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A perspective on Varian edge live view calibration

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Abstract

Modern radiotherapy relies heavily on precise, real-time monitoring of both the patient and the linear accelerator (linac) components. However, current commercial surface scanning systems often overlook the monitoring of linac components, such as the gantry, collimator, and couch, focusing solely on the patient. This study aims to address this issue by developing a comprehensive understanding of the Varian TrueBeam Edge system using a live view calibration method. This method ensures accurate alignment between the machine's 3D model and live camera images, improving the precision and reliability of radiotherapy treatments.

Keywords: Live view calibration; Modern radiotherapy; Patient; Linear accelerator components

1. Introduction

Precision and accuracy are crucial in radiotherapy, making the alignment of a computer-generated 3D model of a linear accelerator with real-time video images essential for successful treatment delivery. The Varian TrueBeam Edge system, an innovative platform for advanced radiotherapy, utilizes a live view calibration process to achieve this alignment. Traditional surface scanning systems focus on monitoring the patient, but the Varian TrueBeam Edge system expands this capability to encompass linac components, including the gantry, collimator, and couch. This advancement represents a significant step forward in radiotherapy, where the precise positioning of both the patient and treatment machine is critical.

The live view calibration process in the Varian TrueBeam Edge system is a sophisticated method that guarantees the accurate alignment of the machine's 3D model with live camera images. This process involves using calibration points with known spatial coordinates, serving as reference markers to determine the camera's position relative to the linac. By aligning the camera's view with the machine's components, the system ensures that the displayed image on the screen corresponds exactly with the actual positions of these components.

This paper presents a comprehensive exploration of live view calibration in the Varian TrueBeam Edge system, providing new insights into its ability to enhance the accuracy and consistency of radiotherapy treatment procedures. The alignment achieved through live view calibration is not solely a technical requirement, but also a crucial safety measure that ensures precise targeting of tumors while minimizing exposure to healthy tissues. Misalignment can result in errors during treatment, potentially compromising patient safety and the effectiveness of the treatment. By increasing our understanding of live view calibration, this study contributes to the ongoing improvement of radiotherapy techniques, ensuring that patients receive the most accurate and effective treatments available.

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2. Materials and methods

The calibration process begins with the placement of a phantom—often a simple spherical object—at various predefined couch positions within the treatment room. These positions serve as calibration points, with known spatial coordinates that are used to correlate the real-world setup with the computer-generated model. The key mathematical tools used in this process are the view matrix and projection matrix, which ensure the correct alignment of the virtual model with the live video feed (Figure 1).

2.1. Theory

2.1.1. Camera Model and Projection

The relationship between the 3D points in the machine's coordinate system and their 2D projections in the camera's image is governed by intrinsic and extrinsic parameters. The intrinsic parameters (contained in the camera's intrinsic matrix) include the focal lengths and optical center, while the extrinsic parameters (rotation matrix and translation vector) describe the camera's position and orientation relative to the machine. These matrices are used to compute the view and projection matrices, which transform world coordinates into camera coordinates and then into screen coordinates, respectively.

The relationship between a 3D point in the machine's coordinate system and its 2D projection in the camera image is represented by the following equation [1, 2, 3, 4, 5]:

$P_{image} = K[R|t]P_{world}$ (1)

P_{image}: Homogeneous coordinates of the point in the image.

K: Intrinsic matrix of the camera, containing focal lengths and optical center.

R and t are the Rotation matrix and translation vector, forming, the extrinsic matrix.

P_{world}: Homogeneous coordinates of the point in the world (machine) coordinate system.

2.1.2. Intrinsic and Extrinsic Parameters

Intrinsic Parameters (K):

$$k = \begin{bmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix} \quad (2)$$

where f_x and f_y are the focal lengths in the x and y directions, and c_x and c_y are the coordinates of the principal point.

Extrinsic Parameters (R and t):

$$[R] = \begin{bmatrix} R & t \\ 0 & 1 \end{bmatrix} \quad (2)$$

This matrix [R |t] describes the position and orientation of the camera relative to the machine coordinate system.

2.1.3. Computation of View and Projection Matrices

The view matrix V is derived from the extrinsic parameters and transforms world coordinates to camera coordinates. The projection matrix P is obtained from the intrinsic parameters and maps camera coordinates to normalized device coordinates (NDC) in the image.

