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# A Photogrammetric Contouring Method for Radiation Therapy

**By confining all known control points and unknown contour points to a plane, a simple one-to-one correspondence from spatial to photographic coordinates is established.**

Abstract: *Photogrammetry is employed to find cross-sectional contours of patients undergoing radiotherapy for use in computerized treatment planning. By confining all known control points and unknown contour points to a plane, a simple one-to-one correspondence from spatial to photographic coordinates is established. Hence, a linear transformation of coordinates is easily solved for. The found contour is then available for routine and well established planning techniques. The system easily integrates into existing radiotherapy equipment. An extension of the technique to three dimensions is outlined.*

## Introduction

The application of computer technology to treatment planning in radiation therapy has had widespread success, as indicated by the number of computer systems now offered by 12 different companies as well as a national time sharing system. The most important feature of a treatment planning system is the external beam planning program. Typically, a cross-sectional outline is presented to the computer program, the entrance points of external radiation fields as from a Co-60 source or a linear accelerator are indicated, and the computer program sums up the effects from all radiation fields and displays a map of the radiation dose distribution.

One problem which continues to plague treatment planning, however, is how to determine the external contour of the patient, the contours of internal gross structures, and the relationship of these contours to the coordinate system of the radiotherapy external beam machine. Accurate data are absolutely necessary if the treatment plan is to have any meaning. Well known established techniques consist in measuring the patient's contour with lead wire or a rod box, marking on the contour corresponding landmarks on the patient's surface, and locating the patient's landmarks with respect to the therapy machine. Internal structures are located by viewing anterior-posterior and lateral radiographs or by consulting a cross-sectional atlas. Each step of this process can introduce considerable error if great care is not taken. Various electro-mechanical and optical aids have been introduced to determine the external contour.[1-8] All of these techniques involve the fabrication of fairly complex instruments or the availability of expensive equipment. A stereo-photogrammetric



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method[14,15] involves two cameras, the solving for coordinates of unknowns identified on both photographs, and a more complex system than that presented in the present report.

The recent availability of computerized tomography (CT) has provided a dramatic means of visualizing internal structures in a cross-sectional image of the patient. The use of these remarkable scanners as a radiotherapy treatment planning device does have several drawbacks: (1) The high cost of the CT scanner cannot be justified for use in radiotherapy alone. A CT scanner is, in general, not available to the radiotherapy department unless the hospital has purchased one for diagnostic purposes. Even then, the scheduling of patients may be heavy and the scanner is not readily available at most institutions for use by the radiation therapy department on demand for routine patient set-up. Also, the monetary cost to the patient may be high. (2) It may be difficult or impossible to position the patient in the CT scanner in the identical treatment position. The limitations include differences in couch contour and those imposed by the tunnel geometry of the CT scanner. The tunnel is most often not large enough to image the entire contour. (3) External markers must still be relied upon to orient the contour on the CT scan in relationship to the coordinate system of the therapy treatment machine.

Our purpose is to measure the external contour of the patient as presented on the table of the treatment machine and use other means, such as the CT scan, to orient important internal structures.

## The Photogrammetric Technique

The present technique differs from a previously reported one[12,13] in which the three-dimensional surface topography was measured. In this report, a complete two-dimensional contour is found. The mathematics is simplified in that there is a one-to-one correspondence between co-planar points in space and image points on the plane of the photograph. Hence, if a contour consisting of unknown points and known "control" points all lie in the same plane, then only one photograph is needed to find the $x$, $y$ coordinates of the unknowns. To accomplish this, the frame shown in Figure 1 has miniature light bulbs mounted around the outside perimeter so that the light bulbs are all in one plane and they protrude beyond the frame. The frame is free to slide on the treatment table while enclosing the patient. It is necessary only to employ some means of marking a co-planar contour around the perimeter of the patient. Any of several techniques may be employed to accomplish this. One would be to use the light field of the therapy machine by inserting a narrow slit in the tray slot, or the cross hair may be used if it is easily distinguishable on a photograph. Side lasar lights that mount on the walls of the treatment room and project a line are available commercially[10] and are excellent for marking the contour. Many institutions have only laser dots, but these may be easily converted to project a line by mounting a cylindrical lens[9,11] (see Figure 8). Alternately, a Ronchi diffraction grating may be mounted to simulate a line.[11] If the contour line is visible on the photograph with room lighting, the miniature light bulbs would not be necessary. Nail heads could be substituted.

