate for a lack of texture, such a procedure is usually too laborious and is rarely feasible. Colour photography is normally beneficial but orthochromatic emulsions and ultraviolet light can also be employed to good effect in overcoming this problem.

11.2.3 Data reduction

The method of data reduction which is adopted depends on a combination of factors such as the data acquisition system used, the accuracy required, and the type and amount of data needed, as well as the equipment available.

The primary choice is between film-based and digital image-based processing. The latter is attractive because it offers a level of automation, without which many medical photogrammetry tasks may be labour intensive. It should be noted that digitizing film photographs and subsequent digital processing is an option which overcomes the disadvantages that most digital cameras have of limited resolution, unless the greater expense of high resolution, micro-scanning or macro-scanning digital cameras can be tolerated.

Analogue

The techniques of analogue photogrammetry are not repeated here, as their use for medical applications follow the well established procedures, but some special medical considerations will be mentioned. Analogue techniques are labour intensive, and the detail and accuracy attainable by these methods are often unnecessarily high for medical work. So, although analogue photogrammetric instruments are widely available, they are little used for routine medical measurement. More importantly, analogue instruments are not always able to cope with the large camera tilts used, nor with those cameras, especially small format non-metric cameras, which have non-negligible lens distortion and/or non-standard focal length lenses. Those analogue instruments based on mechanical projection are generally preferred since they can cope with a range of

camera principal distance settings. The analogue approach is most suitable for use with metric photography and is most applicable if direct plotting of plan and contours is needed.

Analytical

The relevant considerations for analytical photogrammetry, whether using analytical plotters or comparators, are much the same as they are for analogue photogrammetry, but analytical methods are better able to cope with large tilts, lens distortions, unusual focal lengths, and imagery which does not conform to the central perspective projection. These methods produce a set of three dimensional co-ordinates and these are normally fed into CAD systems for editing and plotting out. Analytical methods offer higher accuracy, numerical and digital output and are widely replacing analogue techniques.

Digital

Digital techniques mean that partial automation is often feasible, and full automation is possible in certain cases. Completely automated processing is usually possible where the topography of the medically relevant surface is simple, giving high speed processing and almost immediate results. It is also feasible when comparatively low precisions and accuracies are required, as is often the case for medical work. However, the limitation to digital processing, in many cases, is the need to develop special systems. Commercially available digital photogrammetric workstation equipment is not always suited for close range work particularly if the surface is convoluted. Digital hardware and software systems which offer fully automated digital processing are commercially available for a small number of particular medical purposes (see section 11.3), but they can be expensive. For other purposes, systems may need to be custom made, so digital processing may seem to be disadvantageous to the photogrammetrist when compared to the comparative ease of using film-based analogue or analytical techniques. The advantages and disadvantages of digital systems in medical applications are discussed by Gordon (1992).

The theory of digital image processing in order to carry out image matching is covered in Chapters 3, 5 and 8, and is not expanded upon here.

11.3 Applications

Many hundreds of applications of medical photogrammetry have been published and these extend into many different fields and use many techniques. It is impossible to review all of these in a single chapter and it will only be possible to refer to a small number of typical and instructive applications in each main area. For a more extensive bibliography, the reader is referred to the *International Archives of Photogrammetry and Remote Sensing*, particularly those volumes related to the work of Commission V of the International Society of Photogrammetry and Remote Sensing (ISPRS). The proceedings of various medical symposia, especially the Biostereometrics symposia published by the International Society for Optical Engineering (SPIE), are a useful source of information. Readers seeking overviews of medical photogrammetry are referred to Newton (1980) and Sheffer and Herron (1989), both of which contain useful bibliographies.

11.3.1 Measurement of body form (anthropometrics)

Measurement of body form finds a wide variety of applications. It typically involves surface measurement, as opposed to the measurement of pre-targeted points.

Whole body, trunk and limbs

Measurements of the entire body, the trunk and limbs are useful for studies of body mass or fat distribution, and consequently the photogrammetrist working in this field may find it necessary to incorporate the required calculations of volumes, moments of inertia and so on into the measurement procedures. Photogrammetric measurement is generally more reliable and more accurate than the alternative means of measuring the body and limbs. The common photogrammetric challenge in these investigations is to provide complete all round coverage. This is often achieved by using multiple cameras or sometimes by using mirrors, but once established the photogrammetric procedures are quite straightforward.

