Robotic real-time translational and rotational head motion correction during frameless stereotactic radiosurgery

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Purpose: To develop a control system to correct both translational and rotational head motion deviations in real-time during frameless stereotactic radiosurgery (SRS).

Methods: A novel feedback control with a feed-forward algorithm was utilized to correct for the coupling of translation and rotation present in serial kinematic robotic systems. Input parameters for the algorithm include the real-time 6DOF target position, the frame pitch pivot point to target distance constant, and the translational and angular Linac beam off (gating) tolerance constants for patient safety. Testing of the algorithm was done using a 4D (XYZ + pitch) robotic stage, an infrared head position sensing unit and a control computer. The measured head position signal was processed and a resulting command was sent to the interface of a four-axis motor controller, through which four stepper motors were driven to perform motion compensation.

Results: The control of the translation of a brain target was decoupled with the control of the rotation. For a phantom study, the corrected position was within a translational displacement of 0.35 mm and a pitch displacement of 0.15° 100% of the time. For a volunteer study, the corrected position was within displacements of 0.4 mm and 0.2° over 98.5% of the time, while it was 10.7% without correction.

Conclusions: The authors report a control design approach for both translational and rotational head motion correction. The experiments demonstrated that control performance of the 4D robotic stage meets the submillimeter and subdegree accuracy required by SRS. © 2015 American Association of Physicists in Medicine. [<http://dx.doi.org/10.1118/1.4919279>]

Key words: frameless stereotactic radiosurgery, frameless SRS, motion compensation, feedback control

1. INTRODUCTION

The main challenge of stereotactic radiosurgery (SRS) is precise positioning of the intracranial target. In frame-based SRS, a head ring is rigidly fixated to the patient skull and then bolted to the treatment couch to suppress both voluntary and involuntary physiological motions.¹ Such immobilization can be highly uncomfortable to patients and is not easily adaptable to fractionated treatments.

Frameless SRS (Refs. 2–5) offers the promise of reduced invasiveness and increased setup efficiency. Instead of a head ring, frameless SRS typically uses a custom back of the head mold together with a thermo-plastic face mask for patient immobilization. However, with such immobilization, the head can still move inside the mask, leading to positioning errors during setup and treatment.^{6–9} Wiersma *et al.*¹⁰ presented an approach for reducing position errors by head motion correction. Here, the head motion was tracked in real-time via passive infrared (IR) markers attached to a bite block frame, and a 3D (XYZ) serial kinematic motion stage was mounted under the patient's neck and away from the radiation. If the target motion deviated beyond a preset threshold, an automatic position correction was performed with stepper motors to adjust the head position via the 3D stage. However, the applicability of this system was limited to only translational motion correction, and not rotational deviations that may occur during treatment. Such angular change can include both

voluntary and involuntary patient head motions, as well as mechanical changes such as couch sag. Studies indicated that lesion rotational localization deviation can significantly affect the target dose coverage if it is nonspherical or has multiple sites. Thus, it is particularly concerning in highly conformal radiation therapy.^{11–14}

In this paper, we expand on previous work by extending the robotic framework by the development of a novel feed-forward control algorithm that incorporates both translational (xyz) and rotational (pitch, roll, and yaw) head motions. The control method was experimentally tested on a 4D (XYZ + pitch) robotic device using both phantom and human volunteers.

2. METHODS

2.A. Robotic 4D stage

The head motion correction system included a 4D robotic motion stage, a 6DOF optical tracking system, and a control computer (LabVIEW, National Instruments, Austin, TX). The optical tracking system (Polaris, Northern Digital, Inc., Waterloo, Ontario) consists of two IR cameras and was mounted on a tripod above the patient couch. The camera system tracked IR markers located either on a bite block frame or a forehead frame with a temporal resolution of 12–30 Hz.¹⁰ Real-time 6D coordinates with respect to the camera frame

FIG. 1. (a) Experimental setup for phantom study. (b) Volunteer study (no radiation beam in experiments). (c) 4D stage. (d) The $y-z$ plane of 4D stage. A target was fixed on the top of the 4D stage, which position was specified by the 6D coordinates $(x, y, z, \alpha, \beta, \gamma)$. Tuning θ not only changes the pitch angle of the target, but also changes the y and z coordinates of its center ρ .

of reference were computed onboard, and transmitted to the control computer via RS-232 serial bus.

Four stepper motors were used to govern the translation of the left-right (x), superior-inferior (y), anterior-posterior (z) axes, and the rotation of the pitch (about x axis) around a pivot point at the base of the platform [Fig. 1(c)]. NEMA type 17 motors were used for x and y axes, while a larger NEMA type 23 was used for z and pitch axes due to the weight of the patient's head. These motors were controlled by a four-axis motor controller (PCI-7344, National Instruments, Austin, TX) together with a power amplifier (MID-7604, National Instruments, Austin, TX). The conversion for the unit displacements of the X , Y , and Z axes motors is $N_X = N_Y = N_Z = 900$ steps/mm, and the pitch axis motor $N_\theta = 950$ steps/°.

