FRONTISPIECE. Stereo-pair depicting the lower anterior teeth. Orthodontic bands are cemented on the first bicuspid on each side with hollow tube welded on its outside surface. Removable wire frame in place. Note stops on each vertical member.

HEINZ GRUNER*
Bausch & Lomb, Inc.
J. ZULQAR-NAIN and HELMUT A. ZANDER
Eastman Dental Center
Rochester, N. Y. 14602

A Short-Range System for Dental Surgery

Quantitative data permit positive conclusions as to changes in time of teeth after surgery.

(*Abstract on page 1243*)

THE SHORTAGE OF readily available equipment for the acquisition of photograms in the field of short-range Photogrammetry is attributed to the great variety of conditions under which photogrammetric surveys could solve many tasks in a most direct and economical manner. The frontal size and depth of objects of solid state or transient existence, their surface, light reflecting or emitting properties, their environments (air, vacuum, water, temperature), and the accuracy requirements attached to each problem, pose severe obstacles to the design of universal photogrammetric equipment for field and laboratory use.

General design approaches are usually based on the so called *Normal Case* of terrestrial photogrammetry which is characterized by parallelism of the two camera axes and their normality to the photo base, by metric cameras with adjustable principal distances,

* Presented at the Annual Convention of the American Society of Photogrammetry, Washington, D. C., March 1967, under the title "A Short Range Photogrammetric System for Dental Surgery."

by unsymmetric field formats to forestall the loss of stereo overlap, and by variable separation of their perspective centers along the base bar. Evaluation of resulting stereograms, if done in the analog mode, requires special plotting instrumentation, or conventional heavy universal plotters. If done analytically, instruments of the stereocomparator type with electronic readout and computing accessories are desirable.

The well known variety of means for mapping from aerial photographs, which ranges from moderate to extravagant configurations, design, and price, has a similar counterpart in short range photogrammetry. Here, too, we find highly sophisticated instrumentations as well as some *poor-man's solutions* which serve their purpose. The standard error of their results, admittedly, is not quite the same as that of the aristocratic approach, but acceptable results can be achieved in a most direct manner. The system described here is that of second order. It makes economical use of commercially available components. The geometry of this short range system is built around the "Convergent Case" of photogrammetry. As necessary, parameters are tailored to optimize its use in dental research.

THE PHOTOGRAPHIC OBJECT is the human mouth. The area of interest in each stereogram is limited to about 30 mm in width and height. The topographic relief seldom exceeds 15 mm. Because of the organic instability of the surfaces involved, a standard error in position and elevation of 0.1 mm is a realistic specification. The clearance between the object and the camera equipment should not be less than 200 mm which is required to avoid interference with ambulatory processes.

Figure 1 shows the exposure geometry conforming to this environment. An isosceles basal triangle with a base/height ratio of 1/2.8 is established by a photo base I–II. The two photographic axes which intersect at the apex C_0 at a convergence angle $2\alpha = 2 \times 10°$ represent the two equal sides. Because of the small dimensions of the object located with its center at the point of convergence, the image-forming ray bundles are of narrow angles, and cameras with an angular field of 25° will amply cover the object space.

In the evaluation phase using direct projection plotting equipment this basal triangle is reproduced at 4 times its original dimensions. Consequently, the model surface is generated at a nominal projection distance of 800 mm. The model scale is equal to 4 times the object photographed and is considered most suitable for the purpose in mind. Commercially available Balplex 760 projectors, which have a principal distance of 55 mm, can meet these conditions without modification. Their diapositive frames are prepared to accept smaller plate formats. Their supporting brackets permit tilt angles up to 20° in all directions. The convergent case of $2 \times 10°$ poses no problem of projector orientation. The projection lenses have a depth of focus considerably in excess of the model configuration.

IN OUR CASE OF short-range photogrammetry, we are concerned with a finite object distance, $s = 200$ mm (Figure 2). The conjugate image distance s' depends on the chosen focal length of the camera lens. The ideal

HEINZ GRUNER

HELMUT A. ZANDER, D.D.S.