The combined transformation is given by:

$P_{NDC} = P \times V \times P_{world}$ (3)

This transformation ensures the accurate overlay of the 3D machine model on the live video feed by accounting for both the camera's position and its optical characteristics.

he calibration process involves setting up a phantom, consisting of a ball, at various known couch positions (Figure 2) with corresponding 2D coordinates (U and V) to determine the spatial relationship between the camera and the machine. This data is essential for calculating the view matrix and projection matrix.

2.1.4. View Matrix

The view matrix, also referred to as the camera matrix, is responsible for converting coordinates from world space to camera (view) space. It determines the position and orientation of the camera in the scene.

2.1.5. Camera Position

This parameter specifies the camera's location in world coordinates.

2.1.6. Camera Target

The camera target defines the point that the camera is looking at in the world.

2.1.7. Up Vector

This vector determines the "up" direction in the camera's view. Typically, it is set to the y-axis (0, 1, 0), but it may vary depending on the camera's orientation.

2.1.8. Transformation

The view matrix is created using the above parameters to transform world coordinates into the camera's coordinate system.

The forward vector F is computed as:

$$F = \frac{T-E}{\|T-E\|} \quad (4)$$

Where E is the Eye (Camera) position, T is the Target position, and U is the Up vector.

The right vector R is determined as:

$$R = \frac{F \times U}{\|F \times U\|} \quad (5)$$

and the up-vector U:

$$U = R \times U \quad (6)$$

The view matrix V is calculated as:

$$V = \begin{bmatrix} R_x & R_y & R_z & -R.E \\ U_x & U_y & U_z & -R.U \\ -F_x & -F_y & -F_z & F.E \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (7)$$

2.1.9. Projection matrix

The projection matrix transforms camera space coordinates to screen space coordinates determining how a 3D scene is projected onto a 2D screen. Perspective Projection Matrix: Simulates the perspective view where objects farther from the camera appear smaller. Field of View (FOV): The extent of the observable world seen at any moment.

2.1.10. Aspect Ratio

The ratio of the screen’s width to its height. Near and Far Planes: Define the distances from the camera to the near and far clipping planes.

Depth = Far Near, then we construct the perspective projection matrix as:

$$P = \begin{bmatrix} \frac{f}{Aspect} & 0 & 0 & 0 \\ 0 & f & 0 & 0 \\ 0 & 0 & \frac{Far+Near}{Near-Far} & \frac{2.Near.Far}{Near-Far} \\ 0 & 0 & -1 & 0 \end{bmatrix} (8)$$

where:

$$f = \frac{1}{tan\left(\frac{FOV}{2}\right)} \ (9)$$

The orthographic Projection Matrix: stimulates a parallel view where objects are the same size regardless of their distance from the camera.

The orthographic Perspective Projection is given by:

$$P = \begin{bmatrix} \frac{2}{Right=Left} & 0 & 0 & -\frac{Right+Left}{Right-Left} \\ 0 & \frac{2}{Top-Bottom} & 0 & -\frac{Top+Bottom}{Top-Bottom} \\ 0 & 0 & \frac{2}{Near-Far} & -\frac{Far+Near}{Far-Near} \\ 0 & 0 & 0 & 1 \end{bmatrix} (10)$$

For each calibration point, the transformation sequence from World Space to Camera Space uses the view matrix, followed by the projection matrix to move from Camera Space to Screen Space. This transformation is expressed as:

$$P_{screen} = P_{projection} \times Vview \times Pworld \ (11)$$

Pscreen is the 2D screen coordinate obtained after applying the transformations.

Pworld is the 3D world coordinate corresponding to the calibration point.

2.2. Application in TrueBeam Varian Edgde System

In the TrueBeam Varian Edge system, these matrices ensure that the virtual 3D model of the treatment machine aligns accurately with the live camera images. The combined transformations are often represented as:

