USE OF PHOTOGRAMMETRY IN ORTHOPEDICS AND SURGERY

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Abstract

The orthopedic department of the Basle Children's Hospital (Switzerland) has for a number of years carried out kinematic studies on patients. These also call for static analysis, for which volumes, areas, profiles etc have to be determined. These data are then used as the basis for computing axes of rotation, torque etc of the whole of a patient's body or of various body segments.

In a further medical speciality, oral surgery, the problem of a structural analysis also arises, but in this case it is limited to the maxillo-facial region. The oral surgery clinic of the Zurich University Hospital (Switzerland) deals with pre- and post-operative deformations. The computation of volume, areas and profiles is also of great importance here.

Various techniques used in surveying have for a long time been concerned with these problems, such as Moiré photography, radiography, raster photogrammetry, etc.

At the request of these two institutions, Wild Heerbrugg Ltd have carried out a joint pilot project for which photogrammetry was chosen as the means of solving the problem. The aim of this project was to devise a system which would be both economic and easy to use, and which standardizes the whole process from photograph to restitution to such an extent that a maximum number of patients can be examined in a minimum of time and at minimum cost in material.

1 Introduction

In medicine, photogrammetric techniques have been used for some time, covering both photography and restitution (Herron, 1972; Herron and Karara, 1974; Eriksson et al, 1979; Oestman, 1981; Ghosh, 1983 etc). With a few recent exceptions, analog instruments have been used for restitution in all this work.

But since computer-supported plotting instruments have established themselves as a standard tool in photogrammetric practice, and both system and application software has reached a very high level of development, numerical photogrammetry can also be used efficiently in this field.

The Department of Oral Surgery of the University Hospital Zurich (UHZ) and the Orthopedic Department of the Children's Hospital Basle (CHB) expressed to Wild Heerbrugg Ltd their wish to utilize modern photographic, restitution and data-acquisition techniques as used in photogrammetry for their specific applications. Whilst the point of departure as defined by these two hospitals is not identical, the decision was made to carry out a joint project between UHZ, CHB and Wild. Three main stages were agreed:

a: In the first stage, the photographic conditions should be studied and specifications defined for carrying out the photographic work in the light of accuracy obtainable and instruments available. For reasons of cost, it was decided to try and use existing camera systems and simulate exposure conditions.

b: The photographs produced were restituted in phase b, using conventional photogrammetric restitution methods. The accuracy and practical relevance of the results were analyzed and discussed in detail. Here as in phase a, the aim was to use existing hardware and software components as far as possible.

c: The third stage is devoted to processing the data obtained.

The first two stages were carried out by Wild and the last by CHB and UHZ. To ensure a troublefree transition to phase c and simplify data processing which would be undertaken both elsewhere and at different points in time, a software interface was accurately determined. In this were defined not only the type of data to be recorded but also the specifications for data transfer between the second and third stages.

This paper reports on the first two stages of the project and the know-how obtained in the process. It presents for discussion the results obtained.

2 The CHB/UHZ/Wild pilot project

The purpose of this project is to design a complete system for photography, restitution and data processing that will be suitable for installation in hospitals. Its aim is not merely to try to use photogrammetry successfully in medicine, but to provide proof that photogrammetry can be used in daily medical practice at little cost in time and money, and without requiring specially trained staff.

As a first step, it was decided to carry out two independent benchmark tests for Basle and Zurich respectively, in order to familiarize photogrammetry with medical problems and to acquaint medicine with the methodology used in photogrammetry. These tests were carried out by Wild on the basis of specifications prepared by Basle and Zurich. The results of these benchmark tests are being evaluated by physicians and their assessment will decisively affect the design of the complete system.

For greater clarity, the two benchmark tests are described separately below.

3 Equipment used

The following hardware and software components were used in this project:

The Wild P32 terrestrial camera was used for the photographs, refocused for close-range work. Refocusing was achieved with adapter rings, which together with the requisite calculations were made in Heerbrugg.

Restitution of the photographs was done in Heerbrugg, using the AVIOLYT AC1/AVIOTAB TA2 analytical stereoplotting system (Kreiling and Hasler, 1980; Höhle et al, 1980). The system and application software was run on the AVIOLYT's DG NOVA 4/X computer.