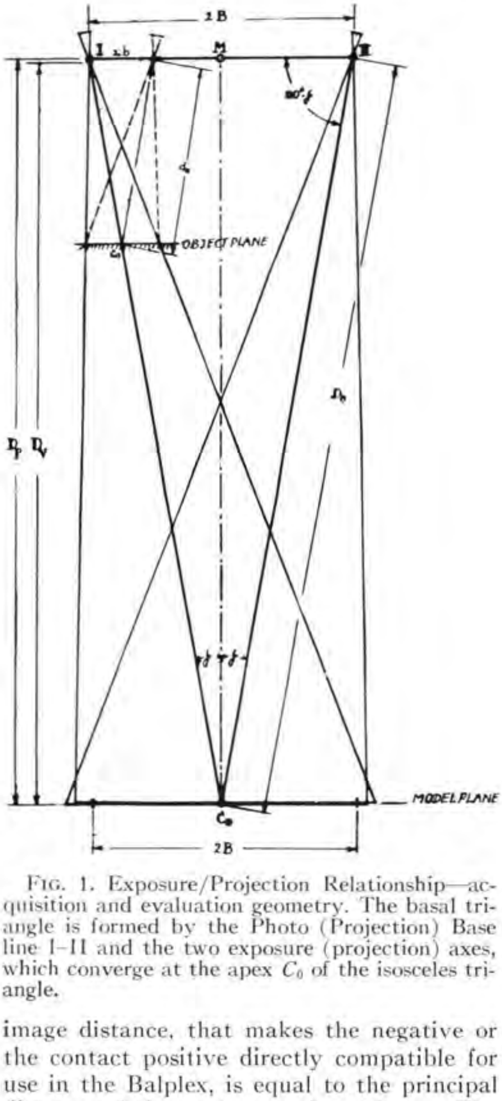

FIG. 1. Exposure/Projection Relationship—acquisition and evaluation geometry. The basal triangle is formed by the Photo (Projection) Base line I–II and the two exposure (projection) axes, which converge at the apex C_0 of the isosceles triangle.

image distance, that makes the negative or the contact positive directly compatible for use in the Balplex, is equal to the principal distance of the projectors, i.e., 55 mm. The focal equation $I/F = I/S + I/s'$, then renders the desired focal length $F = 43$ mm of the camera lenses. The size of the negative I results from the ratio of the conjugates

$$I = (s'/s) \times O = 0.275 \times O$$

where O is the object size. It follows that camera windows of 24×24 mm provide ample image areas for objects that are centered on each camera axis.

The great variety of commercially available cameras, using 35 mm film with camera windows of 36×24 mm, offer a welcome source to draw from. The two prerequisites for eligibility are: (1) a sufficiently rigid housing, and (2) a well defined focal plane in which fiducial marks can be affixed. Desirable features are: (1) convertibility to the use of glass plates, and (2) parallax-free view-finding and focusing. We chose the Honeywell Pentax camera model *H1a* as meeting all required and desirable features including very reliable flash synchronization. The use of focal plane shutters is not objectionable, as objects and cameras remain stationary during the exposure.

The lens had to be especially designed by B&L with a maximum aperture $F/2.5$, optimized for the given object-image conjugate ratio. The photographic resolution on axis is 120 lines/mm; 15° off axis it drops to 100 lines/mm. The radial and tangential distortions, in the half-angular field of 15°, are within the limits of ±5 microns. The two lenses selected for the camera system are matched for equal focal length within 0.1 mm. They are barrel-mounted on the camera housings to the given fixed image distance of 55 mm. The location of the principal point, i.e., the foot of the perpendicular dropped from the interior node upon the image plane, is determined by a special centering micro-

