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Feasibility study of a dry optical CT scanner using aspherical lenses

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Abstract. Dry scanners have been proposed as alternatives to scanners in which a refractive index matching fluid is used. Previous dry scanners either have a small field-of-view or employ a thick cast with a higher refractive index than the phantom. This may not always be feasible. A new design is proposed in this study where two aspherical meniscus lenses are employed to direct the laser beams in parallel lines through the phantom.

1. Introduction
Different optical CT scanners have been proposed in recent years to scan three dimensional dosimeters. The first generation of optical CT scanners are based on a scanning laser beam and a photodetector to measure the transmitted light. The most rapid and less vibration prone optical laser scanners consist of a Galvano-mirror to move the laser beam across the lateral direction of the phantom. In order to avoid refraction of the laser beam on the curved surface of a cylindrical phantom, a tank filled with a refractive index matching fluid is mostly used. The refractive index matching fluid consists mostly of a mixture of glycerol and water for gel based dosimeters and silicone based dosimeters, while a silicone oil is used for polyurethane (PRESAGE) based dosimeters.

For the end-user of 3D radiation dosimeters, the use of a fluid bath with refractive index matching fluid has some disadvantages in terms of practicality: The fluid bath and the fluid need additional maintenance as floating dust particles can create image artifacts in the dose maps. Regular cleaning of the optical scanner and around the scanner is needed as the employed liquids are mostly relatively greasy. Unequal evaporation of the components of the matching fluid may also cause a shift in the refractive index, hence causing a mismatch in refractive index over time. Over time, the fluid bath needs refilling which requires mostly an iterative process to obtain the correct mixture. Motivated by these drawbacks, some research groups have proposed a ‘dry’ approach where no refractive index matching fluid is applied.

The challenge in the design of a dry scanner is to compensate for the refraction of the light by the phantom. A first attempt was undertaken by Maryanski et al using the gel dosimeter phantom as focusing lens [1]. With this design, only an effective field-of-view of 1/3 of the phantom size was obtained. Ramm et al [2] investigated the possibility to extend the field-of-view by adding a thick cast of high refractive index material around the gel dosimeter. The latter approach is limited by the availability of a casting material with a refractive index higher than that of the dosimeter system. Doran and Yatigammana [3] investigated the possibility of removing the refractive index matching fluid tank and capturing the non-parallel light ray trajectories with a CCD camera. Reconstruction of the captured data is performed using an iterative SART reconstruction algorithm. As the light rays are travelling along non-parallel directions, weighting factors need to be applied in the reconstruction that take the divergence of the ray thickness.
into account. The field-of-view of the reconstructed image is restricted to a physical limit which depends on the refractive index of the dosimeter phantom.

In the current study, the feasibility of using lenses to direct as many parallel rays as possible through the dosimeter phantom is investigated. While the proposed method does not allow a complete coverage of the entire cross-section of the phantom, it provides a solution for configurations where the earlier method fails as a result of high refractive index dosimeter systems such as PMMA based (Flexydos3D) and polyurethane based dosimeters (PRESAGE™).

2. Methods and Materials

2.1. Theory

Spherical lenses have a shape which is part of the surface of a sphere. Spherical lenses do not have a constant focal distance at all points across the lens. As a result, spherical aberration occurs. To compensate for spherical aberration, aspherical lenses have been proposed as early as the 10th century by the Persian scholar Ibn Sahl [3]. The lens shape of an aspherical lens is described by the equation:

\[ z(r) = \frac{r^2}{R_l} + \sum_{n=2}^{m} A_{2n} r^{2n} \]  

where \( r \) is the radial coordinate, \( R_l \) is the vertex radius, \( k \) the conic constant and \( A_{2n} \) the coefficients of a correction polynomial for higher-order aspheric optical components. Depending on the value for the conic constant \( k \), different types of conic sections can be identified: \( k > 0 \) defines an oblate elliptic section; \( k = 0 \) a spherical section; \( -1 < k < 0 \) a prolate elliptic section; \( k = -1 \) a parabolic section; and \( k < -1 \) a hyperbolic section.

The optical design for the dry laser scanner consists of two aspherical lenses on either side of the cylindrical dosimeter phantom (Figure 1). With two sections on each side of either lens, this results in 4 aspherical sections that need to be optimized in order to direct parallel lines through the dosimeter phantom. When no higher order terms are considered in equation 1, this still results in an 8-dimensional parametric space for which exist an infinite number of possible solutions. Some additional constraints are needed for the optimization problem. The following geometric constraints were added: (1) a predefined distance between each lens and the phantom; (2) a predefined thickness of each lens and (3) laser light rays follow parallel lines in the first lens. The optimization problem is solved sequentially in four stages each with their own objective function (Figure 1):

- For the entrance section of the first lens, optimize the lens shape \((k, R_l)\) so that all light rays originating from a source at the same focal distance \( F \). The objective function here is the standard deviation of all light ray travelling through lens 1 (equation 2).
  \[ \min_{(R_l^1, k^1)} \sum_{\forall I} (\theta_{i1})^2 \]  

- The light rays leave the first lens under an optimal angle so that light rays will travel along parallel lines within the phantom. The objective function that is to be minimized is the sum of the squared angle of all light rays traveling through the phantom (equation 3).
  \[ \min_{(R_l^1, k^1)} \sum_{\forall I} (\theta_{ip})^2 \]
(3) The light rays entering the second lens are expected to travel in parallel lines. The objective function to be minimized is the sum of the squared angle of all light rays traveling through lens 2 (equation 4).

$$\min_{(R_2^{(III)},k^{(III)})} \sum_{\forall i} (\theta_{i2})^2$$

(4) The parameters of the third lens are optimized by targeting convergence of all light rays in a focal spot behind the lens. The objective function is the quadratic difference between the focal spot of the light rays and the target focal distance (equation 5).

$$\min_{(R_3^{(IV)},k^{(IV)})} \sum_{\forall i} (\Delta F'_i)^2$$

where $\Delta F'_i$ is the difference between the target focal length and the point where light ray $i$ crosses the main axis ($\Delta F'_i = F'_i - F$).