Productive early work on the measurement of the whole body was carried out in the USA. Hugg (1974) photographed the front and back of patients simultaneously using two stereometric cameras. The patient stood between two stands which provided control to permit the two stereomodels to be joined together. Electronic strobe projectors, one mounted between each pair of cameras, and synchronized with the camera shutters, projected a random pattern to add texture to the patient's skin. Cross-sections were measured, from which areas, volumes and surface areas could be determined, and distributions of surface area and volume with height obtained.

An instructive example of the use of mirrors to provide all round photography is given by Kratky (1975b). Two mirrors were placed a little behind the subject, one covering the left rear side and one the right rear side (Figure 11.1). Photography with a single pair of cameras from the front of the subject not only permitted coverage of the front of the object, but also provided stereoscopic views of the object in any of the mirrors. Kratky, and others, have used such an arrangement to measure limbs and limb remnants as part of a procedure for the machining and fitting of artificial limbs.

Wong *et al.* (1992) have employed fully digital photogrammetric methods for studies of growth and the distribution of body fat as needed by specialists in body motion. To obtain full coverage, a total of nine digital cameras were grouped in three triplets, each triplet of cameras being arranged in a triangle 2 m away from the patient. To obtain full stereoscopic coverage of the entire patient, six different poses were adopted. Areas, volumes, and circumferences could be computed.

Back

The back is a suitable surface for photogrammetric recording, as two cameras are normally sufficient to provide coverage and the undulations of the back are not too complex for photogrammetric recording. Moreover, although the most useful spinal measurements are achieved by internal imaging systems (see section 11.4.4), the disadvantages of these systems leaves scope for photogrammetric measurement. However, these same considerations also make the back amenable to measurement by other optical techniques (see sections 11.4.1 and 11.4.2).

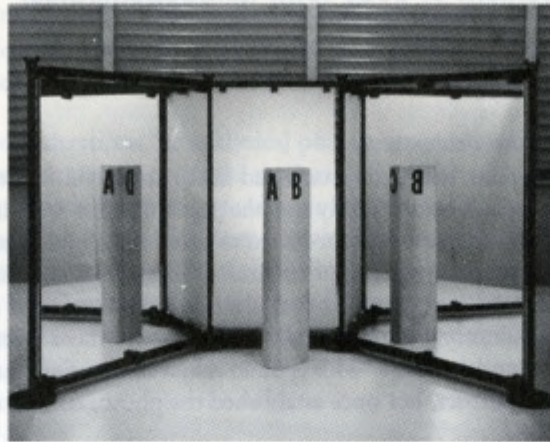


Figure 11.1 The use of mirrors to obtain all round photography of an object, from Kratky (1975b).

The dominant applications for back measurement relate to scoliotic spinal deformities where the measurements are useful for detecting the condition (sometimes by mass screening among the adolescent population), for observing any deterioration in individuals, and for monitoring the progress of treatment. In some cases, full back surface shape may be wanted, especially for cosmetic considerations. In other cases, spinal shape parameters (e.g. Cobb angles of the spine) may be required, in which case targets at medically relevant anatomical points are normally utilized. Hierholzer and Drerup (1989) have been able to provide spinal curvature parameters of the back shape itself.

The need for ergonomic studies on helicopter pilots was the basis for the analytical measurements of the back reported by Gäbel *et al.* (1992). These were undertaken using Rolleiflex cameras, a projected grid and the Rollei MR2 system for data reduction.

Digital techniques are also now being utilised for back shape measurement. Two examples of digital systems under development are given by Peterson *et al.* (1993) and Mitchell (1994). Both systems are intended for scoliosis monitoring and use digital recording cameras at distances of 1.6–2 m from the patient, with a cast texture of a grid pattern or dots. Area based least squares matching on personal computers has been used by Mitchell, who reports precisions at the 1 mm level. The problems of providing appropriate output from fully digital back measurement are discussed by Trinder *et al.* (1994). The commercially available AUSCAN system utilizes digital processing of measurements of reflective targets placed on anatomically important points, lit by strobe lighting and simultaneously imaged with four anterior and posterior CCD cameras. The software then provides numerous spinal shape parameters (d'Amico *et al.*, 1995a).