To provide restitution controls, special control devices were made. These were calibrated by purely photogrammetric means with the ORIENT universal bundle adjustment program (Kager, 1980).

The necessary measurements for this were carried out on the AC1 and the computations were done with the DEC VAX-750 in the computer centre of the Technical University Vienna.

For further processing of the data thus obtained, a DG NOVA 3/C was used in Basle and a DEC PDP 11/44 in Zurich. The off-line programs used for the purpose were developed by CHB and UHZ respectively either specially for this project or in connexion with other work.

To ensure troublefree data transfer between the various computers used, a software interface was accurately defined. The transfer of data and of program modules was greatly facilitated by the fact that the DG NOVA 3/C computer installed in Basle runs with the same RDOS operating system as the NOVA 4/X of the AC1, and that the Institute for Photogrammetry of the TU Vienna uses an AC1 connected directly to its DEC VAX-750. The data transfer between NOVA and PDP was achieved via ASCII files on magnetic tape.

4 Orthopedics benchmark

4.1 Generally

The object is to determine with reasonable acccuracy by photogrammetry the distribution of volumes among the fifteen principal segments of the human body. The aim is that regular measurements be made on patients with disorders of the locomotor system, such as paralytic disorders and damaged joints. Experience shows that the body's proportions in such patients have undergone considerable change by comparison with young men, on whom extensive survey information has been collected (Clauser et al, 1969). This is of importance as regards their locomotor sequences and the stresses to which the joints are subjected.

4.2 Problem outline

Interest in the prevention and treatment of damage to joints centres less on the overall amount of energy required for locomotion than on the magnitude and distribution of mechanical forces amongst various segments of the body. Forces are partly transmitted via the contact surfaces of joints and partly via the musculotendinous units. Since the effects of these forces and stresses on joints cannot as yet be measured directly under conditions of natural use, they have to be computed from anatomical measurements (joint axes, torque produced by various muscles, moment of inertia of pendulum movements of body segments).

In view of the importance of sound knowledge on the behaviour of the human body in static conditions, the Basle hospital now wants to carry out static studies of patients in addition to the kinetic investigations that have been undertaken for some time past (e.g. Baumann and Hänggi, 1977).

Photogrammetry was chosen as the means of carrying out these studies. The measuring system used should be capable of meeting at least the following main three conditions:

a: Production of suitable pairs of stereophotographs as a photogrammetric record of the test persons.

b: Photogrammetric restitution and computation of volumes from·a·above of various body segments defined with their boundaries.

c: Determination from a and b above of the positions of mass centres of gravity and inertial tensors of individual body segments with their anatomical axes indicated by us, and from additional information such as the density distribution in the body's segments.

These conditions were taken into account in the design of this benchmark test. However, the object of the benchmark test as such only covered the first of these two aspects, i.e. to produce and restitute photographs, whilst the further processing of the data recorded for determining the anatomical axes of body segments, torque etc, was to be carried out off-line by CHB as an independent operation.

Due to the fact that the whole of the human body or a segment had to be recorded three-dimensionally, more than a single pair of photographs was found to be necessary.

4.3 Photography

Since the object, the whole or part of a patient's body, must be capable of being recorded from all four sides, the following three alternative camera layouts were considered (fig. 1).

