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IMPLEMENTATION OF FIDUCIAL-BASED IMAGE REGISTRATION IN THE CYBERKNIFE ROBOTIC SYSTEM

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Abstract—Fiducial-based image registration methodology as implemented in the Cyberknife system is explored. The Cyberknife is a radiosurgery system that uses image guidance technology and computer-controlled robotics to determine target positions and adjust beam directions accordingly during the dose delivery. The image guidance system consists of 2 x-ray sources mounted on the ceiling and a detection system mounted on both sides of the treatment couch. Two orthogonal live radiographs are taken prior to and during patient treatment. Fiducial markers are identified on these radiographs and compared to a library of digital reconstructed radiographs (DRRs) using the fiducial extraction software. The fiducial extraction software initially sets an intensity threshold on the live radiographs to generate white areas on black images referred to as "blobs." Different threshold values are being used and blobs at the same location are assumed to originate from the same object. The number of blobs is then reduced by examining each blob against a predefined set of properties such as shape and exposure levels. The remaining blobs are further reduced by examining the location of the blobs in the inferior-superior patient axis. Those blobs that have the corresponding positions are assumed to originate from the same object. The remaining blobs are used to create fiducial configurations and are compared to the reference configuration from the computed tomography (CT) image dataset for treatment planning. The best-fit configuration is considered to have the appropriate fiducial markers. The patient position is determined based on these fiducial markers. During the treatment, the radiation beam is turned off when the Cyberknife changes nodes. This allows a time window to acquire live radiographs for the determination of the patient target position and to update the robotic manipulator to change beam orientations accordingly.

Key Words: **Fiducial marker, Stereotactic radiosurgery, IGRT, Image fusion.**

INTRODUCTION

Dose delivery via focal irradiation techniques either in stereotactic radiosurgery (SRS) or in stereotactic radiotherapy (SRT) has been facilitated with the use of stereotactic frame systems.[1] The stereotactic frame is fastened to the patient's skull and when scanned, using medical imaging modalities such as computed tomography (CT) or magnetic resonance imaging (MRI), allows the identification of points on the CT transaxial images, expressed in imaging coordinates, to be transformed into a stereotactic coordinate system. When a relationship between the stereotactic frame and the dose delivery system such as a medical linear accelerator or a Gammaknife system is established, the target can be positioned to a high level of accuracy of 0.2 to 0.4 mm relative to the isocenter of the treatment unit.[1]

Focal irradiation techniques that deliver a very high dose to a small region using a few fractions require a very high level of accuracy. The uncertainty associated with patient setup for focal irradiation is expected to be less than 1 mm.[1] The use of stereotactic frame has been popular because the system allows a convenient transfer of the coordinates of a lesion or structure visualized on CT, MRI, or angiography's images to the stereotactic frame coordinate system and thereafter to the treatment machine coordinate system. Because the stereotactic frame system can locate a point in a very accurate manner, in the submillimeter range, it has been routinely used in neurosurgery.[1,2]

However, the advances of focal irradiation techniques have been toward frameless systems.[3–5] Stereotactic frame-based focal irradiation techniques pose 4 major disadvantages. First, the repeated use of the stereotactic frame for fractionated treatments can cause patient discomfort, infection, and the possibility of frame movement between treatments. Second, the stereotactic frame has mechanical limitations precluding the treatment of lesions located in the periphery of the brain or in the base of the skull. Third, lesions near the frame are difficult to treat because of the interference of the frame with the direction of the radiation beams. Fourth, stereotactic frame systems are designed for intracranial irradiation and hence exclude extracranial treatments. As such, a number of frameless systems that utilize near real-time image-guidance techniques are being introduced. The objective of this paper is to describe the implementation of image-guided radiation therapy (IGRT) technology for the specialized Cyberknife robotic radiosurgery system using fiducial-based image registration methodology.