The position of a target can be specified by a translational vector $l = \{x, y, z\}$ and a rotational vector $\psi = \{\alpha, \beta, \gamma\}$ (Euler angles: pitch α , roll β , yaw γ). When there is no relative motion between the target and the IR markers (rigid body), the target position can be calculated through the IR markers position. These two vectors can be represented in different reference frames. There are three reference frames in the motion correction system: the camera frame, the normal stage frame, and the Linac frame. The normal stage frame is a reference frame with its x , y , and z axes parallel to the X , Y , and Z motor axes, respectively, when all X , Y , Z , and pitch θ motor axes are in the normal position, see Fig. 1(d). The Linac frame is the linear accelerator reference frame with the origin at the radiation isocenter. For control purposes, the target position was represented in the normal stage frame, allowing easy computation of control, while for display and radiation delivery purposes, the target position was represented in the Linac frame. Transformations between these frames involve a rotation matrix and a translational vector, which can be computed by Kabsch's algorithm,¹⁵ a least-squares fitting algorithm based on singular value decomposition.

The noise in the measured x , y , and z by the camera system was discussed previously.¹⁰ They were normally distributed around zero with standard deviation of $\sigma_x = 0.08$, $\sigma_y = 0.07$, and $\sigma_z = 0.06$ mm, respectively. To evaluate the noise of the angular measurement, an IR marker block was placed on the top of 4D stage, and its 6D coordinates were measured and represented in the cameras frame. The noise

of the measured pitch, roll, and yaw angles was found to be normally distributed with standard deviations of $\sigma_\alpha = 0.025^\circ$, $\sigma_\beta = 0.023^\circ$, $\sigma_\gamma = 0.010^\circ$, respectively.

2.B. Control configurations

Four stepper motors were used to control the translational position and pitch angle of the target. This is a multiple input and multiple output control system, where the rotation of the pitch motor will not only changes the pitch angle of a target, but will also change the y and z coordinates making control design difficult. For example, consider a target with its center at ρ as shown in Fig. 1(d). Here, the target is rigidly fixated to the top of 4D stage, and its translational and pitch coordinates in the normal stage frame are $(x_\rho, y_\rho, z_\rho, \alpha_\rho)$,

$$\begin{aligned} x_\rho &= X, \\ y_\rho &= (b+Y) \cos \theta - a \sin \theta, \\ z_\rho &= (b+Y) \sin \theta + a \cos \theta + c + Z, \\ \alpha_\rho &= \theta, \end{aligned} \quad (1)$$

where X , Y , Z , and θ are the displacements of the X , Y , Z , and pitch θ axes motors from their normal positions, respectively, and a and b are the variables of specifying the position of ρ with respect to the pivot of the pitch θ axis motor. It can be seen from Eq. (1), changing θ will change α_ρ , y_ρ , and z_ρ . The coordinate x_ρ is not coupled with θ , since the rotation axis of the pitch θ motor is parallel to the x axis.

To control such a system, we first consider linear approximation of Eq. (1) when θ is small. Let the normal position $(x_o, y_o, z_o, \alpha_o)$ of the center ρ be the position where $X = Y = Z = \theta = 0$, i.e., $x_o = 0$, $y_o = b$, $z_o = a + c$, and $\alpha_o = 0$. Thus, if θ is small, the translational and pitch displacements of ρ in the normal stage frame, $x_\rho - x_o$, $y_\rho - y_o$, $z_\rho - z_o$, and $\alpha_\rho - \alpha_o$, can be linearly approximated by

$$\begin{aligned} x &= X, \\ y &= Y - a\theta, \\ z &= Z + b\theta, \\ \alpha &= \theta. \end{aligned} \quad (2)$$

We then consider two feedback control configurations, with and without feed-forward.¹⁶ Figure 2 shows the signal

FIG. 2. (a) Feedback control without feed-forward. The system responds after the effect of θ appears in y . (b) Feedback control with feed-forward. The system takes action before θ has effect on y .

flow diagram of feedback control on the displacement y , where y_r is the desired position, e_y is the error, u_y is the controller output, K_y is the feedback controller, and H is the sensor. The effect of θ on the control of y can be viewed as

disturbance as shown in channel 1. When feedback control without feed-forward is applied, the controller responds only after the effect of the disturbance shows up in the system output, and will finally cancel out the effect of disturbance after certain time. On the other hand, in the configuration with feed-forward, a forward channel, labeled 2, is added, which means the disturbance is measured and responded to before it has time to affect the system. Whenever the pitch θ axis motor moves n steps, the y axis motor is controlled to move additional $N_y n a / N_\theta$ steps simultaneously, then the effect of θ on the displacement y will be entirely eliminated. This can also be seen by the fact that the sum of the channels 1 and 2 is equal to zero. Thus, in general, the feedback control with feed-forward will lead to more optimal correction and have better control performance. The displacement z can be controlled in the same way, and the method can also be extended to other coupled axis such as yaw and roll. Note that the parameters a and b as in Eq. (1) and Fig. 1(d) correspond to the relative position between the target and the normal stage frame, and can be computed in the setup procedure.