Head, face and jaw

The face is easily distorted when touched, and some areas, such as around the eyes, are especially sensitive. Consequently, many medical photogrammetric studies have tackled facial measurement. Indeed, photogrammetric measurement has been used for the

face more than on any other part of the body, and there are continuing prospects for extensive routine usage to aid maxillofacial and oral surgeons. Measurements are now typically undertaken with the aim of contributing to the planning of surgical reconstruction involving the skull or jaw, necessitated by injury or by abnormality, if it affects eating effectiveness or appearance. Facial measurement can also contribute to the monitoring of progress after surgical re-shaping, and even detecting possible regression, as well as being useful for observing swelling from more minor, especially dental, procedures. Vivid and lifelike computer graphics output is often desirable, preferably in a form which can be shown to patients with lips, eyes, eyebrows, and in some cases hair, shown. Often this is in conjunction with a depiction of the altered facial form (Linney *et al.*, 1990). The significance of the subtleties of the face generally demands a high accuracy of measurement. The face also has a lot of curvature, especially around the nose, and full coverage of the face may require more than one stereopair otherwise the precision of stereoscopic matching can vary with location on the face. Some applications may also require that the soft tissue position be related to the skull through radiographs. Photogrammetric procedures do not always achieve these aims easily, but it can be crucial to do so if photogrammetry is to be fully acceptable.

Work by Björn *et al.* (1954) illustrates the problem of repositioning the patient for comparative measurements. To chart post-operative facial swelling over time following the removal of molar teeth, a stereometric camera and plotter were utilized with the patient being repositioned using a specially designed cephalostat attached to the external auditory meati plus a nose and neck support and an incisal pin. Face models were described in terms of contours from which volumes were deduced. MacGregor *et al.* (1971) have also employed a special cephalostat in their work to measure facial volume changes following the loss of teeth. Here acrylic pieces, made to fit the ears and nose of the individual patients, were used to fix them into the cephalostat at each photographic sitting. Tests on the repeatability of this and other systems have been reported by Newton (1974).

Facial measurement has also been carried out by Burke and Beard (Burke and Beard, 1967; Burke, 1971) in relation to a number of orthodontic studies. Concerned by the high cost of photogrammetric equipment, these workers developed a simple camera/plotter system based on a pair of Multiplex projectors which were adapted to allow photography. The light projection housings of the projectors were replaced with lightproof film cassettes to photograph a patient lying on a table, facing up toward the cameras, and with a reference frame around the head. After processing, the film was repositioned in the same projectors to allow the anaglyph formation of a life size, three dimensional model of the patient's face. A portable version of this system (Figure 11.2) was also produced which allowed the patient to be seated at the time of photography, and for photography and measurement to be carried out at any location (Beard and Dale, 1976).

Experiments in fully digital facial measurement have been reported by Grün and Baltsavias (1989), Deacon *et al.* (1991), Banda *et al.* (1992) and Urquhart and Siebert (1993), using from two to four digital imaging cameras. All used cast texture, but of different types: vertical lines, dot patterns, square grid, and random points. Various output is possible from their systems, including contours, perspective views of wire-

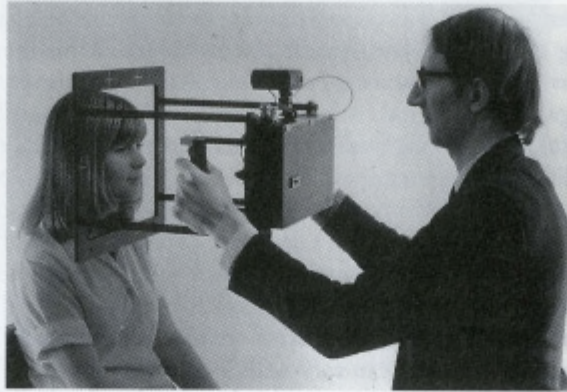


Figure 11.2 Photographing a patient with a Multiplex-based stereocamera.

frame models, shaded figures, draped models and stereopairs on a screen. The capability of such approaches to record subtle facial detail is demonstrated in Figure 11.3.

Feet

Measurement of the foot can be useful in orthopaedic studies (e.g. Newton and Craxford, 1982) or to enable lasts to be moulded to permit appropriate shoes to be made for abnormal feet (e.g. Gordon, 1992). The main photogrammetric difficulty is to obtain all round coverage. Sometimes the underside of the foot must be included which may cause difficulties. In a study of the static foot under load, Newton and Craxford (1982)

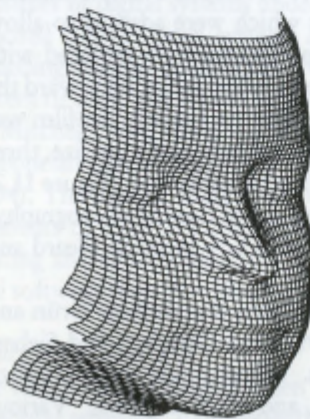


Figure 11.3 Perspective view of wireframe face model from fully digital processing, showing fine lip and eye detail obtainable using area-based image matching and low resolution images, from Grün and Baltsavias (1989).

utilized impressions in expanded polyethylene foam, which were then photographed with a stereometric camera.