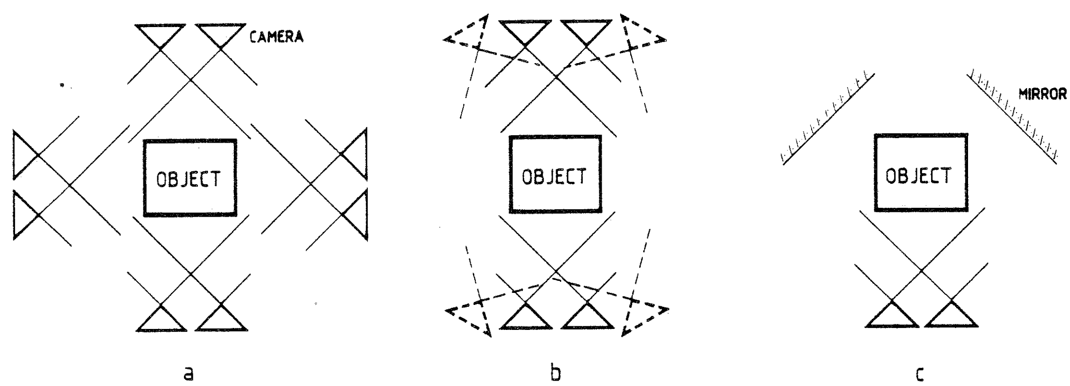


Fig. 1: Alternative camera layouts for the CHB/UHZ/Wild pilot project

a: Eight cameras: four pairs of photographs, each pair forming a stereomodel conforming to the normal case in photogrammetry in which the optical axes are parallel to each other and perpendicular to the base and the picture plane parallel to the plotting plane. Each stereomodel covers one of the four sides of the object.

b: Four cameras: here, two stereomodels are formed, covering only the two sides of the object. The pair of photographs forming a model can have either parallel or convergent optical axes.

c: Two cameras and two mirrors: in this, two exposures form four stereomodels. The optical axes of the two cameras are convergent.

Only a single P32 was available at the time the photographs were to be taken. The decision was therefore made to use a dummy to simulate the patient and employ method (a). Although method (c) must be regarded as the most economic (only two cameras), this was rejected at this stage since for the purposes of a pilot project the manufacture of two 1.50m x 0.60m optically plane mirrors was not regarded as justified. In addition, such a camera layout creates difficulties in model formation and restitution, for example due to large convergence of the optical axes, the definition of fictitious projection centres etc.

The camera layout was then planned on the basis of the following formulae:

$$
\begin{aligned}
m_p &= \sqrt{m_X^2 + m_Y^2 + m_Z^2} \\
m_X &= \frac{Y}{c} \sqrt{m_x^2 + \left(\frac{Y}{B} \cdot \tan \Theta_h - \frac{1}{2}\right)^2 \cdot m_{px}} \\
m_Y &= \frac{Y^2}{B \cdot c} \cdot m_{px} \\
m_Z &= \frac{Y}{c} \sqrt{m_z^2 + \left(\frac{Y}{B} \cdot \tan \Theta_\nu\right)^2 \cdot m_{px}^2}
\end{aligned}
\qquad (1)
$$

where:

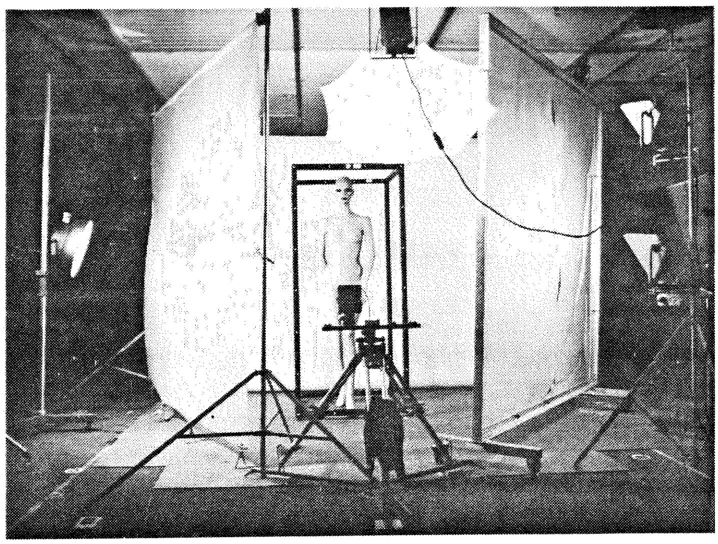
Y	camera distance from object
B	camera base
c	camera constant
Θ_h	max. horizontal photo-angle measured from the optical axis
Θ_ν	max. vertical photo-angle measured from the optical axis
m_x, m_z	mean square error of the image coordinates
m_{px}	mean square error of the horizontal parallax in the photograph
m_X, m_Y, m_Z	mean square error of the object coordinates
	global error in the object

A base/distance ratio of 1:7 was chosen. The specified accuracy m_p was ± 0.250mm and the measuring accuracy of any point in the photograph (i.e. AC1 measuring accuracy + imaging errors of objective + setting inaccuracy due to operator etc) was assumed at + 0.005mm. This resulted in an image scale of about 1:30 at a camera distance of 1.95m. The original camera constant of the P32 (c_0 = 64.00mm at a focusing distance of 25m) was increased by means of adapter rings to c = 66.01mm (focusing distance = 2.10m ± 0.15m).