2.C. Linac beam gating

To maintain patient safety during actual clinical implementation of the proposed method, Linac beam gating can be used. The translational displacement $d = \sqrt{x^2 + y^2 + z^2}$, and

FIG. 3. Comparison of feedback control without and with feed-forward. For all four cases, the target started at the zero position ($x = y = z = 0$ mm, $\theta = 0^\circ$), then controllers were engaged to move the target to the desired positions ($x = y = z = 0$ mm, $\theta = 1^\circ$) in [(a) and (b)], and ($x = 1$, $y = 2$, $z = 3$ mm, $\theta = -1^\circ$) in [(c) and (d)]. In (a) without feed-forward, when the pitch was tuned from 0 to 1° , y and z were away from the desired position at first, and then came back, while in (b) with feed-forward, the target almost remained in the desired translational position all the time when the pitch angle was adjusted. Without feed-forward, there is 80% overshoot on y in (c), while there is no overshoot and faster response with feed-forward (d).

FIG. 4. Comparison of uncorrected and corrected head motion in a phantom study. Uncorrected motion: [(a) and (c)]. Corrected motion: [(b) and (d)]. Without correction, the translational displacements were in the range of $(-1, 2)$ mm (c), while with correction, the translational displacement was within 0.15 mm all the time (b). The pitch displacement was reduced from uncorrected 0.45° (c) to corrected 0.15° (d). Note that the uncorrected and corrected motions had the similar roll and yaw angles, since these two angles were not controlled by the 4D stage.

Euler angles α , β , γ can be selected as the translational and rotational beam gating. Typically, for slow and small patient target drift, the motors move and continuously cancel out the displacement such that the beam off tolerance is not exceeded. For fast and large head motion, the beam tolerance is exceeded and the beam is turned off until the displacement is compensated and goes back within all gating thresholds.

Since the beam gating is computed based on the measurement of the camera system, the uncertainty of the camera system will lead to an expansion of the motion margin due to position uncertainty. To take into account camera uncertainty, a precise calibration between the camera frame to Linac reference frame is required.^{17,18}

2.D. Experimental verification of 4D stage

We first investigated the control system's response when moving a target to a new desired position. Then, both the phantom study and volunteer study were performed to test the 4D stage.

For the phantom study, an in-house 6D motion phantom¹⁹ was placed on the top of the 4D stage and programmed to simulate actual 6D human head motion. The 4D stage was used to compensate such motion [Fig. 1(a)]. The 4D stage was further tested by volunteer study. The volunteers were asked to rest in a comfortable supine position on a head support without the use of the mask or any additional immobilization, and the 4D stage was put under the neck of the volunteers to

compensate for their head motion [Fig. 1(b)]. A virtual target was selected in the parietal lobe and was tracked through the IR markers fixed to a forehead frame. For each experiment, data were acquired over 15 min at 12–30 frames/s. The accuracy of compensation was verified in both studies. In addition, the 4D stage was tested for the correction of head position after severe head motion, such as coughing.

3. RESULTS

3.A. Decoupling of rotation and translation

As shown in Fig. 3(a), during real-time motion correction, a move of the pitch θ axis motor leads to the desired angular correction along the pitch axis, however, inadvertently leads to undesired y and z displacements due to mechanical coupling. Although such y and z displacements were detected by the optical camera, and eventually canceled out over the next 6 s, they nonetheless represented unnecessary translational displacements of the brain target. This was a consequence of the direct independent axes motion control algorithm used.¹⁰ Although such algorithms were suitable for independent axis systems, they were not suitable for serial kinematic robot systems with mechanical coupling. This problem was solved by feedback control with feed-forward. Now, as shown in Fig. 3(b), the translational position remains stable when the pitch angle was changed. Additionally, it can be seen that the feed-forward algorithm reduced the time to the desired

FIG. 5. Volunteer head motion correction. Approximately 99% of time the target was within a 0.4 mm/0.2° displacement. [(a) and (c)] The translational and rotational coordinates of the head. (b) The translational displacement $d = \sqrt{x^2 + y^2 + z^2}$. (d) Stepper motors' positions.

position and lead to less motion overshoot. When moving the target from the zero position to a new desired position of ($x = 1$, $y = 2$, $z = 3$ mm, $\theta = -1^\circ$), the time for correction was found to be 7 s with feed-forward [Fig. 3(d)], compared to 9 s without feed-forward [Fig. 3(c)].