$$MVP = P_{projection} \times V_{view} \times M_{model} \ (12)$$

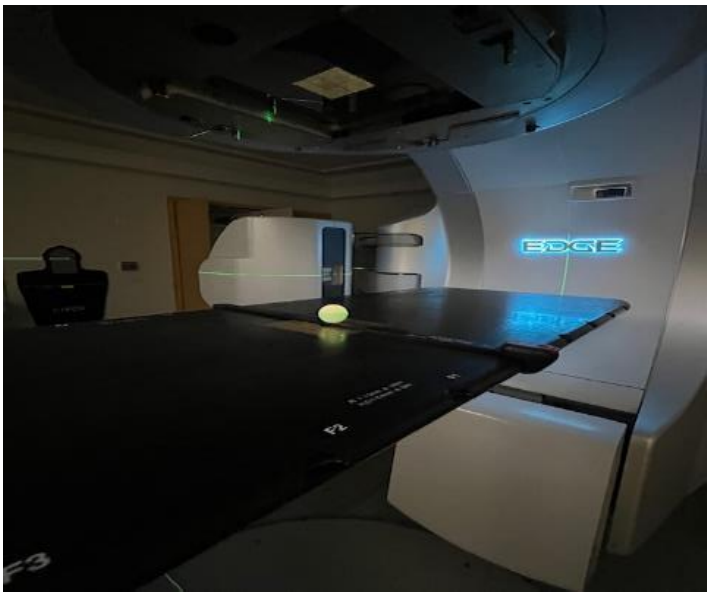
where:

MVP stands for Model-View-Projection matrix,

M is the model transformation matrix.

This MVP matrix can directly transform coordinates from model space to clip space, ensuring the correct representation of perspective, depth, and camera position.

Figure 1 Illustration of the depth camera's position relative to Varian Edge linac isocenter in the vault.

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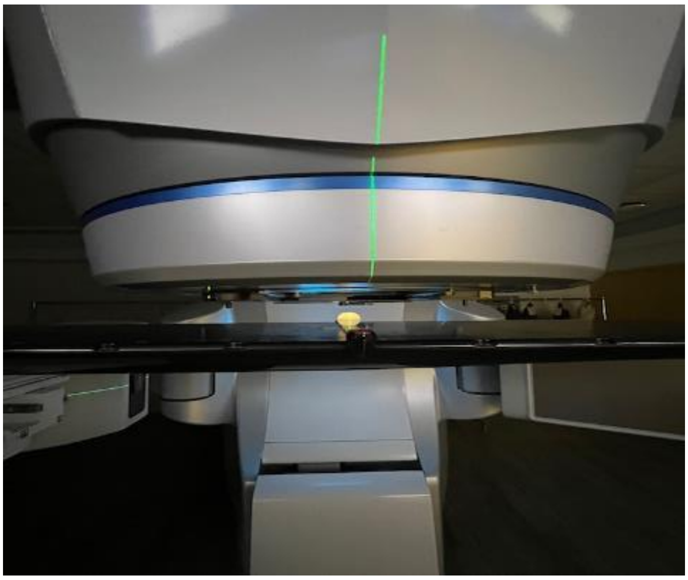

Figure 2 Target at the couch isocenter with various known position for the live view calibration.

3. Results

The calibration results yield two primary matrices: the view matrix and the projection matrix (Figure. 3)

View Matrix

$$\begin{bmatrix} 0.328556 & 0.328556 & 0.328556 & 0.328556 \\ 0 & 0 & 0 & 0 \\ 0.9444845 & 0.9444845 & 0.9444845 & 0.9444845 \\ 41.11518 & 41.11518 & 41.11518 & 41.11518 \end{bmatrix} \quad (13)$$

Projection Matrix

$$\begin{bmatrix} 0.006225304 & 0.006225304 & 0.006225304 & 0.006225304 \\ 0.0005304961 & 0.0005304961 & 0.0005304961 & 0.0005304961 \\ -0.0003939638 & -0.0003939638 & -0.0003939638 & -0.0003939638 \\ 2.384186E-07 & 2.384186E-07 & 2.384186E-07 & 2.384186E-07 \end{bmatrix} \quad (14)$$