11.3.2 *Palate and teeth*

Although small and somewhat inaccessible, the palate and teeth have nevertheless been the subject of numerous photogrammetric measurements to assist dental studies and treatment. Chadwick (1992) provides a review and discussion of photogrammetric measurements in dental research applications including assessments of wear on artificial dentures, temporary restorations and restorative materials, and measurements of the palate.

While some tooth measurements have been obtained from photographs taken inside the mouth, the problem of access to the teeth is more usually overcome using casts. A variety of photogrammetric approaches has been used, including both metric and non-metric cameras, and both analogue and analytical plotters. Accuracies of 10 μm have been achieved. Convergent camera axes have been used to photograph inside the mouth, but in the more common situation when casts are used, stereoscopic overlap has been achieved by translating the cast a small distance under a single camera. The added complication of a microscope was faced by Chadwick *et al.* (1991) who rotated the microscope's upper body between exposures, enabling photography along each of the microscope's axes. A major difficulty with measurement of teeth in dental materials research is to find or establish control which permits positions to be recovered. This problem has to be faced not only with photogrammetry but with other measurement techniques too.

Palatal measurements have invariably been based on casts. The casts of normal and abnormal palates have been photogrammetrically analysed by Berkowitz (1971) and Newton and Evans (1976). Achilli *et al.* (1992) used palatal casts and analytical techniques to study the effect of a rapid palatal expansion device placed in the mouth. Photogrammetric measurement in this work has made it possible to analyse the size and shape of the palate in far greater detail than hitherto.

11.3.3 *Eye*

The uses of photogrammetry in ophthalmology relate mainly to measurement of the optic disc and the detection and treatment of eye diseases and visual disorders. Specific applications include the measurement of keratoconus, exophthalmos (Backlund and Torlegård, 1968), glaucoma (ffytche *et al.*, 1973; Takamoto and Schwartz, 1986), and for contact lens fabrication and verification (Banda and Muller, 1990).

In those applications where photography takes place through the eye, two optical media are involved and the geometry becomes complex. Prior to photography, it is necessary to paralyse accommodation of the eye using drugs which dilate the pupil (and which have the added benefit of reducing the tendency to blink). Normal cameras are of little use and the photographs are obtained using a special ophthalmic instrument, such as a photoslit lamp or fundus camera. Stereopairs are produced by translating the camera between exposures if the patient can be kept still. As an alternative, image splitting attachments can be used with a single exposure. Data reduction has been

carried out using simple parallax measuring instruments, analogue stereoplotters and analytical plotters, the latter giving better accuracies through rigorous modelling. For a more complete discussion see Kratky (1975a).

Monitoring the shape of the cornea, to assist in surgical management during reconstructive surgery and to provide information for the making of contact lenses, has been undertaken by Banda and Muller (1990). A Zeiss stereoscopic keratoscope was adapted to take two 35 mm non-metric cameras. The tear film was stained with orange fluorescein and an illuminated grid was projected on to the eye through a blue filter. The fluorescein gave a greenish-yellow glow which could then be photographed through a yellow filter to record only the green light. Three dimensional co-ordinates were found by image matching on digitised negatives.

In spite of the difficulties, photogrammetry provides the ophthalmologist with a measurement technique giving a better accuracy than the alternative methods.

11.3.4 Four dimensional studies

Studies of patient changes with time are often useful, and the major application areas relate to motion, growth, deformation and respiration. Studies of changes over time normally require the use either of targeted points or of some form of control which enables corresponding points on the object surface to be identified. The provision and recovery of suitable control can be a significant difficulty to the photogrammetrist, especially if the control framework is external to the patient who must be placed in the same position with respect to the framework.