Figure 1. Geometry of the simulations. Fixed parameters are labeled in black, while objective functions are labeled in red. The optimization variables are indicated in green.

2.2. Implementation

The software was written in Matlab code. While Matlab provides built-in routines for minimization of cost functions, the minimum was sought using a brute-force technique where discrete steps were taken through both $R_l$ and $k$ in order to avoid convergence to local minima. All dimensions are considered relative to the radius of the phantom $R$. The values were chosen arbitrary as: $F_1/R = -2.5; t_l/R = 0.2; d_l/R = 0.2; F_2/R = -2.5$; where $F_1$ and $F_2$ are the focal distances for the first and second lens, $t_l$ is the thickness of the lens on the main axis and $d_l$ is the distance from the lens to the phantom (i.e. air gap) on the main axis. While not necessary, $t_l$ and $d_l$ were taken the same for both lenses.

With equidistant angular increments in the incident light rays, small deviations in distance of the parallel light rays in the phantom occur as a result of the divergence of beams after the first lens, the varying lens thickness and the curvature of the phantom. The distance in light rays is plotted as a function of incident (Galvano-mirror) angle.

Three different types of dosimeter phantoms with different refractive indices are considered. In order to test the feasibility of using a dual-wave length scanning approach [5, 6], the chromatic aberration was studied for both red light ($\lambda = 630 \text{ nm}$) and blue light ($\lambda = 480 \text{ nm}$). The aspherical lens parameters
were first optimized for the red light source and ray tracing was applied using the refractive index of lenses and phantom for the blue light source.

| Material                        | 480 nm | 630 nm |
|---------------------------------|--------|--------|
| Gelatin gel (polymer gel)       | 1.347  | 1.340  |
| Polyurethane (PRESAGETM)       | 1.515  | 1.508  |
| PDMS (Flexydos3D)              | 1.419  | 1.412  |
| Glass (Lens)                   | 1.5228 | 1.5152 |

3. Results and Discussion

3.1. Ray tracing and distortions

![Simulations of ray paths for light rays originating from a point source for a configuration containing a gelatin hydrogel phantom without lenses (a) and with two aspherical lenses after optimization (b).](image-url)
Light ray trajectories through a cylindrical phantom with the fluid tank removed are shown in figure 2a. In this simulation, the focal distance was optimized in order to minimize beam divergence in the phantom, i.e. equation 3 as objective function. It is clear from figure 2a, that the rays within the phantom are not parallel, nor do the light ray trajectories in the phantom converge to a single point so that nor a radon transform or fan beam reconstruction can be used. The only valid approach to reconstruct an image from the transmitted rays is by using an iterative reconstruction algorithm [3].

Figure 2b shows the light ray trajectories for the same phantom with optimized aspherical lenses. Only a small deviation from the parallel direction is visible in the outermost simulated light rays within the phantom. However, a plot of the spatial distribution of light rays in the phantom shows that they are closer packed in the centre than at the periphery (figure 3). It was found that a tangent function fits the spatial distribution precisely. This function can be used to correct for the non-uniform distribution.

3.2. Chromatic aberration (dual wavelength scanning)
In earlier work [5, 6], we suggested the use of a blue light scan as a reference scan. As the refractive index of different materials is frequency dependent, it is important to investigate its effect on the light ray trajectories. Figure 4 shows the trajectories of both red light ($\lambda = 630 \text{ nm}$) and blue light ($\lambda = 480 \text{ nm}$) as these are the worst-case central wavelengths of the light sources used in our dual wavelength scanner.

Figure 3. Correlation between the light ray position ($y_c/R$) measured along the central axis of the phantom and the light ray incident angle ($\theta_i$). A fit of a tangent function on the data points is shown as a red solid line.

Figure 4. Ray tracing simulation demonstrating a negligible effect of chromatic aberration for light rays inside the phantom. The solid red lines correspond to light rays with a wavelength of 630 nm, while the dashed blue lines correspond with a wavelength of 480 nm.
While several methods have been proposed to reconstruct CT images with reduced field-of-detection (FOD), a fast alternative reconstruction method has been developed that uses the a priori information that in the dry scanner, the phantoms have a cylindrical shape with a predefined radius. In this method, missing lines in the sinogram are extrapolated prior to reconstruction using a functional relation based on attenuation and continuity between acquired and missing lines in the sinogram (figure 5).

4. Conclusions
In this computational simulation study, the feasibility of dry scanning using two aspherical lenses is demonstrated. It is shown how parallel light ray trajectories can be obtained in a cylindrical phantom by use of two optimized aspherical lenses. The theoretical concept can be applied to different kinds of scanner designs, such as laser scanners, fan beam scanners or cone beam scanners. The field-of-detection is physically limited by the refractive index of the phantom which is similar to another approach where the transmission of parallel lines is abandoned. However, in previous approaches, an iterative reconstruction with high computational power is required, where in the proposed method using aspherical lenses, a simple filtered back projection in combination with extrapolation of missing sinogram data can be applied.

5. References
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