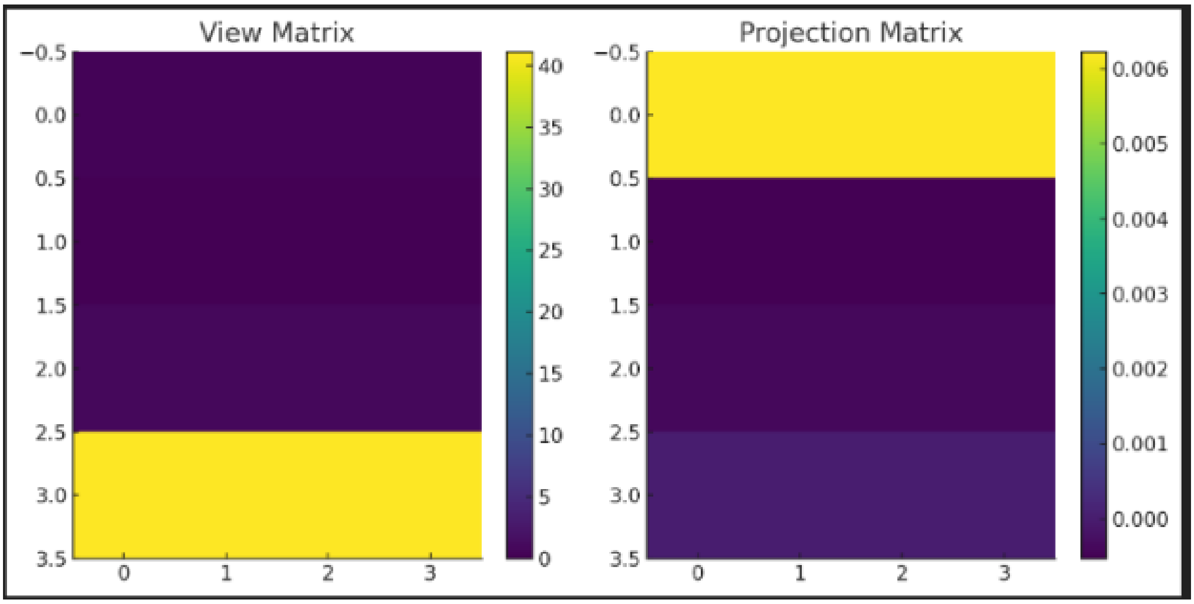

Figure 3 Illustration of the view and projection matrices structure.

These matrices are essential for accurately overlaying the 3D model onto the live video feed. By applying these matrices to the calibration points, the transformation from 3D world coordinates to 2D screen coordinates can be visualized (Figure. 4).