Motion

Dynamic studies of movements of the human body are useful 'to understand the general rules underlying human movement ... [and] ... for an early diagnosis and therapy in motor disorders' (Ferrigno *et al.*, 1990). Motion analyses can also be useful in the design

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      EF:1      2-SEP-1983 10 00 41
      FRAME 1 TO 33. STEP 1. MODE 5. SPREAD 0.000. 0.000
      PLOT OPTION 7
  
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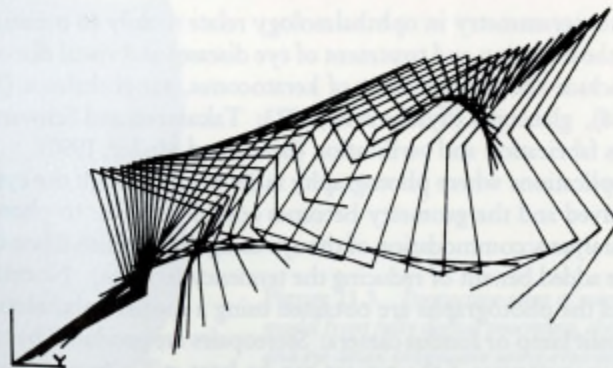


Figure 11.4 Stick figures depicting an athlete's start, from Macleod (1986).

of prostheses and ergonomically acceptable industrial equipment, and as an aid in sports studies. Demand for photogrammetric measurement for gait and other movement analyses is high, as there are few alternatives which can match photogrammetry at providing useful data.

Primarily, motion studies require imagery at high repetition rates. They also demand full coverage of the moving person, which usually necessitates multiple cameras. Measurements are typically based on strategically placed targets, which may be obscured at various stages of the movement, making their location and identification a difficult task. In early research, ciné cameras were used, sometimes with three cameras to obtain views from above, in front of and from the side of patients, but digital systems are now better able to cope with high data collection rates and complex analysis of multi-target positions. Digital data processing involved in a gait analysis system is described by Ferrigno *et al.* (1990). Reflective targets, varying in size from 1 mm to 8 mm depending on object distance, are lit by strobe lighting and imaged with shuttered analogue TV cameras. Targets can be detected by correlation with a 6×6 pixel template, but their positive identification involves reference not only to their size and shape but also to a movement model which anticipates their concealment.

A number of fully digital photogrammetric measurement systems are available commercially for motion analysis. They typically use retroreflective targets, lit by strobe lighting synchronized with the cameras, and high frequency recording rates. Digital data reduction is typically based on pattern recognition to locate targets, rather than image correlation to find corresponding points. Graphic display of the output, usually in the form of moving stick figures of body points in motion, and depicting rotations as well as translations of joints, is offered by such systems (Figure 11.4). Because the positional results are often used in combination with data from other devices, a combination of photogrammetric results with output from foot pressure plates and/or from inserted electromyograph (EMG) probes sensing electrical potential is also a typical feature. Descriptions of a number of commercial systems has been provided by a manufacturers' symposium on image-based motion measurement (Walton, 1990). The VICON clinical gait analysis range (Macleod *et al.*, 1990) is an example based on digital close range photogrammetry. It uses mass-market video cameras and spherical retroreflective targets illuminated by infrared strobe lighting, at frame rates up to 200 Hz. Apparent targets are first detected by thresholding images, and then located by fitting circles to edges (rather than by centroiding) to a claimed sub-millimetre accuracy. The system may accept input from pressure plates and EMG probes.

Growth

A useful example of growth studies based on photogrammetrically collected data is provided by Burke and Beard (1979) who carried out an extensive long term study into growth of the face during adolescence. Annual measurements were carried out on a group of 26 like-sexed twins, with an even sex distribution. Growth was deduced from distances derived from the three dimensional co-ordinates of natural facial 'landmarks', such as the outer canthus, inner canthus and tip of the nose. The study produced estimates of bilateral differences, sex differences and the pattern of changes in the face during growth.

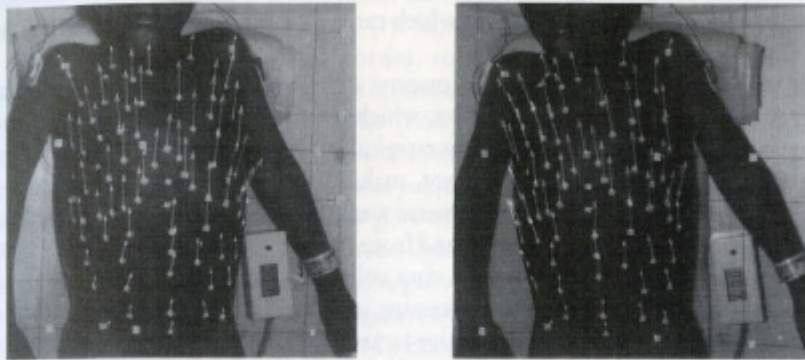


Figure 11.5 Stereoscopic vectors portraying displacements in three dimensions. (This figure may be viewed stereoscopically using a pocket stereoscope.)