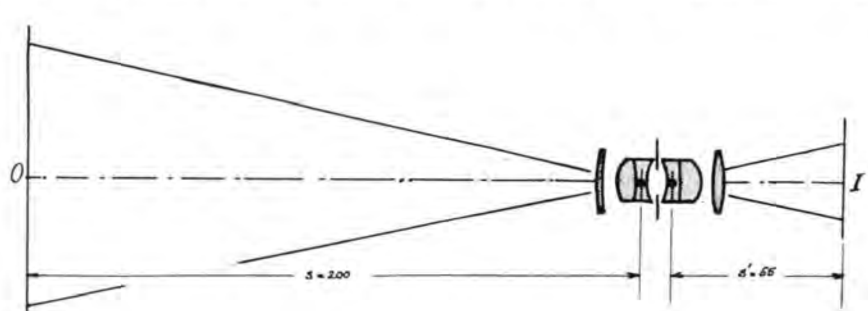

FIG. 2. The Photogrammetric Quadruplet. A special lens designed by B&L to give optimum performance at the conjugate distance ratio of 200/55. It is practically distortion free within the half angular field of 15° and resolves in excess of 100 lines/mm.

scope. In this process, the four midside fiducial markers are also correctly positioned.

THE CAMERAS ARE placed in a cradle (Figure 3). The position of each camera body in this cradle is rigidly fixed by alignment pads. By the release of three locking screws, each camera can be removed from the cradle for servicing in the photographic darkroom. The permanent relative orientation of the two cameras in the cradle is accomplished with a calibration attachment (Figure 4) which can be fastened to the cradle base. The line cross of its target plate establishes the apex of the basal triangle. When the apex is imaged at the principal point of each camera, the basal triangle is established. Its base length is derived from the physical separation of the two principal points. The orientation of the basal triangle with regard to the plumb line is indicated by the cross levels on top of the cradle.

Although exposures are possible if this camera aggregate is held by hand, it is preferred to mount the cradle on a firm support and use the viewfinders for pinpointing and focusing on the object. Simultaneous exposure is made with two flash units, one attached to each camera.

THE EVALUATION PHASE of the resulting stereo pairs offers some interesting aspects. Quite obviously, the orientation of the photographs in the plotting instrument cannot be performed satisfactorily by using the conventional method of clearing the y-parallax from the model. It would be a cumbersome procedure and, because of the small angular extent of the stereo area, it would leave rather large orientation errors undetected, which would cause model deformations. Instead, the projector orientation uses a sequence of opto-graphical steps.

Both projectors are set to an equal height above the tracing table platen (Figure 5). The nadir point of each projector station is found optically, and marked in the mapping plane. The line connecting the nadir points is the horizontal projection of the distance between the projection centers, and expresses the base of basal triangle. Its correct length, i.e., four times the photo base, is obtained by x-displacement of one projector along the support bar. The midpoint of the plotted line is the point of convergence. Each projector is tilted and tipped so that the projection of its principal point coincides with the measuring mark of the tracing table placed over the point of convergence. This takes care of the ϕ- and ω-orientation settings of the projectors. The κ- (Swing) settings are added, using the projected images of the fiducial marks, or of photographic image detail nearby.

The resulting stereo model is now essentially parallax-free. Only very small residual y-parallax may be observed which can be eliminated easily, usually by a by-correction. As this process of projector orientation observes and corrects image displacement in the projection plane at a magnification of four times, it is more precise and convenient than setting the orientation angles by means of angle measuring devices installed at the projector movements.

THE SUBSEQUENT ABSOLUTE orientation of the model, aimed at obtaining the desired correlation between the control points and the

ABSTRACT: *A stereometric camera system comprised of two rigidly mounted 35-mm reflex cameras of metric properties is designed for an object distance of 200 mm and an image distance of 55 mm. The camera axes converge at $2\times10°$ and intersect in the object plane. The nominal base/distance ratio of the resulting stereograms is 1/2.8. Restitution and evaluation is accomplished with a direct projection plotter at $4\times$ plotting scale. Standard Balplex projectors are used at 800 mm projection distance. Three dimensional data are obtained with a precision of 0.1 mm at the object scale. Projector relative and obsolute orientation is accomplished by a simple opto-graphical method supported by control data on the model surface. This system applied to measurements in the human mouth permits for the first time quantitative data which permit positive conclusions as to changes in time of teeth and gingival surfaces as a result of the natural healing process after surgery. This constitutes an important step towards reliable clinical case histories.*

