# X-RAY PHOTOGRAMMETRY AND FLOATING LINES IN SUPPORT OF NEUROSURGERY

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## ABSTRACT

The paper discusses certain aspects of an inter-disciplinary research aimed at facilitating dependable implantation of cerebral probes. This is based on applying stereo-photogrammetric techniques in radiography. An assemblage of mechanical outfits helps control the acquisition of radiographs. The approach considers the object being "interior" to an "X-ray camera" and utilizes "self-calibration". A mensural accuracy of around ±0.1 mm (standard deviation) for each coordinate at any point on the object is obtainable. Finally, an outfit permitting stereo-vision of a "floating line" developped through the research is described.

## SOMMAIRE

L'article traite des considérations photogrammétriques reliées à une recherche pluridisciplinaire visant à faciliter et sécuriser l'implantation des sondes cérébrales. Il est question d'une application des techniques stéréo-photogrammétriques en radiographie et du concept de la "caméra à rayons-X". On y propose une façon simple et efficace d'autocalibrer une salle de radiographies de concert avec une présentation de montage mécanique permettant de transformer l'enceinte radiographique en appareil de mesures. Suivant cette approche, une précision de ±0.1 mm (erreur standard) en ce qui concern la détermination de chaque coordonnée d'un point est obtenue. Enfin, on y parle d'un montage prototype permettant de visualiser spatialement une "ligne flottant".

## INTRODUCTION

For most epileptic patients medication is not the solution. Comparable to electric short circuits, the excessive and disorderly nervous impulses originating from some damaged cells in the brain cause convulsive movements as well as problems of vision and behavior. The only hope of cure today rests with extremely delicate surgical interventions of patient's brain. This remains yet a challenge to the neuro-surgeon interested in full success for all his patients. Committed to this challenge, a multi-disciplinary team of professionals from the Notre-Dame Hospital of Montreal and the Laval University of Quebec is striving to develop a method that can be efficient for both diagnosis and therapy.

An avant-garde experimental technique is based on the analyses of electrical waves inside the brain during epileptic seizures. Such analyses permit the specialist to locate the damaged area in the brain and to eventually destroy it in order to heal the patient. For tracking down such cerebral penetrations, the tool of prime importance consists of rectilinear probes lodged in the brain. Such probes must use the zones free from blood vessels in order to avoid internal cerebral hemorrhages. All aside, it is this problem of ascertaining safe and secure passage of the probe around which rests the success of this new technique.

The search for a safe passage of the probe through the labyrinth of arteries and veins is best done with conventional radiographs of blood vessels(angiographs). Current practices of implanting a probe is constrained into directions perpendicular to the radiographs showing the skull profile. One such radiograph is limited to only a two-dimensional orthogonal view. Three-dimensional information can be obtained, rather indirectly, with two such radiographs taken from mutually perpendicular directions. This is cumbersome, to say the least. In order to overcome this constraint and in view of associated medical considerations, help was sought from the Laval University Department of Photogrammetry.

All things considered, the stereo-photogrammetric approach appears viable in principle. However, a feasibility study with regard to an assessment of the accuracy obtainable vis-a-vis the identification of all aspects was deemed necessary to start with. In this regard, an a priori safety norm of 1mm was considered. That is to say, the arteries or veins must not be within 1 mm of the probe.

The problem being complex with regard to various radiographic, mechanic, neurologic and photogrammetric possibilities, it was decided to limit this initial study to the following:

To determine the precision with which one can locate a point within the braincase (brainpan). The system being non-conventional, an analytical stereo-photogrammetric approach would seem logical in utilizing the X-ray imaging equipment as used currently.

This would involve firstly, calibration of the specific X-ray imaging system, and secondly, determination in a stereo-model of 3-D coordinates of several points which could be verified separately through precision mechanical measuring processes. The development of a working system comes next.

## SELF-CALIBRATION

With regard to precision measurements, it is sensible that the system be calibrated or standardized before its use. Such a calibration process should be directed towards determining not only the instrument's capabilities in terms of obtainable accuracies in the desired outputs but also the involved parameters (elements) and their behavior under given circumstances.

