A REAL-TIME PHOTOGRAMMETRIC SYSTEM FOR PATIENT POSITIONING IN PROTON THERAPY

G. van der Vlugt

H. Rüther
Professor and Head of Department

Department of Surveying and Geodetic Engineering
University of Cape Town
Republic of South Africa

Commission V

ABSTRACT

Traditionally mechanical devices have been used to position patients with intracranial lesions for proton beam therapy. A novel real-time photogrammetric method (Adams and Rüther, 1989) has been developed to replace these techniques with the objective of improving positioning efficiency and patient comfort. This paper reports on the realisation of the initial concepts and describes principles, system hardware, software and operational procedures. Finally, system test results and precisions are discussed. At the time of the formulation of this paper the system is already installed and undergoing testing in the treatment vault of the National Accelerator Centre (NAC), at Faure near Cape Town.

KEY WORDS: Digital Photogrammetry, Real-Time Photogrammetry, Proton Therapy, Automated Positioning.

INTRODUCTION

One of the methods employed in the treatment of patients suffering from intracranial lesions is the exposure of the lesion to a proton beam. For this purpose it is not only necessary to locate the lesion, but also to place the patient in a position guaranteeing correct alignment of the lesion in the treatment beam. The equipment used for locating and positioning the lesion is typically found in different rooms of the same institution or in different institutions. This necessitates the use of a common reference to relate the two coordinate systems employed in these different stages.

When the construction of a proton treatment clinic at the NAC in Faure near Cape Town was discussed, it was recommended by Adams (1989) to use digital photogrammetry based on an existing digital camera system (Rüther and Parkyn, 1990) for the patient positioning component. This approach was accepted as the most economical solution to the problem. Closely associated with this system is the development of a computer controlled patient support chair by the Department of Mechanical Engineering at the University of Cape Town.

Having adopted digital photogrammetry as the positioning principle, the patient positioning problem can now be seen as comprising two principal components:

1. Medical imaging component

   The lesion is located relative to the reference system by means of a medical imaging process, such as the CT (Computer Tomography) or MRI (Magnetic Resonance Imaging) scan.

2. Digital photogrammetry component

   Digital photogrammetry is applied to position the lesion into the proton beam and to monitor the patient's movements.

The digital photogrammetry component of the procedure can be divided into camera calibration, system check, patient positioning and patient monitoring.

In this paper these digital photogrammetric components will be discussed together with software and hardware aspects of the system. A brief overview of the lesion location stage (although not part of this research) is also included in order for the reader to fully comprehend the entire treatment procedure.

THE LESION LOCATION STAGE

Using medical images in conjunction with a technique reported by Adams (1990), the position of the intracranial lesion is determined relative to reference points attached to the patient's head. These reference points are later used to establish the relative position of the lesion with respect to the permanently fixed horizontal beam line in the treatment vault. The lesion and reference targets are simultaneously imaged on the CT or MRI scan. At present, small ball bearings serve as reference targets in the CT scan, while for the MRI scan small plastic capsules filled with fish oil are utilised. These scans have the capability of allowing the determination of three-dimensional coordinates of the lesion and targets in the reference coordinate system (referred to as the scan coordinate system). According to Adams (1990) "it is possible to derive three-dimensional coordinates of well defined targets to a vector precision of approx. 1.5 mms" for CT scans.

Once the lesion is located, medical specialists decide on suitable beam entry points in positions which ensure that no sensitive areas of anatomy (eg optic nerve or spinal cord) are passed through by the beam line. These unmarked points are also coordinated in the scan system. The vectors between beam entry points and the lesion must be aligned with the beam before therapy can commence.

The reference points on the patient's head are later targeted with retro-reflective markers for the digital photogrammetry process. In order to guarantee reproducibility of the target positions between treatment stages, the points can be tattooed onto the patient's skin. Another option under consideration is the use of a personalised patient mask with permanently attached reference targets.

SYSTEM HARDWARE AND CONFIGURATION

Before describing the hardware of the photogrammetric patient positioning system (PPPS), it is necessary to outline its relationship with the other modules of the proton treatment system. Figures 1 and 2 show the hardware configurations of the overall treatment system and the PPPS respectively.