3.B. Phantom study

Figure 4 shows the 6D head coordinates for a 15-min time period with and without real-time robotic head motion correction enabled. The uncorrected position was within the translational tolerance of 0.4 mm and the pitch angle tolerance of 0.2° 17% and 28% of time, respectively [Figs. 4(a) and 4(c)]. With 4D stage correction, the position was within a translational displacement of 0.35 mm and a pitch displacement of 0.15° 100% of the time [Figs. 4(b) and 4(d)]. The computation was based on the moving average, at which

the averaging at each instant was operated on the most recent six data points. As expected, roll and yaw remain uncorrected due to limitations of the 4D robot [Fig. 4(d)].

3.C. Volunteer study

Figure 5 shows the motion correction for one particular volunteer. The sharp motion spike indicates sudden head motion, while several small motion spikes were the result of swallowing.

Overall, 20 head motion correction experiments were performed on seven volunteers, and five uncorrected head motions were recorded for comparison. Figure 6 summarizes the main findings of this study. The cumulative displacement distributions were used to show the percentage of time that a target was within a particular displacement from the desired position. It can be seen from the figures that,

FIG. 6. Cumulative distribution of displacements over the 15 min treatment period. 20 corrected (solid) and 5 uncorrected (dashed) volunteer head motion corrections are displayed. (a) Cumulative distribution of translational displacement $d = \sqrt{x^2 + y^2 + z^2}$. (b) Cumulative distribution of the pitch displacement.

Fig. 7. Volunteer severe head motion correction (coughing). The coughing occurs at $t = 18$ s, and the head reenters the 4D stage workspace at about $t = 26$ s. The translational displacement was reduced within 0.4 mm around $t = 33$ s (a), and the pitch displacement was within 0.2° at about $t = 36$ s (b).

for all corrected motions, over 96% of time the targets were within the translational displacement of 0.4 mm, and the pitch displacement of 0.2° . Across all volunteers, with correction, on average, 98.8% of time the target was within the translational displacement of 0.4 mm, and 99.3% of time within the pitch displacement of 0.2° . An additional calculation also showed that on average, 98.5% of time the target was within both translational and pitch displacements of 0.4 mm/ 0.2° . Without correction, these reduced to 11.4%, 26.3%, and 10.7%, respectively.

3.D. Correction after severe head motion

Since there is no immobilization device, patient coughing, speaking, sitting up, or other actions could lead to substantial translational and rotational displacements. In the event of extreme motion, the robotic stage will automatically turn off the beam, and wait for the patient to reenter the workspace of the stage before resuming motion correction. Figure 7 shows the control system can correct the displacement caused by coughing in 10 s.

4. DISCUSSION

In this work, a novel feed-forward motion control algorithm was demonstrated using a 4D robotic platform that allows for efficient correction of both translational and rotational displacements. The algorithm is designed for stacked serial kinematic motion devices that have a high degree of coupling between motion axes. Therefore, the algorithm is not device specific and can be used on other motion control systems such as the majority of Linac patient treatment couches. Due to the unavailability of a 6D platform, the motion control algorithm was demonstrated on a 4D system; however, it should be noted that the algorithm is fully capable of 6D motion control.

There are two tolerances defined for the system, the beam shut off tolerance and the robot shut off tolerance. The beam tolerance is user defined, whereas, the robot tolerance is defined by the physical limits of the robot. If the real-time target position exceeds the beam tolerance, but is within the robot tolerance, the beam is shut off, but the robot can still move to make the necessary corrections. Based on Fig. 6,

for healthy volunteers, we find that 98.5% of the time the volunteers were less than 0.4 mm/ 0.2° ; therefore, we feel that these values would make an appropriate beam tolerance. On the other hand, if the real-time target position exceeds the robot tolerance, both the radiation beam and robot shut off. An example of this would be a patient panic attack, where the patient suddenly sits up. This would be considered a severe motion case as shown in Fig. 7.

5. CONCLUSIONS

A control design approach for both translational and rotational head motion corrections was developed for frameless stereotactic radiosurgery. It was shown that feedback control with feed-forward was an efficient approach for motion correction control, as it decouples the rotation and translation, leading to efficient motion trajectories, shorter settling times, and less overshoot. The 4D robotic system was shown to achieve submillimeter/subdegree position accuracies. In this paper, pitch angle correction was presented, and roll and yaw correction was considered for future work by adding two more corresponding motors.

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