Very few, if any, of the radiographic systems are subjected to any kind of mensural calibration. Most of these are used in obtaining qualitative information only to facilitate diagnoses and are never considered as mensural instruments. One such desired to be used for mensural contingencies must undergo an appropriate calibration process.

Direct calibration techniques have been with us for numerous years (see eg., Hallert, 1970). There are certain considerations in this respect. A high precision calibration performed with careful laboratory arrangements may not provide adequate data on the instrument's performance under working conditions. Often certain unknown parameters are hidden, which could be derived computationally. In the case of X-rays, a test range of precision control points to be used always could end up being cost-ineffective. Certain individual points may have undetectable but significant errors. In order to overcome such potential difficulties, we have now the procedure of self-calibration (see Kenefick et al, 1972, eg.). This procedure would surmount all such difficulties and would simplify the data acquisition also.

If a self-calibration soft-ware for a photographic camera is available, one can easily make it adaptable to an X-ray imaging system. The modification of such a program becomes easy if one can visualize the geometric similarity between the X-ray imaging system and the interior of a photographic camera. One can accomplish this "X-ray camera" by simply assuring adequate stability of the casette containing the radiographic film and the roentgen tube (the source of X-ray). This source would represent the perspective center in a camera lens and, with the same analogy, the minimum distance between the source and the film plane would correspond to the focal length*. In short, whereas in regular photography the rays originate at the object, in an X-ray system the rays originate at the source and pass through the object. The geometry is similar with the object remaining inside the X-ray camera. Furthermore, a radiograph is a positive image. This causes the only worthwhile modification in the self-calibration program since in the case of photographic cameras almost always the image form considered is negative.

Considering the radiographic 'enclosure' similar to that of a camera, the location of the perstective center with respect to the image is defined in terms of three parameters:

- $f$ : the focal length, or better, the effective principal distance;
- $x_c$ $y_c$ : two photo-coordinates of the principal point with respect to the fiducial references.

Considering the physical phenomena such as refraction, diffraction, etc. similar in concept to those in Brown (1966) for a photographic camera, one can decide here to consider six distortion parameters in order to obtain an effective calibration:

- $K_1$, $K_2$, $K_3$, $P_1$, $P_2$ and $P_3$ : represent the coefficients of two polynomials (see below) expressing the radial and tangential distortions and assumed constants over all radiographs.

The above nine parameters, considered as the elements of 'interior orientation', are retained in the calibration program. The collinearity equations provide the basis for such an analytical calibration. The standard equations of collinearity are augmented with the above parameters to give the following working equations in this case:

$$\left.\begin{aligned} &\bar{x}_{ij} + F(K)\cdot\bar{x}_{ij} + F(P)\left\{P_1(r_{ij}^2 + 2\bar{x}_{ij}^2) + P_2(2\bar{x}_{ij}\bar{y}_{ij})\right\} \\ &\qquad = -f\,\frac{(X_j - X_{oi})A_i + (Y_j - Y_{oi})B_i + (Z_j - Z_{oi})C_i}{(X_j - X_{oi})A_i'' + (Y_j - Y_{oi})B_i'' + (Z_j - Z_{oi})C_i''} \\ &\bar{y}_{ij} + F(K)\cdot\bar{y}_{ij} + F(P)\left\{P_2(r_{ij}^2 + 2\bar{y}_{ij}^2) + P_1(2\bar{x}_{ij}\bar{y}_{ij})\right\} \\ &\qquad = -f\,\frac{(X_j - X_{oi})A_i' + (Y_j - Y_{oi})B_i' + (Z_j - Z_{oi})C_i'}{(X_j - X_{oi})A_i'' + (Y_j - Y_{oi})B_i'' + (Z_j - Z_{oi})C_i''} \end{aligned}\right\} \quad \text{Eqs 1}$$

where the subscripts refer to : o for the perspective center,
i for the radiographs, and
j for the object points;

$\bar{x}_{ij}$ and $\bar{y}_{ij}$ are the photo-(radiograph) coordinates referred to the fiducial system [$x_c$ and $y_c$ being the fiducial coords. of the principal point and $x_{ij}$, $y_{ij}$ being the observed coords., $\bar{x}_{ij} = x_{ij} - x_c$ and $\bar{y}_{ij} = y_{ij} - y_c$];

* In order to establish this analogy, however, one has to assume that the X-ray source is a point. In reality, it is an area of several sq mm. In view of a narrow field angle and a long projection distance, this laxity causes not enough error to justify further refinement. The results testify.