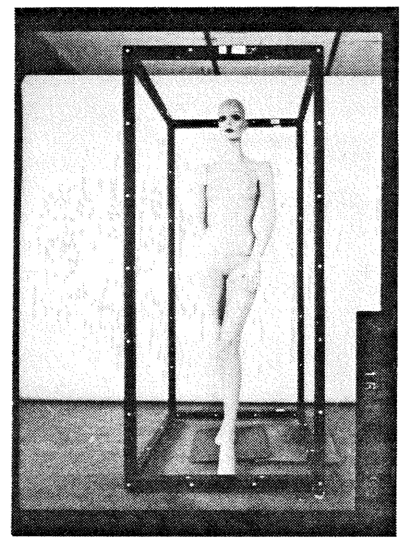
To increase the surface contrast on the dummy, a light grid was projected on the surface by means of a powerful projector (fig. 2). However, the results have shown that the mesh size of the projected grid must be finer for greater accuracy. At the same time, grid projection prevents optimum lighting of the entire surface. The conclusion has therefore been reached that for future photography, the patient should wear a specially woven or patterned stocking, and this solution would be welcomed by the physicians, since it also helps to eliminate any negative psychological effect on the patient to be photographed.

The exposures were made on AGFA AVIPHOT Pan 100 glass plates. Kodak HC 110B developer was used, with a development time of 7 minutes and a mean gradient $\bar{G}$ = 0.6, thus modifying the basic speed of the plates to about 50 ASA.

Light loss through the objective reduces this to 30 ASA. In order to achieve optimum surface contrast in view of this, the aperture should be set at f = 22, with an exposure time t = 0.5s. The exposures were made under artificial light. Fig. 2a shows the layout of the photographic and lighting equipment.



a



b

Fig. 2: a: Camera position and lighting layout

b: One of the P32 photographs used for restitution. This shows the grid projected on the model, prominent points and tie points

4.4 Restitution

For model formation and a comparison of different conditions in the same patient or of the same condition in different patients, a reference or control device was found necessary. A 2.00m x 0.60m x 0.60m rectangular frame was made by Wild of 40mm x 40mm steel profile. The patient stands or sits within this frame and is photographed simultaneously on all four sides (fig. 2).

Target marks, each consisting of a circle having a radius R = 5mm, with two lines passing perpendicularly to each other through the centre of the circle, were made photographically and attached to the uprights of the frame on each of its four sides at intervals of about 350mm. These provide excellent control marks which ensure high setting accuracy at the image scale concerned and for the size of the measuring marks in the AC1.

Calibration of the frame was carried out by purely photogrammetric means, using the ORIENT program. For greater redundancy in adjustment to determine control-point coordinates, four additional photographs were made diagonally to the main exposures.