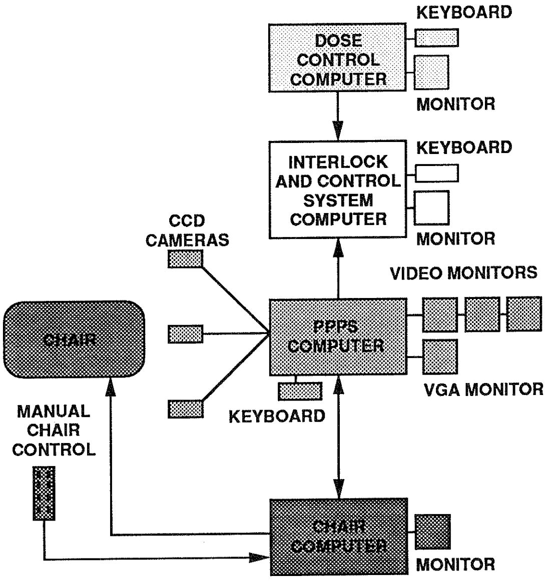

Fig.1. Hardware configuration of the proton treatment system

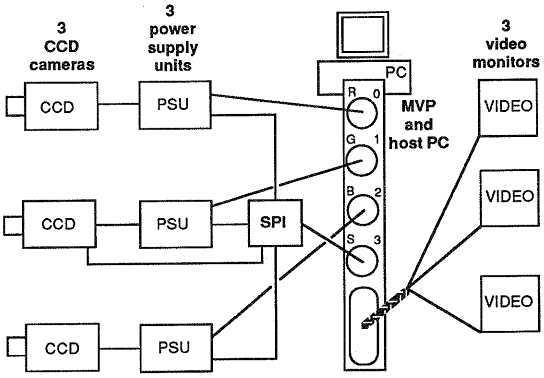

Fig.2. Hardware components of PPPS

The system components are

1. Photogrammetric Patient Positioning System (PPPS)
    - 1.1 Three Philips CCD video cameras, power supply units (PSU) and a signal processor interface (SPI).
    - 1.2 Matrox MVP-AT frame-grabber and image-processing card (512 by 512 by 8 bits image formats)
    - 1.3 Unisys 386 PC with an 8087 Math coprocessor
    - 1.4 Three external Philips video monitors
2. Patient support chair system
    - 2.1 Computer controlled chair
    - 2.2 Computer for chair control
    - 2.3 Manual controller
3. Dose control computer
4. Interlock and control computer

The PPPS computer (which is responsible for all the digital photogrammetry procedures) is connected to the chair computer through its communication port, and to the interlock and control computer through a relay.

The chair can be controlled by a hand-held unit, for provisional positioning by the operator, and automatically by the PPPS (through the chair's computer), for the fine positioning.

The interlock and control system controls the activation and deactivation of the proton beam. Before the beam is activated the system ensures that all necessary safety procedures have been completed. These procedures include activating various switches, passing check points, closing safety gates and various other precautionary measures. These must be strictly adhered to by the operators in the interest of patient and staff safety. The interlock and control system will also deactivate the beam if the PPPS detects any intolerable patient movement.

The dose control computer, which regulates the radiation exposure, is a separate unit connected to the interlock and control computer.

The frame-grabber simultaneously captures three images and stores them in three frame buffers, each with a 512 by 512 by 8 bits format. A fourth frame buffer of equal size is available for image processing operations. From Figure 2 it can be seen that of the four input channels on the MVP-AT frame-grabbing and image-processing card, channels 0 - 2 receive the video signals from the three black and white CCD (Charged Coupled Device) cameras. Channel 3 is used for the synchronisation (sync) input. The power supply units (PSU) provide power for the cameras as well as sync-signals. Originally, difficulties were encountered with the synchronisation of the three cameras. These were overcome by introducing a signal processor interface (SPI) designed by the Department of Electrical and Electronic Engineering at UCT. The SPI acts as a distribution amplifier bringing the sync and video signals up to the required amplitude and waveshape, and isolating the input from the output. Double terminations are thus avoided and perfect matching (75 Ohms) is obtained (Private communication, J. Hesselink).

To enable the system operator to efficiently respond to the image information received from the cameras, the MVP outputs the video images to the three analog output monitors as shown in Figure 2.

CAMERA/OBJECT CONFIGURATION

It was decided to install a total of eight cameras at eight camera stations, uniformly distributed around the patient chair (Figs. 3 and 4). The configuration was designed to allow for different patient treatment positions. Four stations are located at the level of the beam-line and four at approximately a 45 degrees angle above the horizontal. The stations are all roughly 2.5m away from the lesion point, where the lesion point is defined by the intersection of the vertical chair axis and the beam line.

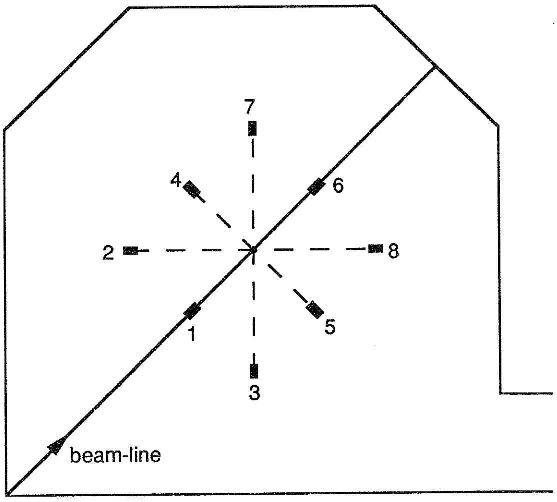

Fig.3 Plan view of camera station positions.