$r_{ij}^2 = (\bar{x}_{ij}^2 + \bar{y}_{ij}^2)$;

$F(K) = K_1 + K_2 r_{ij}^2 + K_3 r_{ij}^4 + \cdots =$ Function of radial distortion;

$F(P) = 1 + P_3 r_{ij}^2 + \cdots =$ Function of tangential distortion;

$P_1$, $P_2$ are correction coefficients for decentering distortion;

A,B,C's are the elements of the orthogonal orientation matrix M of the radiograph, functions of three rotations, $\omega, \phi$ and $\kappa$

and $$M_i = \begin{bmatrix} A_i & B_i & C_i \\ A_i' & B_i' & C_i' \\ A_i'' & B_i'' & C_i'' \end{bmatrix} .$$

These equations are linearized and with regard to various points. In view of redundancy in observation data, normal equations are formed for obtaining least squares solutions. These are widely used regular analytical photogrammetric procedures and need no further elaboration here.

In the solutions, excepting $x_{ij}$ and $y_{ij}$, all other parameters are considered unknowns, of whom

3 (X,Y,Z) depend on the number of object points (j's);

6 $(X_o, Y_o, Z_o, \omega, \phi, \kappa)$ depend on the number of radiographs (i's); and

9 (interior orientation parameters) are the same for all radiographs and remain constant in the system.

Because approximate values of most of these unknowns are obtainable a priori, these were considered as 'quasi observations'. Considering two coordinates (giving two equations) per point per radiograph, the number of equations is 2ij. With these considerations, the number of observations (n) is:

$$n = 2ij + 9 + 6i + 3j \qquad \text{Eq 2}$$

and the number of unknowns (m) is:

$$m = 9 + 6i + 3j \qquad \text{Eq 3}$$

In order to calibrate the system with the best possible intersection angles, four radiographs were taken such that the angle of convergence between opposing images was 90°; that is to say, the axes relate to a tilt angle of 45° to the plane of the radiographs and the views are from four directions. 26 well distributed points were used in the study, ie., i = 4 and j = 26.

Certain amount of correlation between some parameters would be expected. This would create some critical geometry, effects of which can be subdued by using more radiographs with further diversities. The resulting standard errors of the parameters in our case may not appear as very great but the object-space coordinates indicate excellent results and the system appears stable. These are what count most in any mensural procedure.

All measurements in this study were made at the Wild STK stereocomparator with the Laval University Department of Photogrammetry.

## ADDITIONAL EQUIPMENT

The self-calibration necessitated some modifications to the existing X-ray equipment. Primarily, a cassette containing reference marks needs to be provided. This is to help define the system of radiographic coordinates. Several small (of ~0.3 mm diameter) balls made of lead inlaid on the front surface of the cassette serve the purpose adequately. Next, proper placement (interior orientation) of the cassette is to be assured. To this end, two interchangeable implements on a support were developed - one to realize the direction of the X-ray source for the cassette and the other to secure the cassette itself (containing the marks). See Fig 1 for details of the outfit.

It was felt essential to fabricate a pattern of radio-opaque points (lead balls) whose coordinates are at least approximately known with regard to a defined system of object-space coordinates. Furthermore, this network of points must be rotatable in order to obtain highly convergent radiographs which would facilitate self-calibration. After having utilized rather successfully, a plexiglass cube containing fine balls of lead and mounted in the

