A mathematical model for correcting patient setup errors using a tilt and roll device

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An algorithm is presented for determining how to adjust the actuators of a tilt and roll table. The algorithm is based on a geometrical model of the table, which was designed with six degrees of freedom. This design and algorithm allows complete translational and rotational corrections to be applied to the target volume position on a daily basis. [S0094-2405(99)01712-5]

Key words: tilt and roll, setup error correction, algorithm

A treatment table with six degrees of freedom has been designed and built to allow the correction of initial translational and rotational patient setup errors. The mechanical design and specifications of this tilt and roll table have been previously reported.[1] Here we develop a geometric model of the table that will allow previously determined correctional transformations of the patient's position to be implemented by the device.

The tilt and roll table was designed on a standard treatment table platform that has four degrees of freedom: three translational and one rotational. The one standard rotational degree of freedom is about the vertical axis (y axis) through the isocenter (pedestal rotation). The tilt and roll device adds two rotational degrees of freedom: one about the table's left–right axis (x axis, tilt), and the other about the table's superior–inferior axis (z axis, roll). These two rotations are allowed by a modified automotive-type universal joint mounted under the center of the table and controlled by two linear actuators, which support one end of the table. The length of the actuators may be changed to control the tilt and roll angles.

The problem is finding how to (1) translate the table pedestal, (2) rotate the floor turntable, and (3) change the length of the actuators, to correct the target volume position. In solving this problem we assume that the tumor and the top of the treatment table undergo a rigid body transformation since the correctional rotations are small (<5°). (The table may undergo significant mechanical deflection upon loading. However, once the patient is on the table, small changes in patient position do not significantly change this deflection. This is true over the range of angles allowed by the device.)

The geometrical model is set up as follows. The origin of our room-based coordinate system is defined to be at the isocenter, as shown in Fig. 1. The positive z direction is defined by the horizontal vector that begins at the isocenter and points toward the center of rotation of the gantry. The positive y direction is defined to be vertically downward. The three-dimensional rigid body transformation required to correct patient setup is determined (e.g., by comparing the positions of implanted radio-opaque markers, determined from orthogonal digital radiographs, with known reference positions determined from CT volume data[2,3]). This transformation is established in the coordinate system described above and decomposed into translations and rotations that may be achieved with this system.

Conceptually, translations are corrected first to place the reference point of the target volume at the isocenter. The rotation about the y axis, Fig. 2(a), is performed next since this rotation is common to the top and bottom actuator mounts and may be easily accomplished with the floor turntable. Rotations about the x' then z'' axes (tilt then roll), Figs. 2(b) and 2(c), complete the transformation. The order of rotations is chosen based on the mechanical design of the universal joint. (If the table had been designed with the universal joint rotated ±90°, the order of the rotations would be z' then x''.) It should be noted that additional table translations are necessary due to the rotations about the isocenter that change the position of the universal joint supporting the table. This is due to the fact that the universal joint is not placed at the isocenter. The complete room-based transformation, to correct the target volume position, is therefore decomposed as

$$T = \Re_{z''}(\gamma)\Re_{x'}(\alpha)\Re_{y}(\beta)T, \tag{1}$$

where T is a three-dimensional translation, $\Re_y(\beta)$ is a rotation about the vertical y axis of β degrees, $\Re_{x'}(\alpha)$ is a rotation about the left–right x' axis of α degrees, and $\Re_{z''}(\gamma)$ is a rotation about the z'' axis of γ degrees.

In practice, the problem is simplified if a coordinate system centered on the universal joint, termed the couch reference system (CRS), is used. If the reference position is chosen at a table floor angle of zero degrees, the room-based rotations about the isocenter and the universal joint are then the same. In addition, the positions of the actuator mounts, $\mathbf{a}_{np}$, are easier to measure with respect to the universal joint, when the table is level. (Here n indicates actuator 1 or 2 and p indicates the top or bottom mount.) It therefore becomes easy to calculate the corrections.

The table pedestal translations may be found by taking the difference between the final and initial isocenter coordinates.

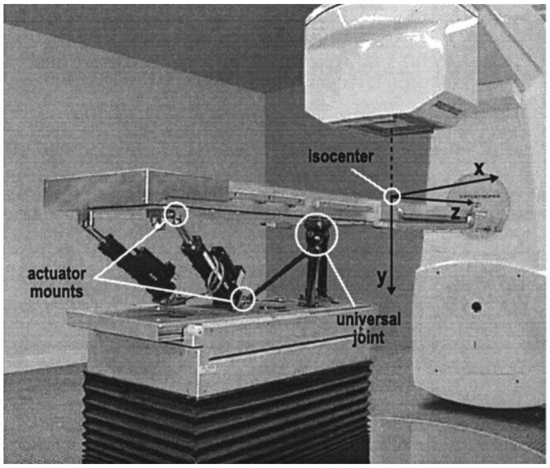

FIG. 1. The tilt and roll treatment table relative to the room-based isocenter coordinate system. The length of the actuators may be changed to control the tilt and roll angles.