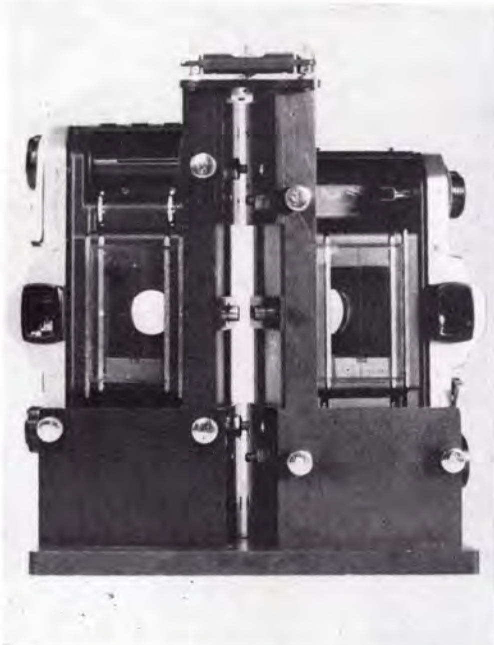

FIG. 3. Cradle for Stereometric Camera Pair (rear view). The two 35-mm cameras are held in upright position side-by-side in a cradle, which secures their orientation in conformance with mid-side fiducial marks by which the camera principal point can be located. The cameras can be released from their calibrated position by sets of three lock screws.

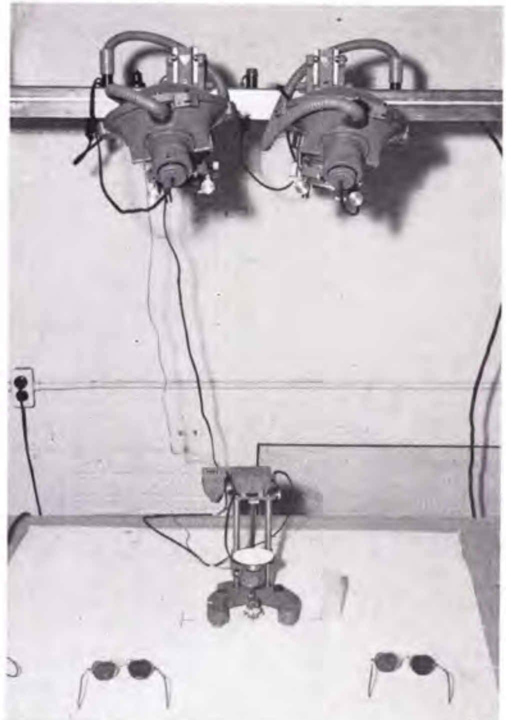

FIG. 5. Projector Orientation. The Balplex projectors are oriented at the supporting bar in such a manner that the exposure geometry is restored at four times the original scale. The tracing table is located at the point of convergence of the projection axes which form the sides of the isosceles basal triangle.

mapping plane, may be executed in the conventional manner of tipping and tilting the projector support bar, or, if convenient mechanical means are provided, by tipping

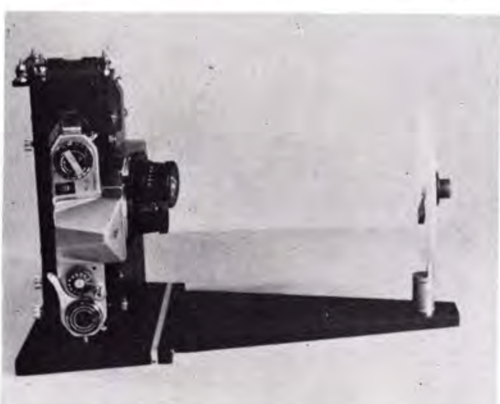

FIG. 4. Calibration fixture attached to camera cradle. The basic camera orientation in the cradle is established and can be restored with the aid of a center cross on the auxiliary target plate. When this cross is imaged at the principal points of both cameras the dimensions of the basal triangle can be checked mechanically.

and tilting the mapping table. If the ϕ-component of the required model rotation exceeds 5°, one may resort to rotating the base of projection by introducing bx- and bz-components as functions of the angle of base rotation. Again, the opto-graphical method may be used for the subsequent reorientation of the projectors (Figure 6). The method proves particularly convenient if the basal triangle is rotated about its midpoint, M. Then the orientation elements are as shown in Table 1.

