Automatic detection of device setup errors in radiotherapy by matching three-dimensional CT data and portal images

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This paper describes an algorithm which can be used to detect and measure device setup errors in radiotherapy without the need of human interaction. The algorithm operates automatically with an accurance that is limited by image quality and processing speed only, because the required computation power is still quite huge for most of today's low and medium level computers.

1. INTRODUCTION

In order to achive best results in radiotherapeutic treatment of tumor tissue, one needs to precisely reconstruct the setup defined in therapy planning before the treatment can start. Inaccuracies in either defining the treatment parameters or transferring positioning markers to the patient's body, errors in treatment device setup or patient motion during the treatment result in a displacement of the irradiated volume. If the dose applied to the clinical target volume (CTV) is reduced, the tumor may not be controlled as predicted and the risk of recidivists rises. In view of the different possible inaccuracies, a planning target volume (PTV) is defined which is larger than CTV and incorporates it. The major goal of the described project is to minimize the difference of PTV and CTV.

In conventional radiotherapy, the patient's setup is performed by using isocenter laser pointers and light projections of the treatment beam which have to match markers on the patient's skin. Then, two or more portal images (PI) are generated to control the patient's positon and to correct setup errors. To detect errors at least semi-automatically, artificial markers must be fastened to the patient or anatomical landmarks have to be selected. This paper discusses an approach where a computer detects and corrects errors at high precision without the need of manual interaction or use of artificial landmarks.

2. MATERIALS AND METHODS

Bijhold et al. [2] mentioned an algorithm which would probably be able to correct any given setup error, even out-of-plane rotations which are in general quite difficult to deal with [7]. Bijhold condemned this approach due to the huge computation which would be required. With todays computers his approach seems to become more realistic and was realized in a project at the Charité Berlin.

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In short, a *virtual registration* is calculated. We invert the task of moving the patient's body until the portal images match the reference images taken during therapy planning. We take the portal images as a reference and try to virtually move the therapy setup until the virtually taken portal images match the real portal images. The result of this operation is in fact the same displacement with inverted sign. Starting with the setup parameters from the beginning of the therapy, the computer simulates an iterative error detection in an ongoing circle of correction and evaluation. The evaluation is done by comparing pairs of two images: a portal image (the reference) taken from the therapy device (defining the device's actual state) and an image generated from the CT data by a digital reconstructed radiography (DRR). The CT data is taken from therapy planning and represents the best possible radiation setup. If no setup error occured, the correlation of these pictures is the highest correlation possible. If an setup error occured, the correlation is less high because the relative position of CT data and the patient's body don't match. In this case, the portal image does not show the same region as the DRR. When we invert the task and declare the portal image to be our reference, we modify the device parameters and compute new DRRs until each DRR and PI match. The displacement between calculated DRR parameters and current real parameters is the measure of setup error and can be applied to the radiation device in a single step.

2.1. Definitions

The algorithm takes a tuple of r portal images $Ref = (ref_1, \ldots ref_r)$, here called reference portals, as they show the target situation for the virtual registration. For each image, a set of seven device parameters (table translation in x, y and z, horizontal table rotations with isocenter and table center, gantry rotation and collimator rotation) is defined. A CT dataset which was acquired during therapy planning is used for DRR. The set of device parameters defining a single therapy device's state is taken as vector $\vec{v}$ being element of the seven-dimensional vector space V. The value at a certain point in V defines the correlation between reference portal and the appropriate DRR. The r sets of device parameters form a tuple $t(v_r) = t(\vec{v}_1, \ldots, \vec{v}_r)$. The tuple $t_0(v_r)$ defines the status quo at be beginning ot the therapy. The DRR which has do be computed for each of the r images can be expressed as function

$$DRR : t(v) \rightarrow (drr_1, \ldots, drr_r) \tag{1}$$

where drr_n is the digital reconstructed radiography which was generated using $\vec{v}_n$ and corresponds to the portal image number n. When registration terminates at step x with the parameter tuple $t_x(v)$, we assume