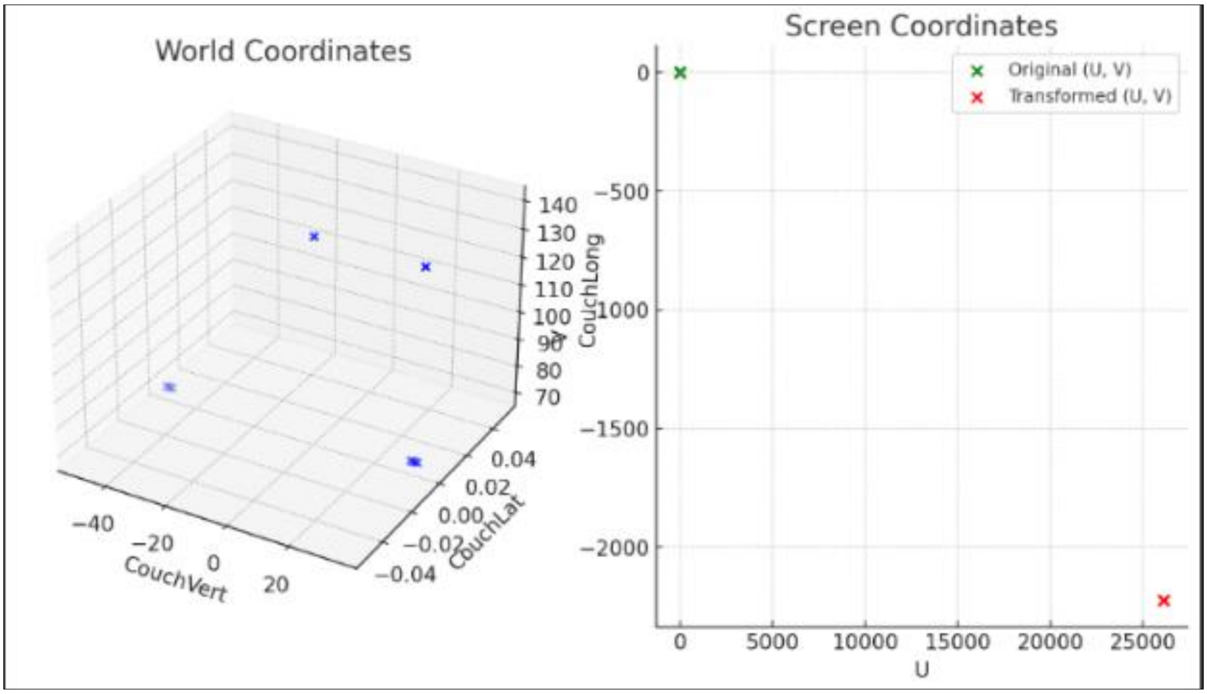

Figure 4 Transformation plot for live view calibration Varian Edge: 3D Plot of World Coordinates: This plot shows the original positions of the calibration points in world coordinates (Couch Vert, Couch Lat, Couch Long); 2D Plot of Screen Coordinates: This plot compares the original screen coordinates (U, V) of the calibration points (green points) with the transformed screen coordinates (red points) obtained after applying the view and projection matrices.

This process ensures that the machine components are represented accurately in the live view, facilitating precise treatment delivery.

The transformation of the 3D points through these matrices resulted in the following MVP matrix derived from Equation 12 as:

MVP Matrix

$$\begin{bmatrix} 0.26387956 & 0.26387956 & 0.26387956 & 0.26387956 \\ -0.02248679 & -0.02248679 & -0.02248679 & -0.02248679 \\ -0.01669942 & -0.01669942 & -0.01669942 & -0.01669942 \\ 1.01061402x10^{-5} & 1.01061402x10^{-5} & 1.01061402x10^{-5} & 1.01061402x10^{-5} \end{bmatrix} \quad (15)$$

The resulting Model View Projection (MVP) matrix can be used to transform coordinates from the model space to the clip space, allowing for the rendering of the 3D scene on a 2D screen through several steps (Figure. 5).