In analogy to the ϕ-rotation, the projector base may also be given a ω-rotation, which leads to the introduction of a third base component, by_I and by_{II} of the projector settings.

A change of model scale requires scaling up or down of the projection base, or its components, respectively, but does not change the rotational orientation of the projectors.

THE PRACTICAL EVALUATION of stereopairs carried out in the Eastman Dental Center of

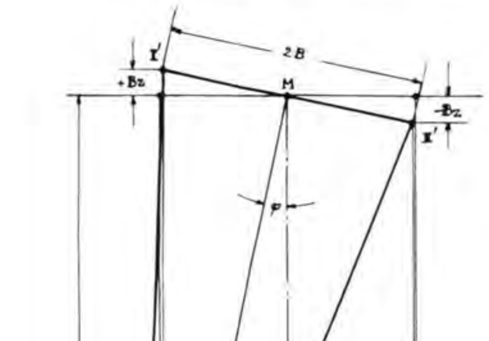

FIG. 6. Exterior Orientation by Base Rotation. As an alternative to conventional levelling of the stereomodel (by tilting the base bar) the basal triangle is rotated on the midpoint M of its base. Base components are introduced at the projector settings and the projection axes are reoriented to converge at the offset apex C_T.

Rochester has resulted in the following experiences.

Aerographic positive plates are not commercially available for the camera window frame of 36×24 mm. It was found that Kodak spectroscopic plates type V–F of suitable size using ultraflat glass for the right speed and fineness of grain (better than 225 lines per mm of resolution) were satisfactory. It was soon found that the inconvenience of reloading the cameras in the darkroom when taking pictures of patients constituted a handicap to the operator; Therefore, we turned to an Estar base film. Recordak Special Micro-File AHU Film Type SO-291 possesses the necessary photographic and physical properties for microphotogrammetry. It has panchromatic sensitivity and extremely fine grain paired with high resolution. As it is not commercially available for 35-mm cameras, it has to be cut and perforated to this size.

TABLE 1. COMPONENTS OF ABSOLUTE ORIENTATION
See Figure 6

$bx_I = -bx_{II} = b\cdot\sin\phi$	With ϕ = angle of
$bz_I = -bx_{II} = b\cdot\cos\phi$	base rotation.
$X_{C_T} = D_p\cdot\sin\phi$	X_{C_T} and Z_{C_T} = Coordinates of displaced Apex C_T of the
$Z_{C_T} = D_p(1-\cos\phi)$	basal triangle.

The exposure time for taking intraoral pictures in the described setup is that of an electronic flash of the order of magnitude of 1/1,500 second. At a lens stop of $f/11$ the shutter setting is at 1/30 second. As we use the double cable release, most likely the flashes from both units expose both pictures. After development and fixation, the negatives are transformed into diapositives by contact printing on a standard sized aerographic positive plate. In this process, care is taken that the positive image has a properly centered position within the format of the glass plate. For proper centration in the Balplex projectors the standard centering device is used in connection with the fiducial marks contained in the photographic images.

After the plates are placed in the Balplex projectors, the three dimensional image is projected on a grid consisting of 2×2-mm squares which have been photographically printed on dimensionally stable sensitized Cronar base drafting film. The grid sheet is then oriented on the mapping table in such a manner that the abscissae and ordinate lines become parallel with the wire frame contained in the stereo model.

The wire frame fits into the patient's mouth by placement of orthodontic bands on two teeth on either side of the area to be plotted (Frontispiece). This procedure allows us to replace the reference frame in an identical position in the patient's mouth at different time intervals. Obviously, future photographs containing this reference frame can then be superimposed upon the original plot in the identical orientation. Measurements can then be made in X-, Y-, and Z-directions of changes that may have occurred with time in regard to the dental structures located within the reference frame.