The initial position of the isocenter in the CRS, **O**, may be calculated from the room-based table coordinates. The translational corrections to move the tumor volume reference point to the isocenter are applied first, so the new position is given by

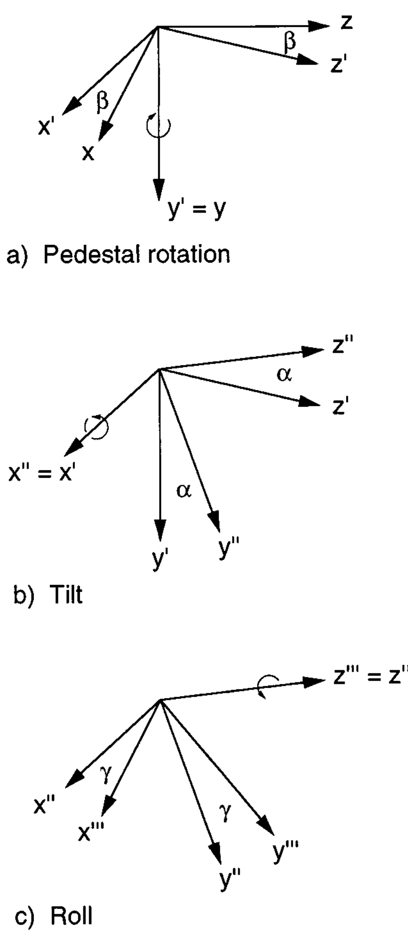

FIG. 2. The Euler rotations performed by the tilt and roll table around the (a) y axis, (b) x' axis, then the (c) z'' axis.

$$\mathbf{O}' = T\mathbf{O}. \tag{2}$$

The rotational correction about the vertical y axis, $\Re_y(\beta)$, may be applied next, as suggested by (1). However, in the CRS the location of the isocenter is independent of the table floor angle by design, so this step may be applied at any time.

The final position of the isocenter in the CRS, $\mathbf{O}''$, is found by applying the tilt and roll rotations to the isocenter coordinates, $\mathbf{O}'$, as shown in (3):

$$\mathbf{O}'' = \Re_{z''}(\gamma)\Re_{x'}(\alpha)\mathbf{O}'. \tag{3}$$

The table pedestal translations are then given by

$$\Delta\mathbf{O} = \mathbf{O}'' - \mathbf{O}. \tag{4}$$

This translation may be thought of as the sum of two components. The first corrects for translational errors in the initial setup of the tumor, while the second consists of the translations of the universal joint due to rotational corrections about the isocenter.

Finally, the change in length of the actuators is found by applying the tilt and roll rotations to the top actuator mounts, as shown in (5):

$$\mathbf{a}'_{nt} = \Re_{z''}(\gamma)\Re_{x'}(\alpha)\mathbf{a}_{nt}. \tag{5}$$

The positions of the bottom actuator mounts, $\mathbf{a}_{nb}$, never change in the CRS. If L_n was the original length of actuator n, the change in the actuator length is

$$\Delta L_n = |\mathbf{a}'_{nt} - \mathbf{a}_{nb}| - L_n. \tag{6}$$

The table pedestal translations are given by (4), the floor turntable has been adjusted by β degrees, and the change in length of the actuators is given by (6).

The accuracy with which the target volume may be positioned is determined primarily by the accuracy of the determined transformation, the initial mount positions, finding the isocenter in the CRS, and the accuracy with which table translations may be performed. Studies, in which a phantom was offset by known translations and rotations, indicate a positioning accuracy of roughly ± 0.2 cm in each translation and $\pm 1.0°$ in each rotation. This includes an uncertainty of roughly ± 0.1 cm and $\pm 0.5°$ in the determined correctional transformation. The remaining translational uncertainty is primarily due to limitations of the table translation control system that has one millimeter position resolution. This limits the accuracy with which the correctional translation may be applied. From (5), uncertainties in the top mount positions of ± 0.1 cm lead to uncertainties in tilt of $\pm 0.05°$ and $\pm 0.2°$ in roll, for independent angular corrections of 5° about each axis. Measuring the mount positions is difficult, as the positions must be measured to the center-of-rotation of a joint. However, these may be adjusted in the software so that the calculated angles agree with the measured angles, with a maximum uncertainty of 0.033°.[1]

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