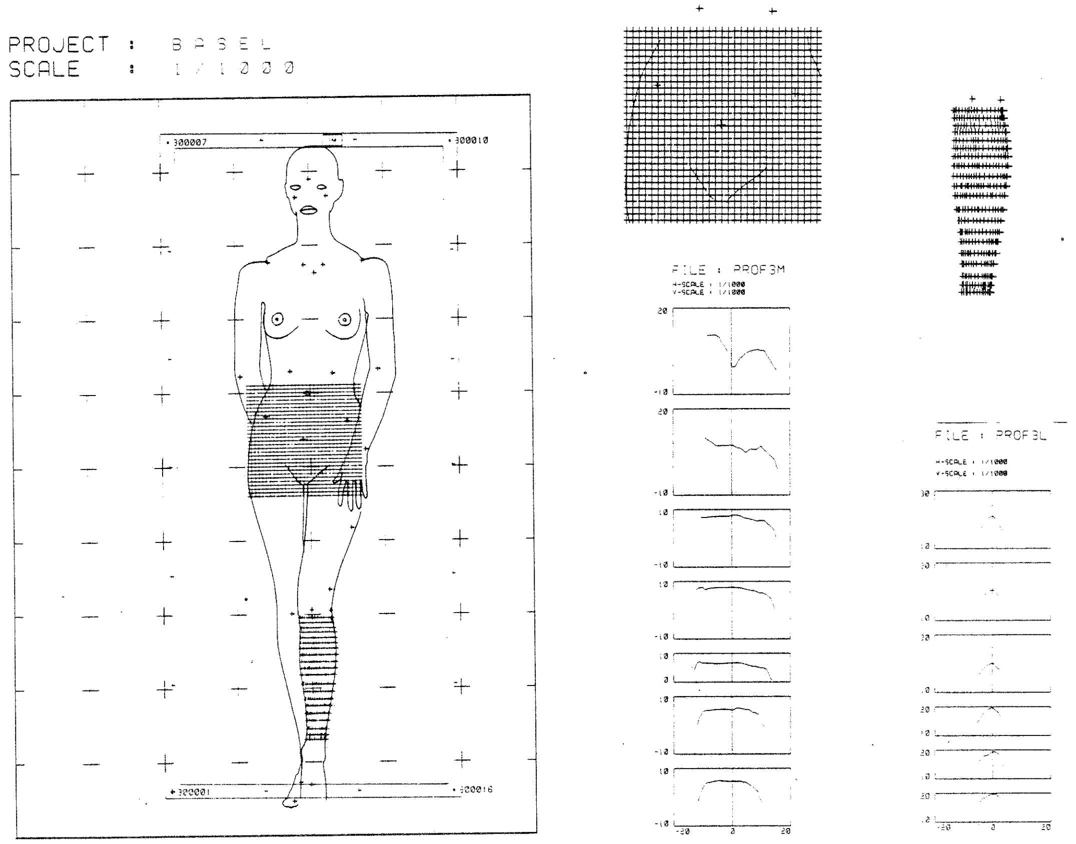
All target marks were measured monoscopically and stereoscopically in the AC1 in each of the 12 photographs in which they occur. The data files thus produced, the parameters of inner and approximate values for outer orientation were sent on diskette to the Institute for Photogrammetry at the TU Vienna, together with two distances measured on the frame. The AC1 installed in Vienna was used to transfer these data to the DEC VAX-750 of the computer centre for adjustment. All control points were determined in a local Cartesian coordinate system. With an observation error $\sigma = \pm 0.004$mm in the photograph, adjustment resulted in a mean coordinate error $\sigma_0 = \pm 0.150$mm in the object.

Calibration of the frame should be repeated from time to time to ensure accuracy.

At the time that restitution was carried out, the AC1 could not accommodate the orientation of photographs deviating substantially from the normal case in aerial photography. Hence, tie points were necessary for bridging between models. The control points marked on the frame were used for this purpose. For bridging diametrically opposite models, pins with spherical heads were fixed to the dummy. The models were oriented in four independent local coordinate systems. In each model, 16 control points were measured in four vertical planes (interval between planes approx. 0.20m). Orientation produced a mean residual y parallax of 0.005mm.

Prominent points of the body of significance for the physician were specially marked, and measured and adjusted together with the tie and control points.

As a result of this restitution, three-dimensional coordinates were defined of significant points, prominent points and mass points which can be either laid out in a special pattern (e.g. sections, profiles, points distributed in regular grid etc.) or in any position. Hence only that part of the AC1 system software had to be used which is normally employed in digital restitution. Graphic output was limited to check plots produced either during restitution or off-line later. Figure 3a shows an outline of the complete body and an on-line check plot of significant points, together with points forming a square grid (central part of body) and profiles (left leg). Figure 3b shows an off-line plot of the last two of these sets of points and profiles of the same parts of the body as those plotted on-line.



a b

Fig. 3 a: On-line check plot of outline of body and digital data recorded
b: Off-line plot of data and profiles recorded on-line

These data, together with the coordinates of the control points, were delivered to CHB for further processing on their NOVA 3/C. The control frame was also supplied to the Basle laboratory to permit comparisons of various methods of measurement.

Processing of the data has shown that the accuracy of points not marked by the grid is of a low order. This is mainly attributable to the fact that the human body was simulated by a dummy having a low surface contrast.

5 Oral surgery benchmark test

5.1 Generally

Until recently, for recording facial morphology, it was necessary to depend on two-dimensional measurements directly on the face, normal photographs and X-ray photographs. A number of considerable disadvantages are inherent in this method. Measurements directly on the face are not reproducible postoperatively, whilst measurements made on two-dimensional documents provide only a limited amount of the information necessary for accurately planned surgery and for prior assessment of its effects with any degree of certainty. Particularly in asymmetrical facial deformity, a method capable of providing the information required is essential.