The patient is positioned as for treatment. The control frame is then placed on the table so as to enclose the patient (Figure 2). By sliding the frame to the appropriate position, the side laser lights are used to locate the position of the frame relative to the isocenter of the therapy machine. The isocenter is the

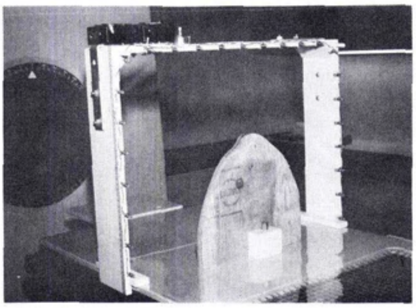

FIG. 1. The light bulb frame in position on the couch. The wood board represents a cross section of a patient.

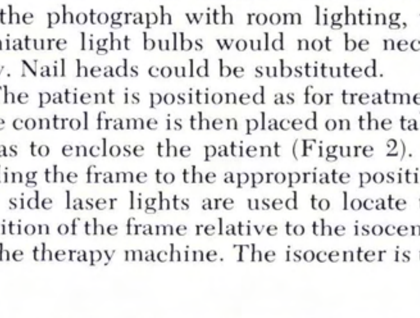

FIG. 2. The EMI (now ATC) linear accelerator. A side laser light mounted on the far wall can be seen. The machine can rotate around the couch.

point in space about which the machine rotates. Alternately, the central axis of the light field and range finder may be used to determine the same. The mounting of a plastic ruler on the top and sides of the control frame will facilitate this operation. The scale has been adjusted so that the two coordinates obtained are the $x$ and $y$ coordinates of the isocenter relative to the coordinate system of the control frame. These two numbers are recorded. The control frame must then be slid so that the light bulbs and contour are in the same plane.

Any number of photographs may now be taken of the patient's contour and control frame, although two will usually suffice. One should attempt to get as many light bulbs as is possible in each photograph. The gantry may be rotated during this procedure if using the source light, for example, to the position of each treatment port. The photographs in Figure 3 were taken with a Polaroid model 450 camera with a portrait lens and type 107 film. In this case the source light of the treatment machine was used to project the sheet of light necessary for marking the contour. With the room lights off, a 2 second exposure is typically required with the camera mounted on a tripod. The intensity of the light bulbs was decreased by the use of a potentiometer so that their images would not be too large on the photograph.

An opaque projector[11] is now used to project each photograph directly onto the graphics terminal of the treatment planning computer system (Rad-8, available from ATC Medical Technology, Sunnyvale, California, Figure 4). By locating the images of the light bulbs, the transformation of coordinates between the object space and photograph is determined. The $x$, $y$ spatial coordinates of the light bulbs were previously determined and stored on a disk file which is referred to by the computer program. The contour is then traced using the graphics terminal. In addition, tick marks may be located on the contour by indicating visible landmarks present on the photograph, such as the entrance points of the radiation fields. Introduction of the coordinates of the isocenter as found above will allow the plotting of the isocenter within the contour, so that the contour is now located relative to the treatment machine.

Since portions of the contour found on multiple photographs may overlap, a routine was provided to arrange the contour points sequentially. This is accomplished by first locating the center of mass of the maximum and minimum $x$ and $y$ spatial coordinates, respectively. The contour points are then arranged in order of increasing angle relative to the direction of the negative $y$ axis ($y$ is positive vertically upward) through the center of mass. A second pass is then optional in which the next closest contour point not already picked is found, arranging the contour points in the order picked, starting with the first contour point found above. Lastly, the contour is closed by dropping a line vertically to the table top, running across the table, and then up vertically to the first contour point. The resultant contour and actual contour are shown together in Figure 5, from which a typical plan may be computed.