Deformation

Deformation measurements have mostly related to the spine. Miskin (1956) monitored distortion of the spine during pregnancy. Hugg *et al.* (1971) have studied deformation of the spine in scoliotic patients by using front and rear view contour plots to exhibit any asymmetry and abnormality. Karras and Petsa (1993) have also carried out comparative studies including the changing shape of the abdomen during pregnancy.

Respiration

An extensive study of respiration using photogrammetry to record changes in the trunk has been carried out by Kováts *et al.* (1989). A grid was projected onto the body, which was photographed every second during the breathing cycle. Several photographic arrangements were used including a pair of cameras and a single camera with a mirror.

Adams and Klein (1986) have measured the movement of targeted points on the chests of small children during the breathing cycle, using non-metric cameras and a stereocomparator. Later, Adams *et al.* (1989) proposed a fully digital photogrammetric system for the same purpose and its use was reported by Adams and Tregidga (1992). Because contours or perspective views of the displacements are hard to interpret, Adams and his co-workers have created stereoscopic representations of the displacement vectors. These are most useful if superimposed on to stereophotographs, so that the displacements can be related to the chest structure (Figure 11.5).

11.4 Applications of other forms of imagery in medicine

In any discussion which concerns itself with photogrammetric measurement in medicine, it is important to realize that the medical profession now has access to an enormous range of competing imaging and measuring systems. Some are of interest to the

photogrammetrist because they can be used for the same sorts of tasks as photogrammetry. Others are of interest because they use similar principles and techniques. In this section, some of the more important of these measurement systems are outlined. They are conveniently divided into two categories:

- systems which are used, as photogrammetry is, to measure the various *external* surfaces of the body.
- *internal* measurement systems, which 'look' inside the human body.

Of most interest to photogrammetrists are the external measurement systems which are based on optical principles, and which therefore usually have a lot in common with photogrammetry. Indeed, most of them use a camera to record the results.

11.4.1 *Light sectioning*

One technique which has more in common with photogrammetry than do most other techniques is that which uses 'structured light'. In its simplest form, it involves the use of a projector and a camera, rather than the two cameras as in simple photogrammetry. The projector is used to cast a pattern onto the object, which is then photographed, or otherwise imaged, from another point. Clearly, the projector is equivalent to the second camera used in photogrammetry, and similar principles of light ray intersections define the position of the point in space. Any point of light projected in a known direction by the projector and identified on the photograph can now be positioned in three dimensions. The determination of three dimensional position involves the intersection of light rays by analogue or analytical reconstruction of the camera/projector relationship, so considerations of lens distortions and principal point positions (for the cameras and projectors), point identification and so on, are the same as in photogrammetry. Securing certain orientations can simplify the processing and with a simple camera/projector relationship three dimensional co-ordinates are easily deduced. In practice, more than one camera or projector is often used and various types of light pattern, ranging from a single point to a series of parallel lines, are projected on to the object. With a single spot or single line, the image position is easily identified immediately, which is a great advantage with digital processing, and the position is easily deduced. But the disadvantage for medical applications is the length of time needed to move the spot or line around the relevant medical surface. Projection of a series of parallel lines is often preferred but now the line identification problem has to be faced. This is possible by projecting a unique pattern of light and heavy lines as shown in Figure 11.6.

Structured light techniques are amenable to digital methods and the simple image processing allows high speed results. Because the technique is best suited to simple surfaces where cast lines are not interrupted, it finds its widest medical application in the measurement of backs. A noteworthy example of successful usage is provided by the commercially offered ISIS system (Turner-Smith, 1988), of which a number of units have been sold. Another important automated measurement system is that using video rasterstereography, as described by Frobin and Hierholzer (1991), which is now commercially available as the Formetric system from Jenoptik (formerly Zeiss), Jena. Other automated systems are described by Elad and Einav (1990) and Bae and Altschuler (1990).

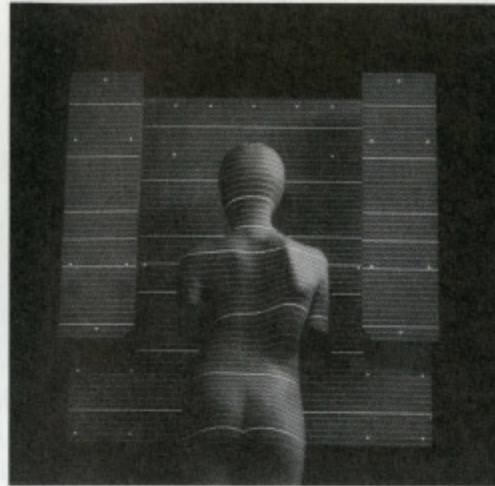


Figure 11.6 A structured light image, from Hierholzer (1989).