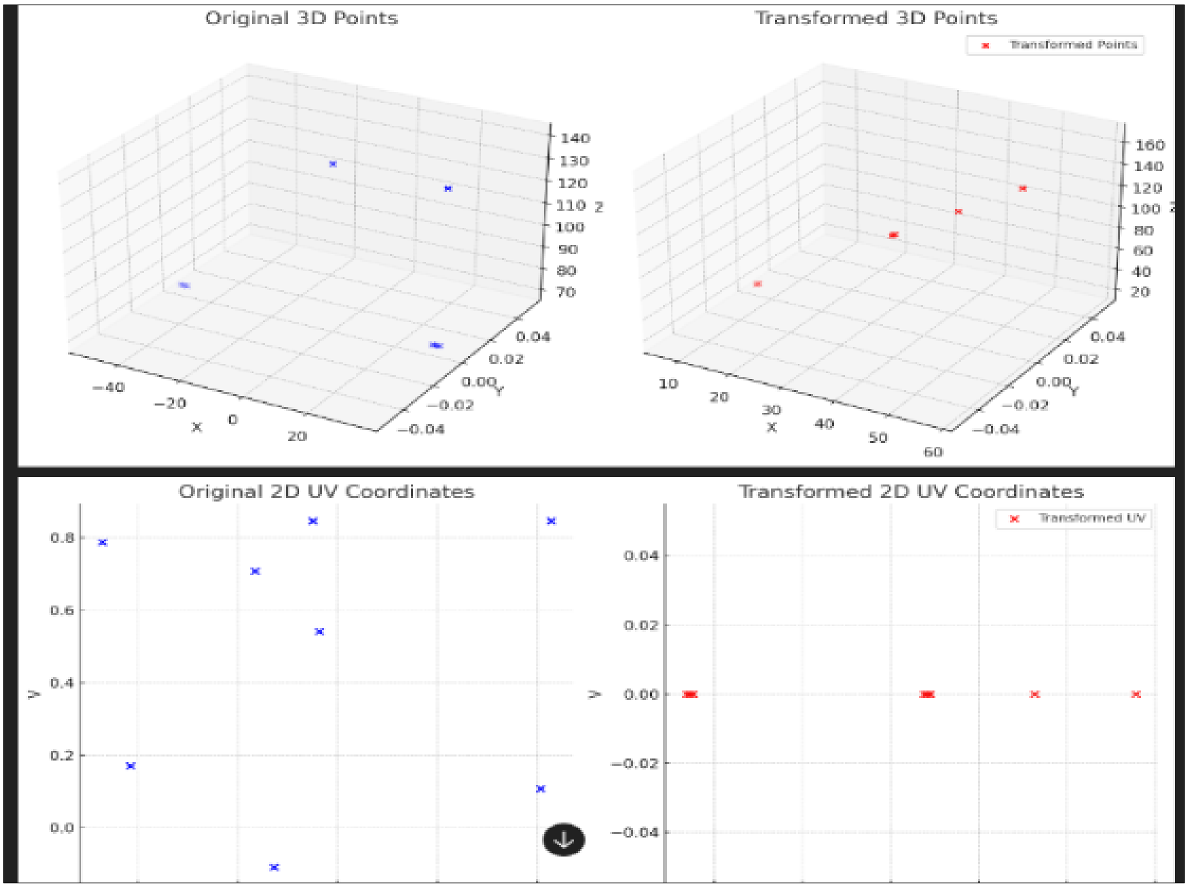

Figure 5 Transformation of 3D points and corresponding 2D (U, V) coordinates for Varian Edge live view calibration.

These graphs help visualize how the system's components and accessories (such as the gantry, collimator, and couch) are represented and transformed in the Varian TrueBeam live view calibration setup. The transformation matrix (view matrix) modifies both the 3D positions and their 2D projections, which is crucial for accurate rendering and monitoring.

Figure 6 shows the calibration results of the couch, gantry, and collimator, with each arrow indicating the orientation and movement of these devices.