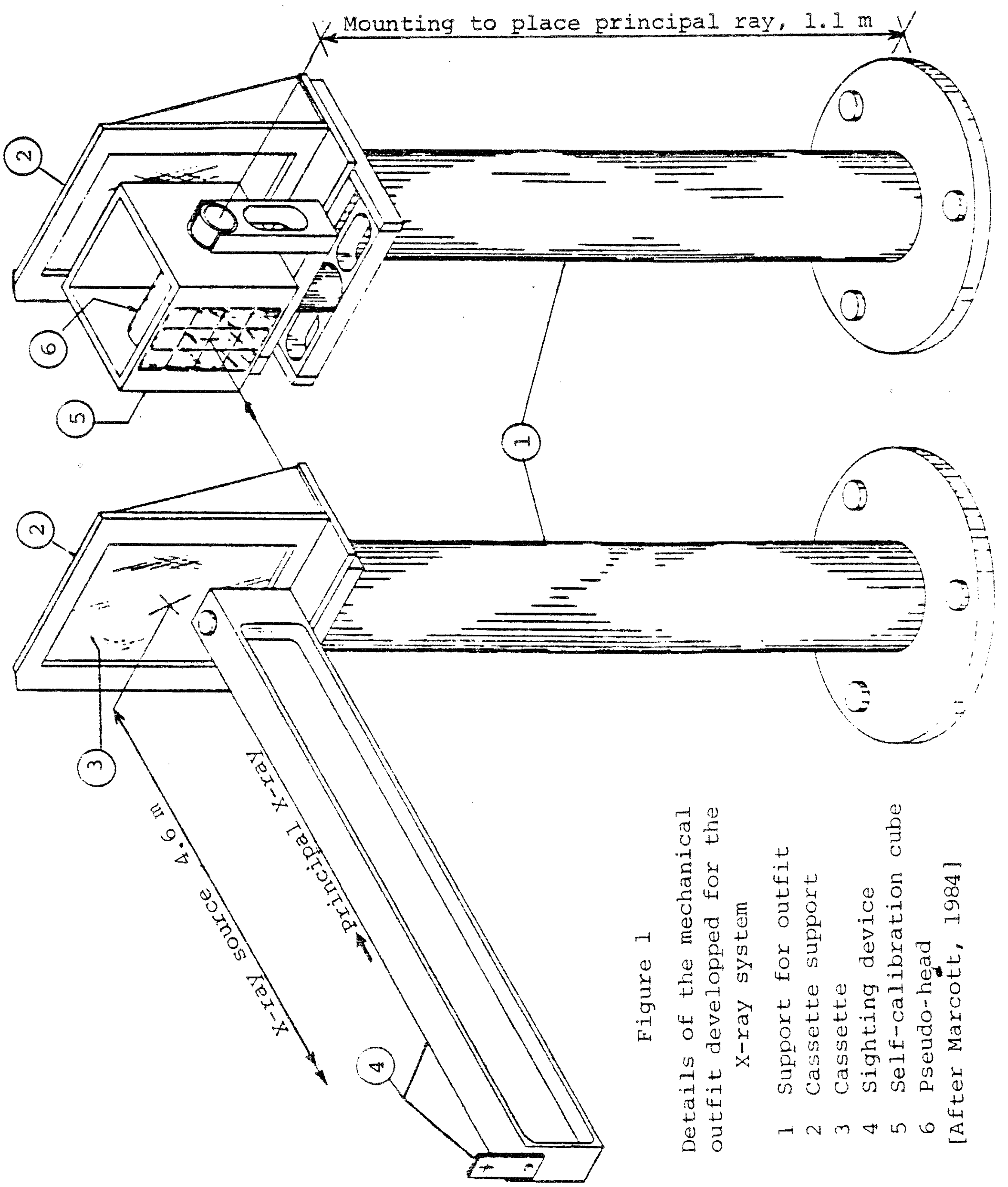


Figure 1

Details of the mechanical outfit developped for the X-ray system

1 Support for outfit
2 Cassette support
3 Cassette
4 Sighting device
5 Self-calibration cube
6 Pseudo-head
[After Marcott, 1984]

manner of a gyroscope (Fig 1), one can safely recommend similar outfits for such purposes. It is also preferable to provide a removable sighting device which would permit to approximately locate the principal point (Fig 1).