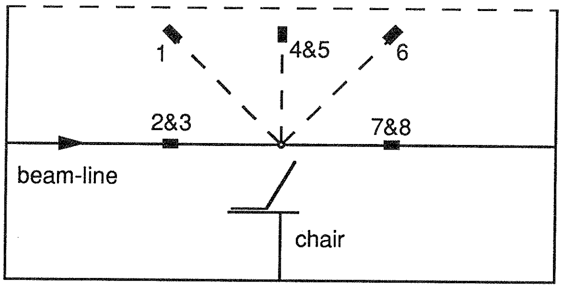

Fig. 4 Vertical section along beam line.

Of the eight cameras, only three, on adjacent stations, will be used at any one time. This arrangement provides acceptable geometry and target visibility, as well as redundancies for system reliability. More than three simultaneously active cameras would demand additional frame-grabbing capabilities and complicate operator procedures unnecessarily.

CONTROL FRAME

The CCD cameras need to be regularly calibrated in the beam coordinate system using control targets of known position. For this purpose a total of twelve to fourteen control points, visible on each image, was considered suitable. This number of points in an appropriate configuration is sufficient to obtain the required precision and reliability. To guarantee a minimum of twelve visible points per camera station, a total of 40 suitably placed points had to be mounted on a removable, but stable frame of cube-shape.

Permanent mounts are incorporated into the treatment room floor so that, for each calibration procedure, the frame can be placed in an identical position with its centre approximately at the lesion point.

The targets were coordinated to sub-millimetre precision using theodolite observations and bundle adjustment algorithms (Brown, 1985).

TARGET DETECTION AND CENTRE DETERMINATION

To enable automatic target detection it was necessary to introduce point markers which are readily distinguishable from the background in the controlled environment of the treatment room. Retroreflective tape, the use of which is widely reported in the literature (Brown 1982, Fraser 1988), proved appropriate for this application. This material requires suitable lighting originating from the direction of each camera, best achieved by a ringshaped light source around the camera lens.

The target detection algorithm developed for the system relies on binary images, necessitating a thresholding procedure to separate targets and background. A computer-aided routine allows the operator to choose a suitable threshold value by inspection of the output images, resulting in a binary image in which targets are represented by bit value one (white) and the background by value zero (black). This binary image is then easily searched for targets and the target boundaries are determined for centre determination on the original grey images.

After detailed investigation of target centre determination algorithms (Rubinstein and Rüther, 1991) the weighted centre of gravity model in conjunction with background-reduced circular targets emerged as the most efficient method for automatic centre determination. For the system, circular targets of approximately eight millimetres in diameter, equivalent to about seven by six pixels on the image given the geometric parameters, proved ideal as control point markers.

THE DIGITAL PHOTOGRAMMETRIC PROCEDURE

The photogrammetric procedure can be divided into four stages:

1 **Camera calibration** - the position as well as the interior and exterior orientation of each camera is found using the control points.

2 **System check** - the camera calibrations and the chair position are checked.

3 **Patient positioning** - the patient is moved into the beam-line.

4 **Patient monitoring** - possible patient movements are monitored to ensure that correct alignment is maintained.

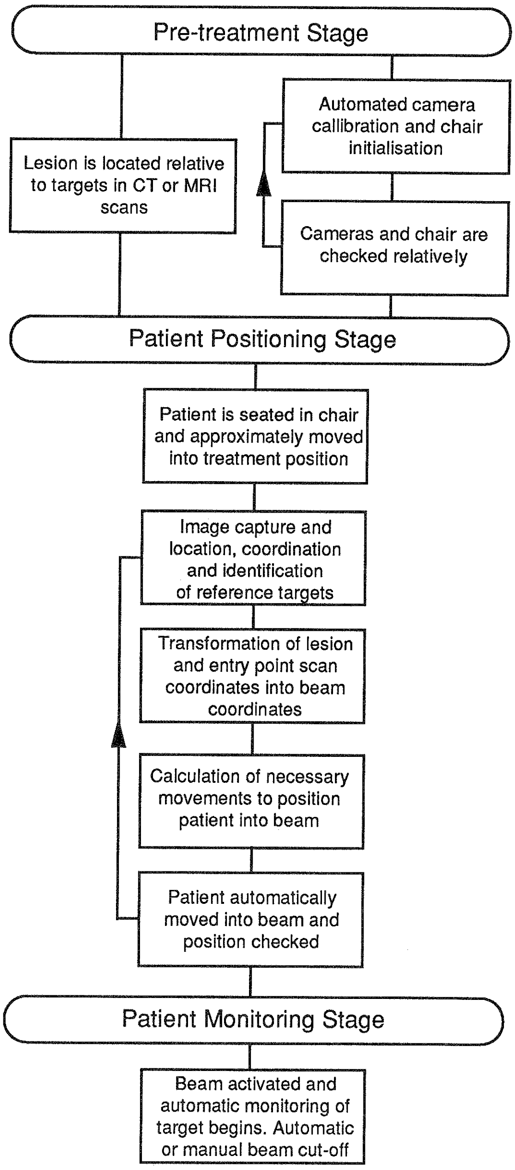

Fig.5 Flowchart of positioning stages.