Dynamic studies of movement of the trunk during breathing have been attempted using a structured light system by Duffy *et al.* (1990).

A more complete discussion of structured light methods is given by Hierholzer (1989).

11.4.2 Moiré topography

Interference patterns which are created by the superimposition of two similar patterns in slightly different positions have been used to great effect in some medical surface studies, particularly in relation to the back. With a suitable choice of light and grating geometry, the fringe pattern appearing on the surface will represent 'contours' at known levels.

The fringes, known as moiré fringes, can be created in two ways – by the shadow moiré technique and the projection moiré technique. In both cases, a grating of parallel lines is used. Figure 11.7 shows an example of the interference fringes produced.

The moiré method is well suited for use by a medical practitioner. It is convenient and safe, and interpretation of the photographs is relatively simple. Moreover, no costly equipment is required beyond just one camera, a grating and a light source. Posing of the patient is straightforward since the fringes are visible and the patient can be rotated relative to the grating until a satisfactory orientation and fringe pattern is achieved.

The method can be used to obtain quantitative information, but in order to do this it is necessary to order the contours and determine the direction of the spacing. Also the contour interval is not constant when using a simple point source and this limits the accuracy of the method. Some attempts have been made to automate the procedures (e.g. Neugebauer and Windischbauer, 1995).

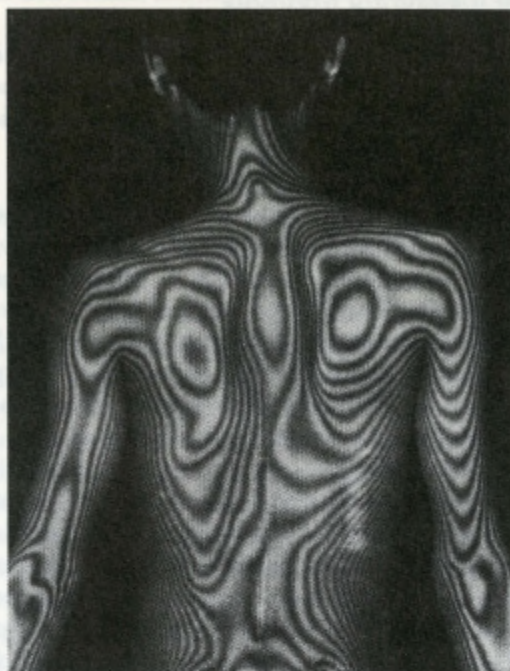


Figure 11.7 Example of moiré interference fringes, from Kanazawa *et al.* (1975).

The moiré technique is well suited to mass screening work as well as clinical studies. Adair *et al.* (1977) and Neugebauer and Windischbauer (1995) have used the technique successfully in mass screening of children for scoliosis. Suzuki *et al.* (1995) have defended the use of the moiré techniques as a clinical tool in scoliosis studies, and Kanazawa *et al.* (1975) have evaluated the effects of surgery on scoliotic patients through before and after moiré patterns. Terada and Kanazawa (1974) have recorded, using video, movement of the fringes on the torso resulting from arm movement and on the face during mastication.

Further information on moiré topography can be found in Pekelsky and van Wijk (1989).

11.4.3 Hologrammetry

Some attempts have been made to use holography for medical measurement, e.g. Mikhail (1974). However, its use does not seem to be widespread, probably because of the sensitivity of the method to movement, the need for elaborate apparatus, and the limitations on the size of objects which can be measured. Moreover, after production of the hologram, measurement on it to produce three dimensional co-ordinates is then necessary. All these matters make the method unsuitable for widespread clinical use.

11.4.4 Internal measuring methods

Health and medical workers have access to a wide range of internal imaging and measurement systems. Many have little relevance to the photogrammetrist, but a small number of them are of interest because of the growing use of digital image technologies similar to those used in digital photogrammetry.