5.2 Problem outline

A method of measurement and the equipment for dealing with problems that arise in oral surgery must meet the following basic conditions:

a: The data provided by the system should be sufficiently accurate and simple to process

b: The system should be sufficiently flexible to allow on-line computations to be carried out, e.g. to determine volumes and areas

c: A patient's pre- and post-operative data should be stored in the same coordinate system that can also be used in cranio-facial surgery

d: The facial segment to be measured should be comprehensively covered

To fulfil conditions (a) and (b), stereophotogrammetry is the obvious choice. To simplify restitution and achieve the requisite flexibility, digital restitution was chosen. To meet condition (c), UHZ has developed a special control device, a so-called cephaleostat. The last of these conditions has considerably influenced the choice of camera layout.

Such a system should make it possible to plan oral surgery three-dimensionally, since the operation is also three-dimensional. Asymmetrical deformities such as dysostosis otomandibularis, harelip and split-palate patients would greatly benefit from this. The measuring system can also be used to record the effects of bone displacements on soft tissue in various surgical techniques and situations.

A new possibility provided to record the movements of the mandible directly in all three dimensions and to reproduce these movements will further benefit diagnosis in the progress of diseases and of therapies affecting the functions of the masticatory apparatus. Computation of volumes and representation of areas could provide objective evidence of the progress of tumors and the effects of various exfoliant drugs.

In the design and execution of this benchmark test, we tried to meet these requirements as nearly as possible.

5.3 Photography

It was decided to adopt the same camera layout as for 4.3. Since in this case only the facial region is of interest, a total of six photographs is adequate. The unsatisfactory experience made with simulation of the human body in 4.3 led to a dummy head being made of soft plastic and finished professionally with make-up. A special device permitted simulation of pre- and postoperative conditions in the mandibulo-maxillary region. The first test photographs showed that despite exhaustive preparation the lack of adequate surface contrast made accurate photogrammetric restitution impossible and the decision was made to use two synchronized cameras and a test person. Although only two cameras were used simultaneously, a specially made device allowed bridging from the two lateral models with the anterior model. This device is fixed to the patient's neck and allows the whole body to be rotated about a vertical axis. For testing 'mirror photography' a normal mirror was also used in the photographs. Figure 4a shows a P32 photograph of the dummy head, and figure 4b is a general Hasselblad photograph showing the camera layout with a test person.

a b

Fig. 4 a: P32 photograph of the dummy head
b: Hasselblad photograph showing general layout with a test person

The specified accuracy in this case was given as ± 0.100mm. The camera layout was determined by similar considerations as for 4.3.

If the familiar formula for depth perception is used (2), it will be seen that the additional accuracy required in this case must be achieved either by reducing the factor Y^2/B or increasing $d\gamma$:

$$dY^2 = -Y^2/B \cdot d\gamma \qquad (2)$$

where:

Y = camera distance
B = camera base
$d\gamma$ = difference between the parallax angles at two object points

In the former case, this means that with the camera distance given, the camera base must be increased, whilst in the second the photographs used in restitution must be enlarged. With a camera distance Y = 0.60m, a base B = 0.20m was chosen. The camera constant of the two cameras refocused to 0.60m was c = 72.49mm. Hence, an image scale of 1:12 was obtained.

The same photographic material was used here as in 4.2. Exposures were taken with a 'Bron' studio flash unit. Exposure time in this case was determined by the time lag due to the fact that the two P32 cameras are connected in series (t = 1/15s). f = 22 was the stop used.

5.4 Restitution

For the same reasons as in the orthopedics benchmark test, a reference and control device was also required here. UHZ designed and built the so-called cephaleostat. This consists of an aluminium frame which is placed over the patient's head. Any required position relative to reference points, such as the pupils of the eyes, the point of the chin etc is possible by means of special screws, guides and rails, and permits the definition of various reference planes (fig. 4). The same target marks were fixed to the cephaleostat as those used on the control frame for orthopedic purposes, and these were subsequently used as control points in restitution. Unlike the calibration of the orthopedics frame, the cephaleostat has to be calibrated afresh for each exposure and each patient. Control points which remain constant irrespective of the setting ensure accurate and unambiguous transformation of the data obtained into a higher-order coordinate system.