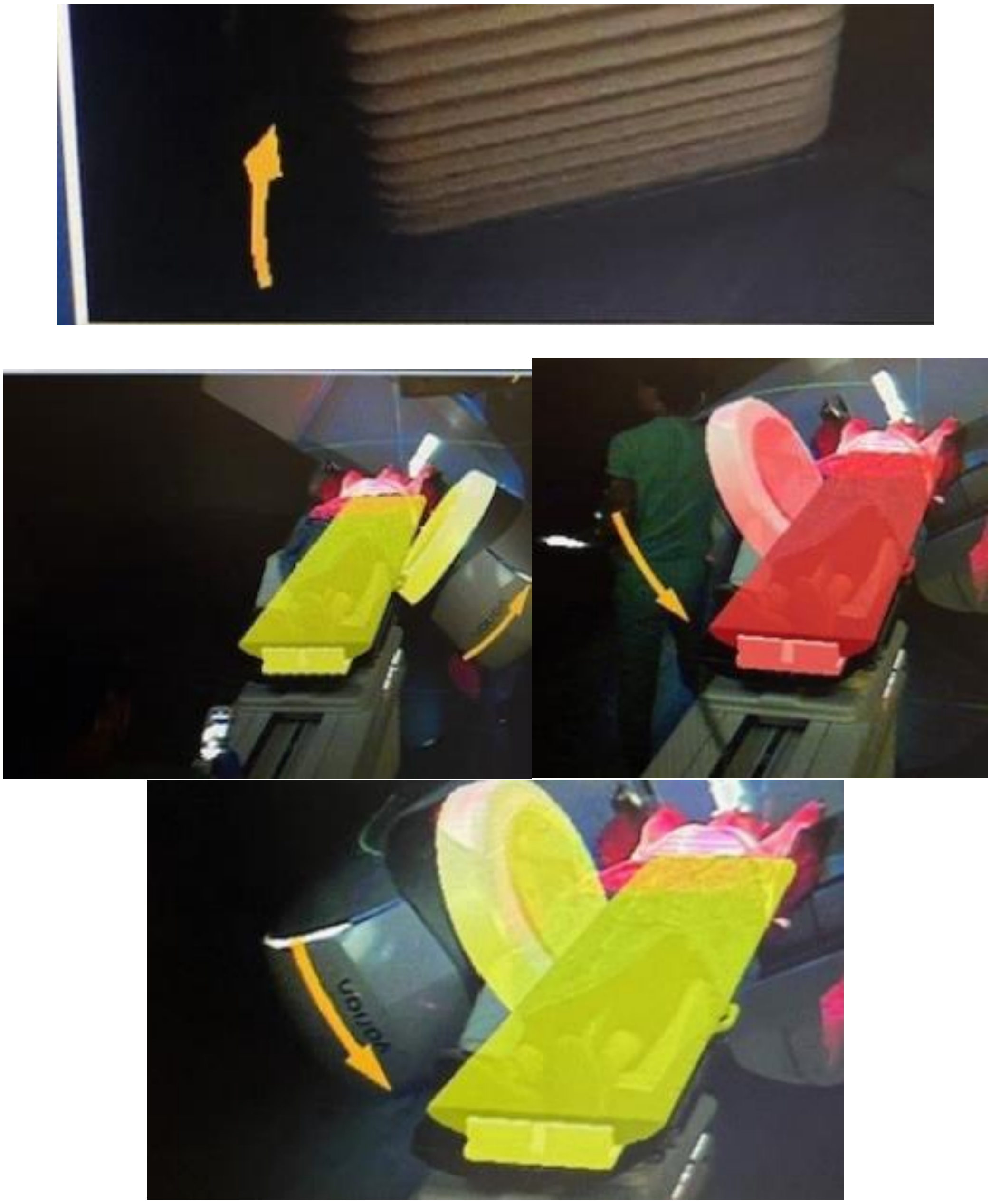

Figure 6 Gantry, collimator, and couch after live view calibration of Varian Edge

3.1. Error Quantification

Error quantification, through comparison of original and transformed coordinates, highlights the accuracy and reliability of the calibration process.

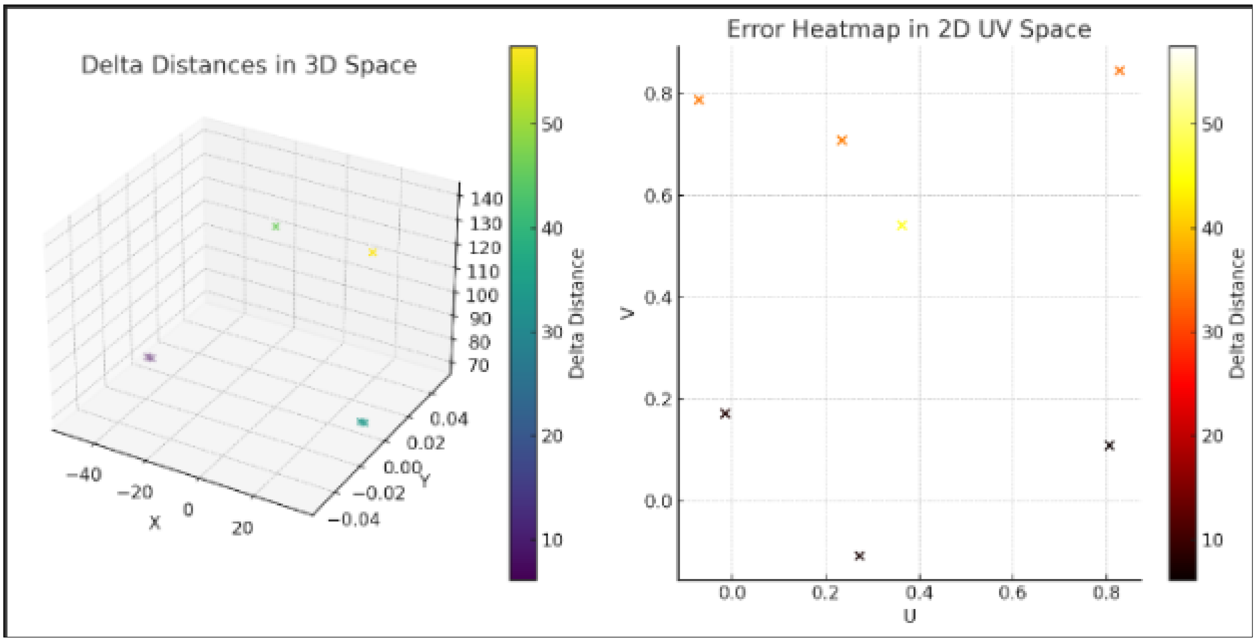

Figure 7 Depicts the errors (delta distances) between the original and transformed UV coordinates.

The scatter plot shows the 3D positions of the points, with colors representing the magnitude of the errors. This visualization illustrates how much each point deviates from its expected position after transformation. The Error Heatmap in 2D UV Space displays the error magnitude in the UV coordinate space, where the color intensity indicates the degree of error. This aids in identifying areas with larger discrepancies. These visual tools offer a concrete and measurable assessment of the accuracy of the transformation using the view matrix. The delta distances indicate the variance between the expected and actual positions of the phantom's rendering, highlighting potential calibration inaccuracies or system deviations.