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CYBERKNIFE ROBOTIC RADIOSURGERY SYSTEM

The Cyberknife robotic radiosurgery system consists of a lightweight X-band 6-MV linear accelerator (compared to a conventional linear accelerator) mounted on a robotic arm as shown in Fig. 1. The movement of the robotic arm is computerized and controlled by a 6-axis robotic manipulator. This robotic arm movement offers a significantly increased range of beam directions for aiming at the target than conventional gantry-mounted radiotherapy linear accelerators, as shown in Fig. 2. The system is also capable of performing non-isocentric beam delivery to generate highly conformal radiation dose distributions to irregularly shaped target volumes with steep dose gradients that minimize radiation to the surrounding structures. The dose rate for the third generation Cyberknife system is 400 monitor units (MUs)/min and has increased to 600 MU/min for the fourth-generation Cyberknife system to shorten the treatment times.

The system also has a target-locating subsystem (TLS) to perform IGRT by localizing the target and subsequently tracking it. The TLS consists of 2 diagnostic x-ray source–detection system pairs and software for image registration. The 2 diagnostic x-ray sources are mounted on the ceiling as shown in Fig. 3. When energized, they will produce 2 real-time orthogonal radiographs (referred to as live radiographs) captured on the 2 detection systems positioned on the left and right sides of the treatment couch (Fig. 4). The image detection systems consist of amorphous silicon detectors of 20 × 20 cm for third-generation unit (41 × 41 cm for fourth-generation unit but mounted in the floor) capable of generating high-resolution digital images. The images are processed automatically and image registration is performed to determine the target position. The position determined from the live radiographs is communicated through a real-time control loop to the robotic manipulator that adjusts and directs the radiation beam accordingly to within 1-mm spatial accuracy.

The Cyberknife system can adapt to the changes in patient position during the dose delivery period. Typically, 100 to 150 beams are used in a single fraction. Each beam is defined by a node (x, y, z) position. At each node, the linear accelerator has 12 rotational positions defined by the solid angles (α, β, and γ) for beam

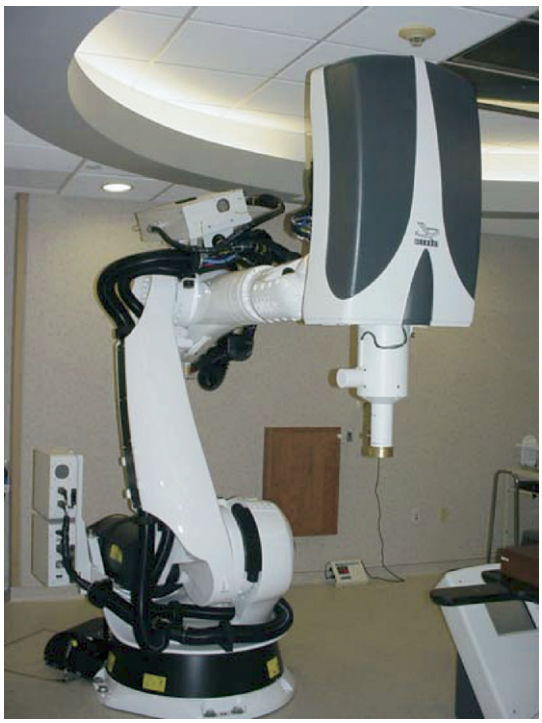

Fig. 1. A third generation Cyberknife™ robotic radiosurgery system.

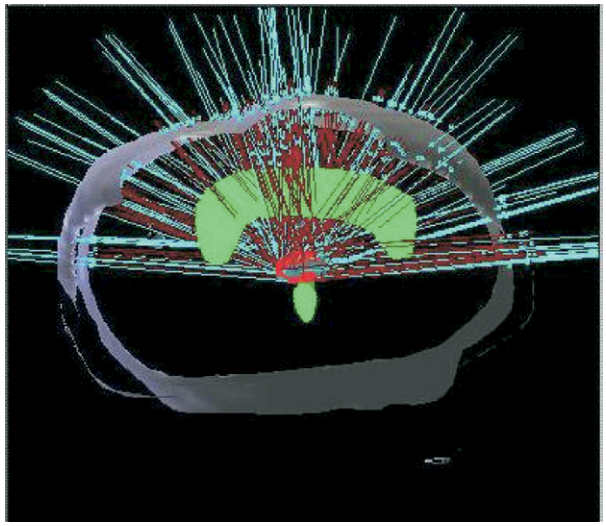

Fig. 2. A number of nodes available on Cyberknife™ system for dose delivery.

Fig. 3. A kilovoltage x-ray source mounted on the ceiling to produce orthogonal live radiographs.