For the calibration of the cephaleostat, all control points in the six photographs were measured with the AC1 and adjusted with the ORIENT program. It is essential here to measure at least one distance on the cephaleostat. Although it would have been an advantage in carrying out adjustment to have additional photographs to provide greater redundancy in the resulting measurements, only the six P32 photographs were in fact used. The reason for this resides in the fact that the image scale and the base/-distance ratio are sufficiently large to provide accurate results. Further, use of two additional cameras would unduly increase the final cost of a future system.

The accuracy obtained in calibration was ± 0.003mm in the photo scale. In this study, restitution was again required in digital form, and graphic output of the data was also wanted in various forms.

At the time, the general orientation program was already available for the AC1. With this, any photograph of any outer orientation can be oriented in the AC1. Introduction of azimuth angle α, nadir distance ν and kappa κ, instead of ω, φ and κ as used in aerial photography, facilitate determination of the approximate values necessary in this type of orientation. When small-format photographs such as those from the P32 are used in the AC1, several models can be oriented at the same time. Hence, all six photographs were placed on the picture carriers (three per carrier) and oriented after one another in a single process. The reference system used for all three models was the higher-order coordinate system defined by ORIENT. Orientation produced a mean coordinate error of ± 0.085mm in the object.

When the AC1 is used for restitution, use of the XY plane of the reference system as plotting plane is no longer essential (Vozikis, 1983). In fact, any projection plane can be defined during restitution. The reference plane of the measuring mark (i.e. the plane defined by the X and Y handwheels) can also be freely selected.

A substantial advantage in using the AC1 for restitution is the fact that with small-format photographs, several models can be restituted at the same time. For example, a profile extending from the left to the right ear can be continuously recorded over all three models. Digital data of all types (e.g. single points, profiles, points arranged in a regular grid etc) can be recorded alternately in all three models and stored in the higher-order coordinate system. This accelerates restitution and makes off-line coordinate transformation unnecessary. As a result, all the requirements specified by the physician can be taken into account in restitution.

Fig. 5a shows a plot of the recorded data projected on a plane which contains the two pupils and the point of the chin. In figure 5b, the object is projected in a different reference plane defined during restitution. However, the coordinates of the points recorded refer to the same system as those in figure 5a. Figure 5c shows a vertical profile through the nose as recorded in the central model. After this profile was recorded, horizontal profiles at 10mm intervals were found automatically and recorded continuously for all three models by various methods (e.g. manual release, release by time or distance intervals etc). Figure 5d is an off-line plot of the parallel profiles (original scale 1:10).

The data recorded were transferred as ASCII files on magnetic tape to the PDP 11/44 of the Zurich hospital for further processing. The accuracy obtained here was very substantially greater than in the orthopedics benchmark test. This is due not only to the improved camera layout (better base/distance ratio, larger image scale etc) but also due to the use of a test person instead of a dummy.