Good accuracy is critically dependent on the light bulbs and contour being co-planar. This requires careful alignment of the light bulb frame but can be accomplished by noting where the slit of light falls on the light bulbs or other protruding structures of the frame. In addition, there should be a large angle between the camera axis and spatial plane of the contour. Consider a photograph of the contour edgewise where the $x$ spatial axis has been collapsed so that 6 mm on

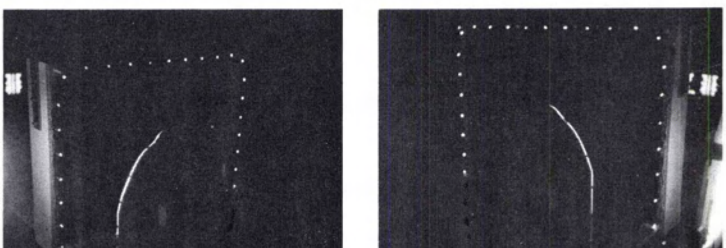

FIG. 3. Polaroid photographs of the board in Figure 1. The source light of the accelerator was used to project the slit of light. The four bottom light bulbs of the far side of the frame in each picture were not used as control points since a patient would have blocked their view.

FIG. 4. The SHM (now ATC) Rad-8 computer system. An opaque projector (upper center) has been mounted to project Polaroid photographs onto the graphics terminal (right).

## MATHEMATICAL THEORY

Consider the coordinate system depicted in Figure 6. Let the center of perspective, $C$, (the location of the camera lens) be given by $Xc$, $Yc$, $Zc$ in spatial coordinates. The center of the photograph, $O$, (principle point) is at $Xo$, $Yo$, $Zo$; the image point, $P$, at $Xp$, $Yp$, $Zp$; and the object point, $A$, at $X$, $Y$, $Z$. The photographic coordinate system is designated by a prime. The principle point is at $e_x'$, $e_y'$, $O$; and the center of perspective is at $e_x'$, $e_y'$, $f'$. $P$ is given by $x' - e_x'$, $y' - e_y'$, $O$. Then the vector $CP$ in both coordinate systems is related by

$$\begin{pmatrix} x' - ex' \\ y' - ey' \\ 0 - f' \end{pmatrix} = \begin{pmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{pmatrix} \begin{pmatrix} Xc - Xp \\ Yc - Yp \\ Zc - Zp \end{pmatrix} \quad (1)$$

We have from colinearity

$$\begin{pmatrix} Xp \\ Yp \\ Zp \end{pmatrix} = T \begin{pmatrix} X - Xc \\ Y - Yc \\ Z - Zc \end{pmatrix} + \begin{pmatrix} Xc \\ Yc \\ Zc \end{pmatrix} \quad (2)$$

where T can be found by considering that CO $\perp$ OP and, therefore, CO $\cdot$ OP = 0.

$$T = \frac{(Xc - Xo)^2 + (Yc - Yo)^2 + (Zc - Zo)^2}{(X - Xc)\,(Xo - Xc) + (Y - Yc)\,(Yo - Yc) + (Z - Zc)\,(Zo - Zc)} \quad (3)$$

the projected photograph would represent 60 cm in space. To obtain spatial coordinates within 3 mm would require distinguishing to within 0.03 mm on the photograph, a not very likely prospect. Therefore, the camera axis should make at least a 45° or larger angle with the plane of the contour.

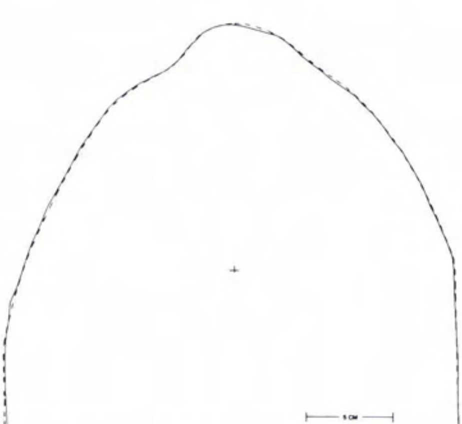

FIG. 5. A comparison of contours found from the photographs in Figure 3 with the actual shape of the board. The dotted line is the actual contour. The solid line was determined from the photographs through use of the computer and incremental plotter.