- **Radiography:** Radiographic techniques are of interest to photogrammetrists not only because of the growing use of digital (or digitized) X-ray images and hence of digital image processing (e.g. d'Amico *et al.*, 1995b and Ross *et al.*, 1995), but also because of the use of stereoscopic methods (e.g. Merolli *et al.*, 1995). X-ray projections are equivalent to those taken with cameras with longer principal distances than the distance between the object and radiographic machine suggests. Once taken, the stereoradiographs may be evaluated according to established photogrammetric procedures. Further information on X-ray methodologies is given by Veress (1989).
- **Computed tomography:** A three dimensional model of the internal structure of part of the human body can be built up using multiple recordings from a narrow beam X-ray projected from various points and in many directions through the given region of the body. The attenuation of the radiation level along each path is indicated by a radiation detector rather than by a record on photographic film. Complicated integration of the signals received at all detector points enables a three dimensional model of densities at points within a given volume to be deduced. The procedure, now widely used in medicine, is variously known as *computed tomography (CT)* or *computerized axial tomography (CAT) scanning*. It is of interest to medical photogrammetrists because of its ability to produce three dimensional information, but it is not a technique which photogrammetrists themselves can expect to utilize.
- **Magnetic resonance imaging (MRI)** (also called *nuclear magnetic resonance imaging* or *NMR imaging*) is used to compile detailed models of the three dimensional molecular structure within a living body in a tomographical procedure not unlike CAT scanning with X-rays. However, MRI utilises the phenomenon that individual nuclei in certain elements act like small magnets and can precess when under the influence of a strong magnetic field. Under the influence of a weak radio field applied simultaneously with the magnetic field, the precessing nuclei can resonate, absorbing energy from the radio field. Different elements absorb different amounts of energy, and information is provided from measurement of attenuations of the radio transmission. The procedure is claimed to be hazard free, but the procedure is slow and expensive.

11.5 Conclusions

The applications reviewed indicate that photogrammetry is an effective medical measurement tool which has a number of advantages over alternative methods. These include the following:

- the method is non-contact and hence it avoids distorting, hurting or infecting the patient.
- data collection is quick, and movement of the patient is overcome even in dynamic situations.
- data collection is convenient for the patient and medical practitioner with data processing being carried out as a separate operation.
- a permanent image record is provided which may be consulted and remeasured at any time in the future.
- recording in wavelengths outside the normal visible range can reveal conditions not apparent otherwise.

Despite its appeal, the implementation of photogrammetry in medicine is not always straightforward. Only a few fully developed systems are available commercially, mainly for dynamics analysis and back shape measurement, and it is often necessary to develop a special system for each application. This is a matter of applying basic photogrammetric techniques to medical situations but with some adaptation. It entails obtaining suitable equipment and/or processing software to suit the special needs of the application. Multiple cameras need to be obtained, control and/or calibration arranged and access to a data reduction system organised. Potential difficulties, such as the requirement to obtain all round coverage and imagery with good skin contrast, also need to be resolved. Further, the photogrammetrist will need to feel comfortable working with human patients and medical practitioners in unfamiliar surroundings.

If these constraints can be overcome, there are few alternatives to photogrammetry in many cases of external measurement in medicine and because of this photogrammetry has been widely investigated as a tool for medical measurement over the past century and a large number of papers have been produced. However, only a small percentage of the applications have resulted in routine usage and there are very few medical institutions and related health units that use photogrammetry. Thus, the real impact of medical photogrammetry on the world seems quite limited. There has been a lot of development but not much clinical or surgical application and a certain amount of wastage of effort. Newton (1980) commented that *'The present situation of medical photogrammetry appears as a highly contradictory one. Although almost every researcher in this field has recognised the immense capabilities and usefulness of photogrammetry, the technique has remained largely experimental and is still far from being introduced into routine medical procedures.'* This concern still has some validity in the 1990s and it would be encouraging to see photogrammetry being more widely utilized for medical measurement purposes. However, it must be recognized that there are different types of developments in medical photogrammetry. Some are one-off projects, which are not viable commercial activities nor intended for wider implementation, carried out as legitimate and productive academic research. On the other hand, some developments are clearly intended for wider and even routine usage. On the positive side, there has been a number of noteworthy, successful implementations of photogrammetry and even some significant commercial developments.

The future will undoubtedly see photogrammetry facing increasing competition in some applications from alternative, usually optical, measurement techniques. As a re-

sult, automation through the use of digital techniques and the provision of medically meaningful output could be crucial issues for further acceptance of photogrammetric procedures. Photogrammetrists interested in medical measurement would be well advised to give these issues a high priority.

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Close Range Photogrammetry and Machine Vision

edited by

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Department of Photogrammetry and Surveying
University College London

Whittles Publishing



Typeset by
Whittles Publishing Services

Published by
Whittles Publishing,
Roseleigh House,
Latheronwheel,
Caithness, KW5 6DW,
Scotland, UK

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ISBN 1-870325-46-X

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Printed by J.W. Arrowsmith Ltd., Bristol