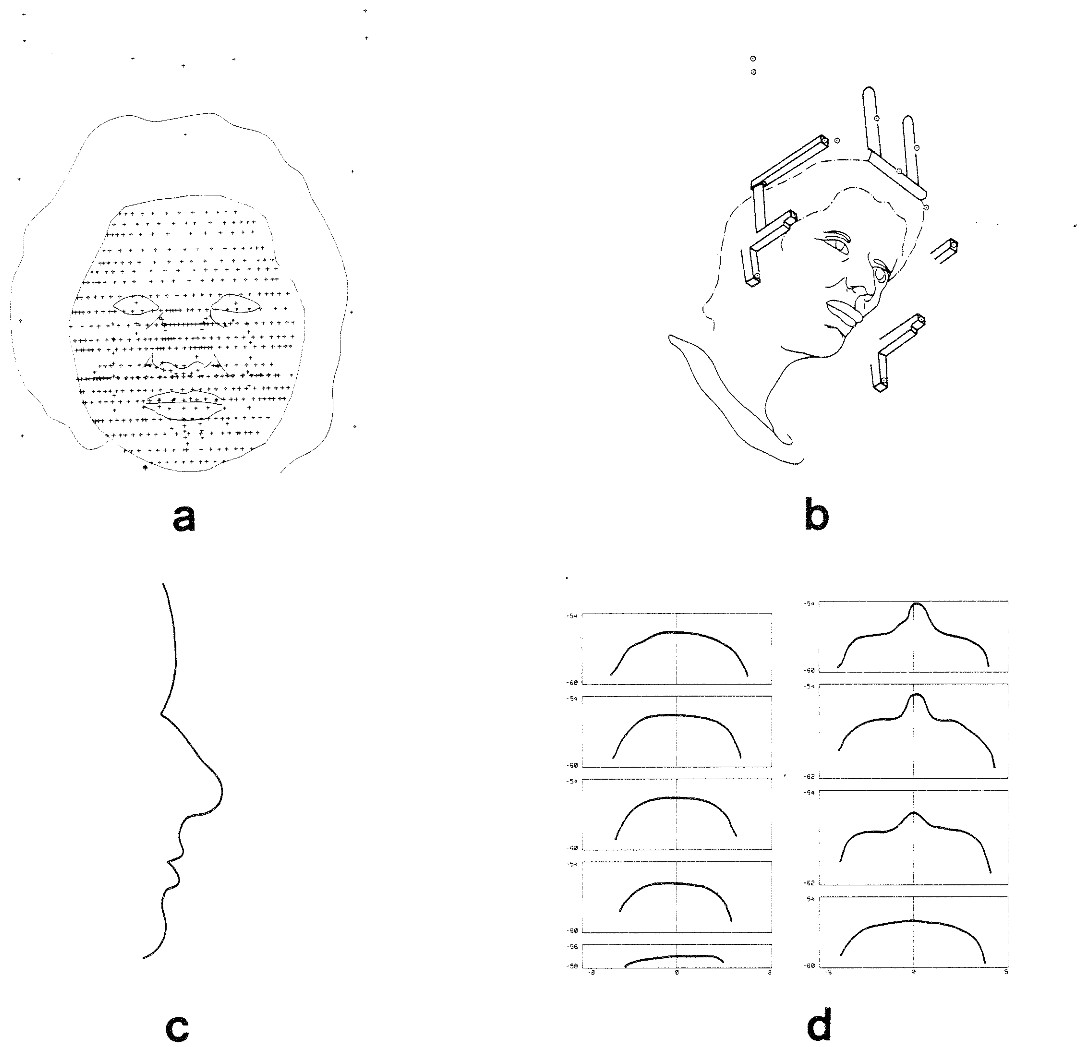


Fig. 5 a: Overall view of points recorded and restituted (on-line plot)
b: Projection of situation in a freely defined plane (on-line plot)
c: Vertical profile obtained from central model (on-line plot
d: Parallel horizontal profiles obtained from all three models (off-line plot)

6 Conclusions

These two benchmark tests have shown beyond doubt that photogrammetry is a suitable method for solving problems of measurement in medicine.

Simulation of the human body by a dummy produces results of low accuracy.

The specified accuracy does not necessarily call for the use of metric cameras and could be achieved equally well by using amateur cameras and special software.

A photogrammetric instrument designed and equipped for restitution of topographic information can be used for any problem of measurement in medicine, but it is very expensive and unduly complex for medical purposes. Acceptance of such a measuring system is assured only if it can be used all the way from exposure to restitution and data processing. A simple, user-friendly 'human interface' is an equally important condition for success.

The CHB/UHZ/Wild project was carried out for purely practical ends and not academic purposes. One requirement stated by the physicians was that such a system should allow them to obtain the photogrammetric restitution of the records from several patients in a minimum of time. This can be met only if such a complete system is developed. The know-how obtained in this pilot project may prove useful in designing and producing such a system.

The need must be emphasized of using plotting equipment with a universal bundle program tailor-made for this specific problem. In oral and facial surgery it has to be used for the calibration of the cephaleostat after every photograph taking.

Despite the successful results obtained in these benchmark tests and other projects carried out to date by various institutions on either an academic or a commercial basis, there are still many open questions in this field. All three authors are convinced that such a system which is economic, fast and simple to operate is capable of realization. They hope that their joint efforts will achieve a satisfactory solution in the foreseeable future.

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