## RESULTS OF SELF-CALIBRATION

Principal results of this self-calibration are presented in Table 1. At the first glance it would seem that the standard errors are considerable. The values are, however, valid and usable with reliability. Firstly, the self-calibration approach would be indisputable if one can realize the impossibility of obtaining the values of the parameters directly by any other means. Secondly, in utilizing these obtained values of the parameters, the deviation of any coordinate at any point of radiograph is less ±5 µm as has been established by Boulianne (1983). It may be noted here that the pointing accuracy in this case was estimated as ±10 µm. This is due to the unsharpness inherent in radiography and to the physical dimension of the balls. The large amounts of the standard errors, therefore, reflect the correlations amongst the parameters. This was apparent in the analyses with regard to the variance-covariance matrices (see Boulianne, 1983). On the other hand, the self-calibration solution gives a stable and interlocking state amongst the parameters, whereby to a photogrammetrist what counts most is the final result in the mensural values on the object. This was ±0.1 mm in our case.

Table 1. Results of Self-calibration (interior orientation parameters)

| Parameters | Units | Obtained Values | Standard Errors |
|---|---|---|---|
| $x_o$ | mm | 9.95 | 5.4 |
| $y_o$ | mm | -19.82 | 4.9 |
| f | mm | 4457.00 | 6.1 |
| $K_1$ | $mm^{-2}$ | $-8x10^{-11}$ | $9x10^{-4}$ |
| $K_2$ | $mm^{-4}$ | $5x10^{-19}$ | $9x10^{-16}$ |
| $K_3$ | $mm^{-2}$ | $4x10^{-36}$ | $9x10^{-27}$ |
| $P_1$ | $mm^{-2}$ | $-8x10^{-13}$ | $9x10^{-10}$ |
| $P_2$ | $mm^{-2}$ | $3x10^{-34}$ | $9x10^{-21}$ |
| $P_3$ | $mm^{-2}$ | $-4x10^{-55}$ | $9x10^{-27}$ |

## VERIFICATION

Once the calibration was accomplished, it was considered necessary to test the performance of the X-ray imaging system as a mensural tool. In order to do that, 5 points in a mechanical mock-up called "pseudo head" (Fig 1) were used. The 3-D coordinates of these points were established with precision mechanical means in the High Precision Tools Laboratory of the Laval University Department of Mechanical Engineering. One stereo-pair of radiographs of this pseudo-head was obtained with a parallactic angle of 15°. By using the values of the parameters obtained from the calibration process, the stereomodel was oriented analytically (with stereo-comparator observation data) and the 3-D coordinates of the same points were derived. Their comparison (Table 2) would attest satisfactory performance of the system.

Table 2 shows a maximum difference of 0.3 mm between the mechanical and photogrammetric coordinates at a point. Assuming the possibility, in the worst

Table 2. Comparison of 3-D Coordinates

| Points nos. | Three-dimensional coordinates (mm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Mechanical | | | Photogrammetric | | | Differences | | |
| | X | Y | Z | X | Y | Z | X | Y | Z |
| 27 | -30.0 | -25.0 | 0.0 | -30.0 | -24.8 | -0.1 | 0.0 | -0.2 | 0.1 |
| 28 | -15.0 | 0.0 | -25.0 | -15.0 | 0.0 | -24.7 | 0.0 | 0.0 | -0.3 |
| 29 | 0.0 | 25.0 | 0.0 | 0.0 | 24.9 | 0.0 | 0.0 | 0.1 | 0.0 |
| 30 | 15.0 | 0.0 | 25.0 | 15.1 | 0.0 | 24.9 | -0.1 | 0.0 | 0.1 |
| 31 | 30.0 | -25.0 | 0.0 | 30.1 | -24.8 | 0.0 | -0.1 | -0.2 | 0.0 |

case, of a difference of 0.3 mm at each of three coordinates of any point, this would give a maximum possible positional error of ±0.5 mm. The precision of the mechanical coordinates, nonetheless, remains uncertain to some degree. On the other hand, if one can hold on to the results of the photogrammetric self-calibration, a standard error of ±0.1 mm at each of the three coordinates of any point would give a positional error much more indisputable and certainly more than adequate in the present case.

## FLOATING LINE

Subsequent to the success reported above was considered the problem of implantation of the probe. This would be a "child's play" if the surgeon could be provided with a reliable scale-model of the patient's brain such that he could find the most suitable "path" to introduce the probe through an eye-ball inspection and establish a one-to-one correspondence between that model (on which all necessary measurements and surgical preparations can be made) and the patient's brain itself.