By substituting Equations 3 and 2 into 1, rearranging, absorbing all unknowns and constants, and relabeling, we get the following equation:

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \dfrac{X\,b_1 + Y\,b_2 + Z\,b_3 + b_4}{X\,a_1 + Y\,a_2 + Z\,a_3 + 1} \\[2ex] \dfrac{X\,b_5 + Y\,b_6 + Z\,b_7 + b_8}{X\,a_1 + Y\,a_2 + Z\,a_3 + 1} \end{pmatrix} \quad (4)$$

Now if all object points are co-planar, we may set Z = 0. We are then left with eight coefficients, which may be solved for by using known control points. Rearranging Equation 4, we have

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} X & Y & 1 & 0 & 0 & 0 & -x'X & -x'Y \\ 0 & 0 & 0 & X & Y & 1 & -y'X & -y'Y \end{pmatrix} \begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \\ b_5 \\ b_6 \\ b_7 \\ b_8 \end{bmatrix} \quad (5)$$

where the unknown coefficients have been relabeled. The system is thus linear. Upon solving for the unknown coefficients $b_1$ thru $b_8$ by using least-squares techniques, we can compute the $X$ and $Y$ coordinates of unknown points from their photographic coordinates using the equation below:

$$\begin{pmatrix} X \\ Y \end{pmatrix} = \begin{pmatrix} \dfrac{(x' - b_3)(b_5 - y' b_8) - (y' - b_6)(b_2 - x' b_8)}{(b_1 - x' b_7)(b_5 - y' b_8) - (b_4 - y' b_7)(b_2 - x' b_8)} \\ \dfrac{(b_1 - x' b_7)(y' - b_6) - (x' - b_3)(b_4 - y' b_7)}{(b_1 - x' b_7)(b_5 - y' b_8) - (b_4 - y' b_7)(b_2 - x' b_8)} \end{pmatrix} \tag{6}$$

### Extension to Three Dimensions

The technique may be extended to find multiple contours for a short section of the patient. In the simplest case, the patient may be translated along the Z axis (which runs along the length of the table) and the above described technique repeated. However, if multiple parallel plane contours can be marked on the patient simultaneously, then one photograph can be used to find all the contours on one side of the patient. All that is required is that the control points have different Z coordinates as well as X and Y, and that the Z coordinate of each parallel plane be known. If the Z coordinate in Equation 4 is not set to zero, then the equivalent of Equation 5 is now

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} X & Y & Z & 1 & 0 & 0 & 0 & 0 & -x'X & -x'Y & -x'Z \\ 0 & 0 & 0 & 0 & X & Y & Z & 1 & -y'X & -y'Y & -y'Z \end{pmatrix} \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \\ c_5 \\ c_6 \\ c_7 \\ c_8 \\ c_9 \\ c_{10} \\ c_{11} \end{bmatrix} \tag{7}$$

Equation 6 now reads:

$$\begin{pmatrix} X \\ Y \end{pmatrix} = \begin{pmatrix} \dfrac{(c_6 - y'c_{10})(x' - c_4 - Z(c_3 - x'c_{11})) - (c_2 - x'c_{10})(y' - c_8 - Z(c_7 - y'c_{11}))}{(c_1 - x'c_9)(c_6 - y'c_{10}) - (c_5 - y'c_9)(c_2 - x'c_{10})} \\ \dfrac{(c_1 - x'c_9)(y' - c_8 - Z(c_7 - y'c_{11})) - (c_5 - y'c_9)(x' - c_4 - Z(c_3 - x'c_{11}))}{(c_1 - x'c_9)(c_6 - y'c_{10}) - (c_5 - y'c_9)(c_2 - x'c_{10})} \end{pmatrix} \tag{8}$$

Equation 7 may be used with known control points to find the coefficients $c_1$ through $c_{11}$, where we now require a minimum of seven control points compared to five previously. Properly identifying the contour to be found so that the correct Z coordinate is employed, Equation 8 may be used to find the coordinates of unknown points on the contour. Hence, one would proceed by first identifying all visible control points at the computer graphics terminal, and then tracing each contour. The technique would be very similar to that previously reported[12,13] but differing in that continuous contours are generated rather than entering specific points. One photograph would be sufficient in most cases for each side of the patient. The technique would be superior to a reported stereo-photogrammetric technique[14,15] in that data is found along the sides of the patient rather than just the top surface.