$$DRR(t_x) \approx Ref \tag{2}$$

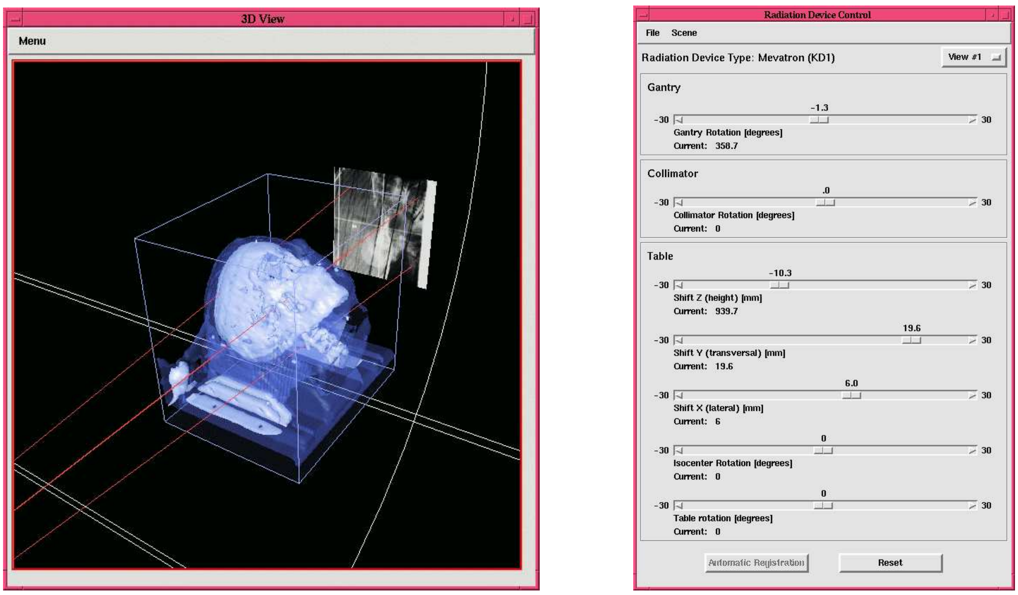
The task to solve is to find the vector tuple $t_x(v)$ which is the set of parameters for which the virtually taken portal images (DRRs) match the set of reference portals Ref. The displacement vector can be calculated by subtracting $t_v - t_x$. The elements of this vector are correction values which can be applied to the therapy device.

2.2. Algorithm

The starting vector tuple $t_0(v)$ is defined by the device setup at the beginning of radiation therapy. When the iteration starts, the gradient for each of the vectors $\vec{v}_1 \ldots \vec{v}_r$

is computed in subsequently modifying each of the device parameters. In doing so, a gradient in the seven-dimensional vector space V for each $\vec{v}_n$ is approximated and the resulting DRRs are created, which makes a total of 15 DRRs for each of the n vectors. All DRRs are compared to their corresponding reference portals and an overall matching factor is calculated which forms the value in V. Ongoing plans are to find a maximum in a seven-dimensional vector space. Comparison of each pair of images can be easily done with low-performance algorithms like least-square-matching [1,8], cross-correlation [4,5] or by simple subtraction [6].

The task of finding the overall maximum correlation can be accomplished by any desirable algorithm like resilient propagation, simulated annealing or backpropagation to name just a few [9]. Well-known problems such as local maxima which are interfering with the algorithm for finding the global maximum may occur, though this problem seems to be less relevant, since the patient's body is placed with reasonable accuracy when the algorithm starts. Only small amounts of setup displacements should occur. Dealing with local minima seems to be less interesting when optimizing the search, because for each iteration $n \times 15$ DRRs have to be computed and $n \times 15$ pairs of pictures have to be compared. The main performance problem is the large amount of DRRs needed.



(a) (b)

Figure 1. The figures show some views of the implemented application. (a) shows an observer's view in which camera position and magnification can be altered by the user. This window enables the user to get an idea of the situation and to view the device setup. (b) shows the control window with sliders for each of the device parameters. The sliders are in position and the user can easily read out the device setup errors.