Figure 5 depicts a flow chart of these photogrammetric stages including the lesion location stage, which is carried out separately as described above. This diagram emphasises the patient positioning stage of the project.

Camera Calibration

System cameras must be calibrated at regular intervals, after changing camera positions for different treatment positions or after accidental disturbance.

When a calibration is needed, the chair is lowered below the floor and the control frame is placed in position. All three camera images are then thresholded and automatically searched for control targets. The target positions are stored and displayed by circles on the video monitors for verification by the operator. The targets are then automatically identified by comparing their observed image coordinates with a list of expected image positions of all the control points visible from that station.

A least squares DLT solution provides the transformation parameters, which are stored for subsequent target position determinations.

System Check

In a pre-treatment check the camera/chair system is tested. The test entails the coordinate determination of a set of check points situated on the chair. Here, as in all other stages, target coordinates are evaluated by means of least squares space intersections. Results within preset tolerance levels confirm that the transformation parameters still reflect the true camera parameters and that the chair system is in adjustment. Failure of this test necessitates a full re-calibration of all three cameras and re-initialisation of the chair.

In the interest of patient safety, system protocol prohibits entry into the patient positioning stage until this check is passed.

Patient Positioning

Now the crucial stage of the procedure, the positioning of the patient into the proton beam, is initiated. The software is structured to execute this in three steps:

1. coordinating the reference targets on the patient's head
2. calculating the translations and rotations necessary to position the patient into the beam line
3. instructing the chair to move the patient accordingly

To realise this process the patient is seated and provisionally aligned with the beam by means of the manual chair controller.

After image capture, thresholding and target detection and centring, the operator interactively identifies reference targets on the patient's head to correlate with the target numbers allocated in the scanning stage. The reference target coordinates are then calculated in the beam system.

The scan coordinates of beam entry point and lesion are transformed (iterative least squares model) into the beam coordinate system via the reference targets, now known in both systems. These transformed positions are then used to evaluate the necessary translations and rotations for aligning the lesion/entry point vector into the beam line.

The alignment information is sent by communication port to the chair computer, which converts this into mechanical translations and rotations for the chair. The chair is automatically moved to place the patient into the treatment position. Finally, before beam activation, the patient position is redetermined by PPPS as a check.

Patient Monitoring

Throughout the treatment, the patient, exposed to the active beam is closely monitored for possible movement. It is here that the highest computing speed is needed and real-time capability is most essential. A modified processing approach, characterised by the following, is thus implemented:

1. The interactive thresholding and target identification stages are eliminated as the relevant information is assumed to remain practically unchanged.
2. The target detection stage is omitted and the target centring routine occurs in predetermined search windows centred around the expected image coordinates of the reference points.
3. As any substantial movement is likely to be discovered on coordinating the first reference target, point by point processing (centring and intersection) is employed to provide a fast intermediate check on any unwanted patient movement.
4. As a main check a non-iterative transformation is used to compute the positions of lesion and beam entry point. If one of these positions is found to have moved beyond a preset tolerance the beam is immediately deactivated.

If no patient movement occurs, monitoring continues at a high frequency until the required dose is received. As a precautionary measure, a manual overdrive can at all times deactivate the beam.

SYSTEM TESTS

Laboratory tests proved entirely satisfactory for the intended application. Sub-millimetre accuracy of target positions was achieved in simulations, compared to expected CT scan accuracies of ± 1.5 millimetres. Tests with the chair showed sub-millimetre agreement between chair movements evaluated with PPPS and as recorded by chair decoders. Monitoring speeds of ± 0.3 seconds for a complete check loop were registered for three images with 8 reference targets and 9x9 pixel search windows.

CONCLUSIONS

Digital close range photogrammetry appears ideally suited for the placing and monitoring of patients undergoing proton beam therapy. The system tests have resulted in satisfactory precisions acceptable within the NAC parameters. At the time of preparing this paper, the PPPS system has been installed at the NAC in Faure and is undergoing tests. Beyond the application discussed in this paper a wide range of other positioning problems could be solved using slightly modified versions of the PPPS concept.

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