It is not entirely necessary that the contours lie in parallel planes. If a slide projector were to project parallel lines that sweep out planes, so that the planes result from a central point projection, the contours of each plane can still be found from one photograph. Equation 7 would be used to find the coefficients $c_1$ through $c_{11}$ as before. It is then only necessary to know a transformation for each plane in the form of Equation 9, i.e.,

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} a_1 & b_1 \\ a_2 & b_2 \\ a_3 & b_3 \end{pmatrix} \begin{pmatrix} u \\ v \end{pmatrix} + \begin{pmatrix} d_1 \\ d_2 \\ d_3 \end{pmatrix} \tag{9}$$

where $u$, $v$ is a two dimensional coordinate in each plane and the constants $(a_1, a_2, a_3)$; $(b_1, b_2, b_3)$; and $(d_1, d_2, d_3)$ define vectors transforming $u$, $v$ to the spatial coordinate system, $X$, $Y$, $Z$. By substituting Equation 9 into Equation 7, $u$, $v$ may be solved for in terms of $c_1$ through $c_{11}$, $x'$, $y'$, and the constant vectors in Equation 9. Hence, by identifying the proper plane, $u$, $v$ may be found from photocoordinates and Equation 9 is employed to find spatial coordinates.

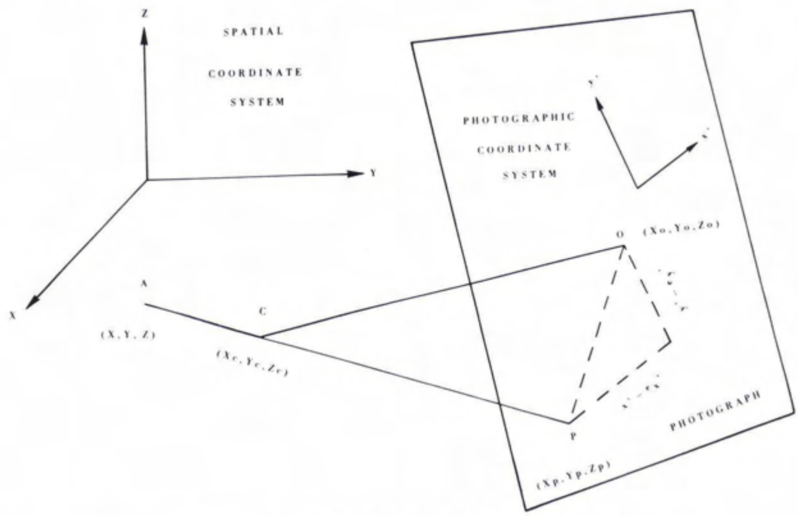


FIG. 6. Spatial and photograph coordinates.

Although the resultant contours are not in parallel planes, suitable algorithms can be written to present the three dimensional shape of the patient in any form desired.

## EXAMPLE CASE

Shown in Figure 7 are two photographs of a patient who is to undergo radiotherapy for recurrent carcinoma of the cervix. The lines marking the patient's sides were projected from laser lights mounted on the walls with a cylindrical lens added as in Figure 8. A ¼ inch glass stirring rod was used for the lens. The round base used for mounting the cylindrical lens may be rotated to another opening so as to recover a single laser ray for finding the position of the isocenter on the patient, which was the original purpose of the laser lights. To mark a line from above, a Ronchi ruling with 200 lines per inch was mounted on the ceiling laser light. The central maximum of the diffraction pattern enables visualization of the original single ray, thus eliminating the need to climb to the ceiling to rotate the round base.