4. Discussion

The live view calibration process is crucial for the Varian TrueBeam Edge system to deliver radiotherapy with exceptional precision. By aligning the computer-generated 3D model of the linear accelerator with real-time camera images, the system improves the monitoring and positioning of both the patient and the machine's components during treatment. This precise alignment is vital in radiotherapy, as even the slightest discrepancy can lead to significant deviations in treatment delivery, potentially affecting patient safety and treatment efficacy.

Our study underscores the significance of the calibration process, highlighting its effectiveness in preserving the system's accuracy. However, it also emphasizes the necessity of continuous verification and potential recalibration to maintain precision over time. Due to the dynamic nature of radiotherapy procedures, ongoing monitoring and adjustments are essential to address any shifts or alterations in the system's components that may impact alignment.

One of the key findings of our study is the significant role of transformation matrices in the calibration process. These matrices are essential for accurately scaling and translating 3D points onto a 2D plane for visualization, ensuring that the virtual model and live images are perfectly synchronized. The uniformity of the matrix elements contributes to consistent transformations across different axes, which is vital for maintaining the fidelity of the 3D model. However, our analysis also revealed some limitations in the current calibration system, particularly concerning depth perception and potential distortions.

The current system, which relies on a single depth camera, may encounter a loss of depth information or distortions, particularly in scenarios involving extreme scaling or translation values. This limitation is evident in the large translation component of the view matrix and the small scaling factors in the projection matrix, both of which can compromise the model's depth accuracy. To address these issues, enhancements to the calibration process are necessary, such as integrating an additional camera. A second camera would enhance depth perception, reduce the likelihood of distortions, and provide a more accurate representation of three-dimensional space.

In the broader context of radiotherapy, the effectiveness of calibration and quality assurance processes is closely linked to the underlying hardware and software technologies. Regular inspection of equipment to ensure it meets established performance standards is essential for maintaining system accuracy. Currently, there are no specific methods or standards dedicated to live view calibration within Varian systems, aside from the procedures integrated into the treatment module. While visual inspections—such as monitoring the indicators that show the movements of the gantry, couch, and collimator—are useful for assessing calibration accuracy, they are insufficient on their own. Limitations of optical devices, including systematic distance errors, depth in homogeneity, noise, and object reflectivity, must be addressed in the development of live-view systems for radiotherapy. Further advancements are necessary in the form of rigorous calibration standards and methods specifically designed for these systems. Such improvements would not only enhance their accuracy and reliability but also improve the safety and effectiveness of radiotherapy treatments. Reason: The revised text improves clarity and readability by refining sentence structure, enhancing vocabulary, and correcting grammatical errors. Additionally, it maintains the original meaning while providing a more polished presentation.

5. Conclusion

The live view calibration process for the Varian TrueBeam Edge system represents a groundbreaking advancement in the field of radiotherapy. This study, the first to investigate the integration of a computer-generated 3D model with live video feeds for monitoring essential components such as the gantry, collimator, and treatment couch, underscores the critical importance of precise calibration in achieving optimal patient outcomes.

The findings from this study highlight the significance of transformation matrices in maintaining system accuracy, as well as the need for continuous verification and potential recalibration to ensure precision over time. Accurately aligning the virtual model with real-time camera images is essential for the precise targeting of tumors, thereby reducing the risk of exposing healthy tissues to radiation.

However, the study also identifies limitations in the current system, particularly concerning depth perception and potential distortions. The reliance on a single depth camera may introduce errors, especially in scenarios involving extreme scaling or translation values. To address these issues, future research should focus on enhancing the calibration process, potentially through the integration of additional cameras to improve depth perception and minimize distortions.

Looking ahead, the establishment of more stringent calibration standards and methods specifically tailored for live-view systems in radiotherapy is essential. These advancements would not only improve the accuracy and reliability of these systems, but also enhance the overall safety and effectiveness of radiotherapy treatments.

As the first paper to address live view calibration in the Varian TrueBeam Edge system, this study establishes a foundation for future research in this area. The insights gained from this work will be invaluable for refining calibration techniques and exploring innovative approaches to enhance the precision of radiotherapy, ultimately improving patient outcomes and advancing the field of radiation therapy.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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