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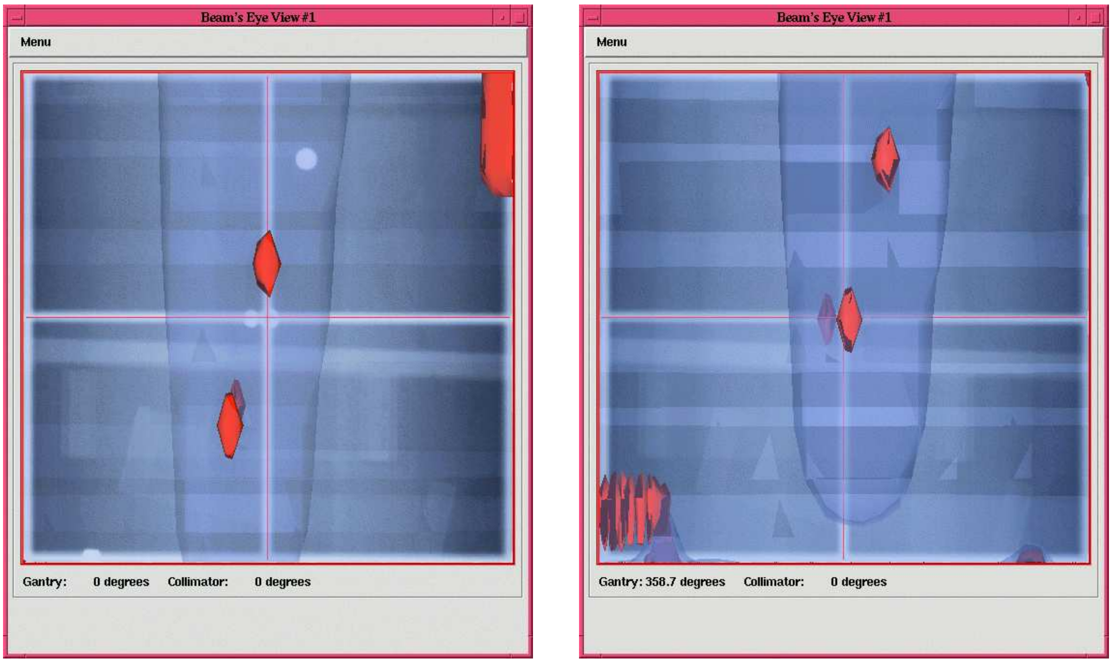
3. RESULTS

An application was implemented using the visualization software *AVS/Express* and a special C++ class library providing the time-critical routines. The class library was implemented along with other projects at the Charité. The automated error detection could not be implemented completely due to several technical problems. Only parts are implemented which allow a manual registration using a beam's eye view onto CT data and portal images. Results in using the implemented manual registration show high accuracies which, as expected, depend on the image quality only. Accuracies of 0.5mm/0.5° can be achieved easily if the required computation power is available. The application runs on Silicon Graphics O_2 machines which tend to be underpowered for this application.



(a) (b)

Figure 2. This figure show a window called *Beam's Eye View* which is available for each of the n therapy beams. The window shows the portal image overlayed by an isosurface model computed from CT data. (a) shows the view before and (b) after registration of a cylinder phantom with three landmarks. The spheres depict the landmarks' shadows on the reference portal, the three dimensional objects are the landmarks shown by the CT isosurface model.

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4. CONCLUSIONS AND OUTLOOK

The described approach gives a full automated and highly device-independent algorithm to detect setup errors. Using interfaces which connect the computer directly to the therapy device, would allow to correct the setup error directly with the computer. No anatomical and a priori knowlegde is used during the detection process. The precision of error detection is not limited by the algorithm itself or the anatomical region of irradiated tissue, but by the resolution of CT data and portal images. Virtually any precision needed can be obtained if the image quality is good enough.

Clinical evaluation of the manual registration is in progress at the Virchow-Klinikum, Charité Berlin. Estimations about the usability and performance of the prototype application are expected after several weeks of testing the software with clinical data. After retrospective evaluation, it has to be considered if the software will be used in the clinical routine.

On subsequent projects, the described approach will be re-implemented at the Technical University of Berlin with different software engineering tools. Work concentrates on reducing computation time by further optimizing the software as shown in [10].

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