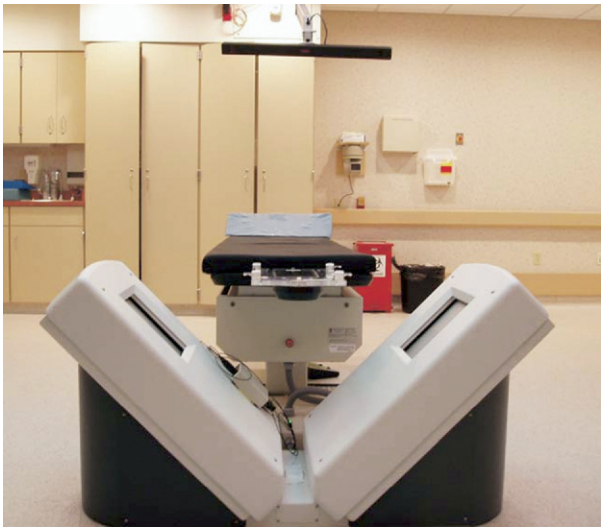

Fig. 4. An x-ray detection system consisting of 2 flat panel detectors mounted both sides of the treatment couch.

orientation. The radiation beam is turned off during movement between nodes, as defined in the treatment plan. After the linear accelerator moves to the next node, live radiographs can be acquired to assess the target position again. If there is a change in the target position, the linear accelerator is updated accordingly and the beam orientations are adjusted for accurate conformal dose delivery. Although the target position can be evaluated after each nodal dose delivery, the evaluation is typically performed after irradiating through a few nodes. As presented, the machine essentially tracks the target position during treatment to perform an adaptive radiosurgery or radiotherapy. An analysis of the accuracy of the Cyberknife radiosurgery system found that the machine has a clinically relevant accuracy of less than 1 mm.[6–8] Hence, the Cyberknife precision is comparable with published localization errors in current frame-based focal irradiation system.

PATIENT ALIGNMENT AND TARGET LOCALIZATION

The Cyberknife robotic system offers no stereotactic frame-based option but relies on IGRT for patient alignment and target localization. Patient alignment and target localization are performed by taking orthogonal live radiographs and comparing them to a library of digitally reconstructed radiographs (DRRs). The library of DRRs was generated from the CT image dataset acquired for treatment planning with systematic variation of patient positions and orientations to simulate patient movements. A particular DRR that best matches the live radiographs is identified through the fiducial-based image registration methodology. The new target position is transmitted to the robotic arm manipulator so that the radiation beams will be redirected based on the updated target position. This process can be repeated between nodes, thus allowing the treatment unit to track patient position changes during treatment.

In a typical patient setup prior to treatment, the patient is immobilized and positioned in such a way that the target is within the bounds of the imaging system. Next, the treatment couch is moved so that the fiducial markers fall approximately at the center of the imaging system. After the treatment room is cleared, live radiographs are acquired. The fiducial extraction algorithm is invoked to search for a matched DRR from the library of DRRs. If the search is successful in the automated "Search" mode, the software returns with the couch correction values as shown in Fig. 5. If the patient is not within the tolerance limit specified (± 10 mm for LFT, POS, INF; ± 1° for RGT and H-DWN and ± 3° for CW), the operator will be warned of the fact. Repositioning of the patient is therefore necessary and a new set of live radiographs is taken. The process is repeated until the software accepts the appropriate patient position within the specified limits.

If the automated fiducial markers extraction fails, the operator will have to switch to the "Track" mode to visually aid the computer in the search for the fiducial markers. In this mode, the software searches for each fiducial marker independently by dividing the live radiograph into regions of interest (ROIs) corresponding to the expected location of each fiducial marker. To ensure successful fiducial extraction, the operator can move each ROI over the fiducial marker of the cluster seen on

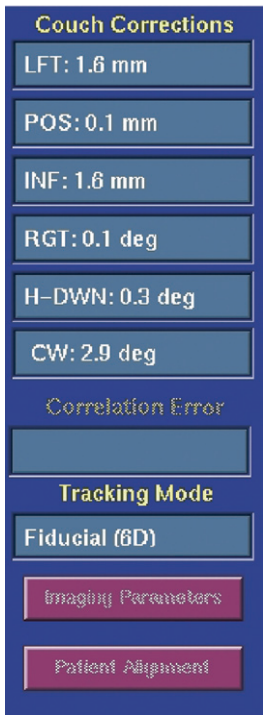

Fig. 5. Couch correction values. Couch movement is not performed if its values are within the tolerance limits.