Since the probe has to be rectilinear, its placement designs and final implantation can best be made by using a "floating line" as against the use of a "floating mark", which is well established in photogrammetry. If one can float a point in a visual model, it should be easy to float a line also. Such a floating line would, of course, contain two definitive points at the two ends. Depending on their locations, the distance between them and the direction of the line joining them should be variable freely and conveniently within the model space. On the other hand, the purpose would not be served with just only the two end points, because the space coming between them needs to be constantly checked for safety reasons.

In this regard, the center of the damaged cell within the brain would remain always one end of this floating line while the other end needs to be determined by the neurosurgeon. In view of the above, an analogue device has been developped. This prototype outfit (Fig 2) works with any standard mirror stereoscope. It consists of a sort of a ruler on a portable tracing table that can move parallel. There are two acrylic discs (transparent) which can be slided along the length of the ruler while the discs can be individually rotated freely around their centers. Each center carries a perforated hole. Each disc carries a fine radial line engraved on its lower side to be in contact with the photograph (emulsion side).

Finally, the extremities of the lines are broken so that under stereovision, with appropriate orientation of the two lines, the floating line can be regulated for its length in space. Furthermore, at the ends of the lines, the disc is perforated to facilitate marking points as may be necessary.

This portable ruler is placed under the stereoscope and over the photographs such that the center of each disc rests on the center of the image of the damaged cell. The line joining the centers of the discs, thus, remains parallel to the stereo-base.

Utilization of the apparatus is simple and does not require any better stereovision that normally desired in stereo-photogrammetric works. The operator follows the following steps:

1. Orient the stereo-radiographs.
2. Determine the target point (ie., the damaged cell) which the probe must reach. This also must correspond to the fused centers of the discs. This is done by moving and separating the discs - (something like a parallax-bar in common practice).
3. Rotate the discs (ie., the lines) such that firstly the radial lines fuse to give a floating line, and secondly, under stereo-vision, the floating line does not appear to intercept any blood vessel and permits sufficient space around to make the operation successful.
4. Transfer/mark on the radiograms, through the perforations, the target point and the end point for each radial line.
5. Determine the spatial coordinates of these two points by regular photogrammetric procedure at an analytic plotter or with comparator data.
6. The information is sufficient for the neurosurgeon if the data are referred to a system identifiable with the patient's brain/head.

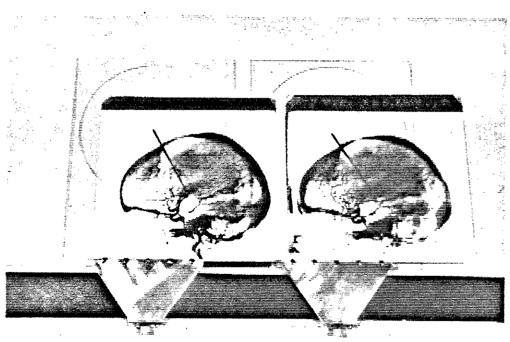

Figure 2: Floating Line Device (Prototype)

CONCLUSIONS

The following general conclusions may be drawn from the research discussed briefly in this paper:

1. The type of projection forming a radiographic image can be considerer to be, for all practical purposes, central perspective.
2. The self-calibration technique used for a conventional photogrammetric camera can be easily adapted to an X-ray imaging system.
3. The effects of certain physical phenomena, refraction and diffraction in particular, may be neglected in the context of medical practices

and the X-rays may be considered to follow straight line paths.

4. The residual distortion (after considering a 6 parameter correction for radial and tangential components) is proven to be less than ±1 μm on the radiograph. With a set-up as the one used in the study (ie., the perspective center being more than 4 m away, such distortions contribute errors not more than ±10 μm on the micrograph.
5. The analytical photogrammetric approach followed in this research is capable of yielding a positional (in three dimensional space) accuracy of ±0.2 mm on the object.
6. The floating line device seems to be admirably successful in its use. An "on-line" possibility would, however, be of better usefulness.

The results being satisfactory, this multi-disciplinary research is now directed towards further applications in the wide medical fields. The use of analytical plotters with regard to such radiographs seems obvious. Capabilities of obtaining certain derived data "on-line" for such applications would be essential in numerous cases.

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