The use of laser lights enables one to quickly take the photographs in Figure 7, once the machine is rotated at a 45° angle to clear all projected lines. Employing the source light of the machine as was used in Figure 3 necessitates rotating the machine for each photograph, which is not as satisfactory.

Only about five minutes is required sitting at the computer to generate the contour from the photographs. A radiation plan may then be generated such as that shown in Figure 9 for this patient. Two partial rotations of 80° each with the isocenter (center of rotation) separated by 4 cm were employed to generate the radiation dose distribution shown. The orientation of the bone structures were determined from a CT scan. The accuracy of the computer generated radiation dose map is dependent on the accuracy of the external contour.

## CONCLUSIONS

The photogrammetric system is accurate enough for clinical purposes (Figure 5). The system will integrate into existing therapy equipment, the only fabrications required being the light bulb frame (Figure 1) which is a fairly simple device. Modification of the room laser lights may also be required as was shown above.

The only drawback in the technique is the

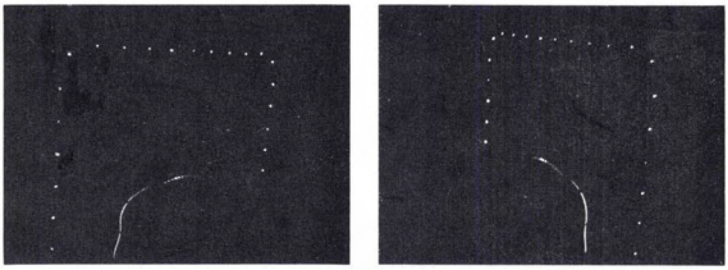

FIG. 7. Two photographs of a patient's pelvis. Side laser lights were used to project a line, and a Ronchi Ruling was used over head.

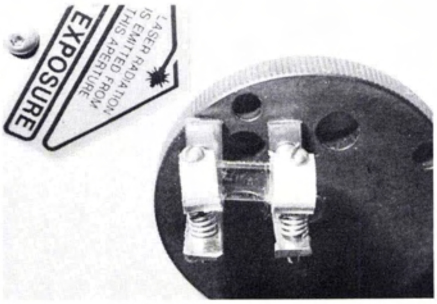


Fig. 8. Modification of the side laser light to project a line by mounting a cylindrical lens.

need to align the lightbulb frame with the sheet of light every time the technique is used. An error in alignment will degrade the accuracy of found coordinates. One is thus not automatically assured of correct alignment every time the technique is used, which is a disadvantage from a quality assurance standpoint. One way to overcome this difficulty might be to mount laser tubes directly on the light bulb frame to project co-planar sheets of light. Hence, the alignment would only need to be done once and the quality of found contours would be assured each and every time. The cost of such a modification might be around $600, which would lessen the advantage of an inexpensive technique, but would still be cost-effective compared to other techniques. One could also have a dedicated table for measuring contours.

Other possible improvements would be the use of a TV camera. By fixing the camera so it cannot move and by using wall mounted lasers, the transformation of coordinates need only be determined once, eliminating the lightbulb frame. A direct link to the computer system would provide a rapid system through use of a "light pen" to identify image points on a TV monitor.

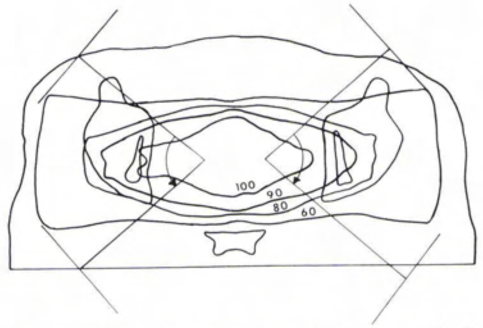


Fig. 9. The computer generated plan for the patient in Figure 7. Shown are the 100, 90, 80, and 60 percent isodose lines. Two 8 by 15 cm x-ray beams (the 8 cm dimension is in the plane of the contour) are rotated through an 80° arc.

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