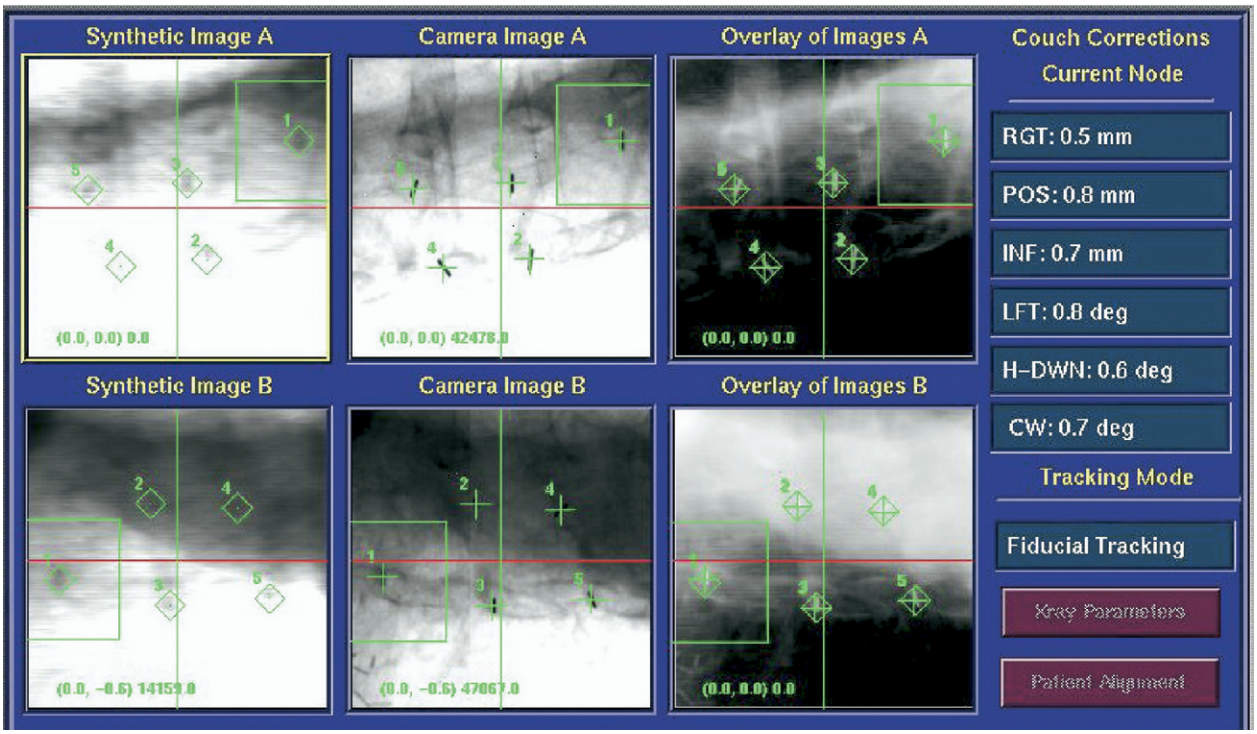

Fig. 6. Repositioning of the region of interest (ROI) on live radiographs to extract fiducial markers.

the live radiographs (Fig. 6) and then invokes the fiducial extraction algorithm. Instead of moving each individual ROI, the operator can also move the live radiographs over the DRR so that the fiducial markers in the 2 image sets are matched. Once this has been done, the amount of movement can be determined and forwarded to the robotic arm manipulator to update the beam orientations.

FIDUCIAL EXTRACTION ALGORITHM

The identification of the fiducial markers from the live radiograph is carried out using the fiducial extraction software.[9] Initially, an intensity threshold is set on the live radiographs to generate white areas on black images. In each extraction, the region being searched is processed multiple times at different threshold values to create a library of threshold samples. White areas on a black image, referred to as "blobs" in these threshold exposures are compared throughout the library of DRRs, and those with the same location in each sample are assumed to originate from the same object. The number of appearances (n) of each blob is counted.

Next, the fiducial extraction software reduces the number of occurrences of each blob from n to 1 and ranks them in order of likelihood of being a fiducial marker. This is accomplished by comparing all the samples for the blob against a set of predefined characteristics that includes shape, size, and exposure levels. The sample of the blob that most closely matches the expected characteristics is identified as the "blob of the best fit" and its characteristics are retained as the defining characteristics of the blob. Blobs that do not match the expected characteristics are discarded. The remaining best-fit blobs are then ranked by the fiducial extraction software in the order that their characteristics fit the expected parameters, thus creating a hierarchy of blobs most likely to be fiducial markers.

The third step in the fiducial extraction process is to create a 3-dimensional (3D) potential fiducial marker from the 2-dimensional (2D) blobs. Blob locations in the 2 live radiographs are compared against the inferior-superior axis of the patient. Those blobs that have the corresponding positions in the 2 radiographs are assumed to originate from the same object in the patient, and the location of this object can be calculated in 3 dimensions by projecting backward from the 2 live radiographs. These 2 blobs are now considered as a single fiducial candidate.

In the final step of the fiducial extraction, the software creates a fiducial configuration from all the potential fiducial candidates. To execute this step, the fiducial extraction software compares all the potential configurations created by all the fiducial candidates against the reference configurations from the dose planning CT image set. Any configuration that does not match the expected configuration (rigid-body constraints) is discarded. Those that match the configuration are ranked according to best-fit or highest quality fiducial markers until only one configuration remains, hence defining the

individual fiducial markers. It is important to realize that the entire configuration must pass the extraction process. If one fiducial marker in the configuration fails the extraction process, the entire configuration will fail.

LIMITATIONS OF FIDUCIAL-BASED IMAGE REGISTRATION

The fiducial-based image registration methodology assumes that the fiducial markers are held rigidly in the target or the patient anatomy. This implies that (1) the relationships between fiducial markers are rigidly or geometrically fixed and (2) the shape of the target cannot be deformed with respect to the locations of the fiducial markers. Hence, fiducial markers should be implanted in target and surrounding tissue that show very little to no movement. In addition, the target and surrounding tissue cannot be subjected to deformation, either due to physiological or mechanical pressures. It is clear that the normal physiologic activities associated with breathing, digestion, and the cyclic filling and emptying of the bladder and rectum make the assumptions of stability only approximately true. If fiducial markers migrate relative to each other, the relationship of the fiducial markers no longer describes the 3D shape of the target.

The accuracy of the fiducial extraction improves with the number of fiducial markers. If a single fiducial marker is used, the software provides only the translation correction values. A minimum of 3 fiducial markers is needed to generate both translation and rotational correlation values. Furthermore, the fiducial markers should be implanted with a minimum separation of 2 cm and within 6 cm of the lesion. It is also recommended that the fiducial markers be implanted in a non-collinear fashion. A minimum of 15° angle between any grouping of 3 fiducial markers is suggested. Lastly, the implantation of fiducial markers is an invasive procedure, which can cause a variety of minor and major complications. The most serious of these commonly encountered is pneumothorax after fiducial placement in the lung, a particular concern, in that patients selected for definitive radiation therapy for lung cancer are typically those whose pulmonary function is quite poor, and which has precluded surgery.

Because the ability to identify the location of fiducial markers is crucial in this image registration methodology, the markers must be clearly visible on live radiographs, as shown in Fig. 6 for image processing.[7,8] Gold or stainless seeds are commercially available for this purpose.

Although fiducial-based methodology provides a very viable means of performing image-guidance target localization with high accuracy, it is still an invasive process. There is a tendency to move toward non-invasive image guidance techniques. One such technique is the implementation of the mutual information fusion technique. This technique is more likely to succeed if the 2 images are from the same medical imaging modality and the contrast level in each image is large, as exemplified by bony anatomy. These features have been incorporated into the spine-tracking algorithm, which became commercially available in 2005 for the Cyberknife system. The spine-tracking algorithm uses bony landmarks and nonrigid image registration methodology. It promises to be a valuable tool for target localization in the treatment of spinal tumors.

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