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A novel near real-time laser scanning device for geometrical determination of pleural cavity surface

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Abstract

During HPPH-mediated pleural photodynamic therapy (PDT), it is critical to determine the anatomic geometry of the pleural surface quickly as there may be movement during treatment resulting in changes with the cavity. We have developed a laser scanning device for this purpose, which has the potential to obtain the surface geometry in real-time. A red diode laser with a holographic template to create a pattern and a camera with auto-focusing abilities are used to scan the cavity. In conjunction with a calibration with a known surface, we can use methods of triangulation to reconstruct the surface. Using a chest phantom, we are able to obtain a 360 degree scan of the interior in under 1 minute. The chest phantom scan was compared to an existing CT scan to determine its accuracy. The laser-camera separation can be determined through the calibration with 2mm accuracy. The device is best suited for environments that are on the scale of a chest cavity (between 10cm and 40cm). This technique has the potential to produce cavity geometry in real-time during treatment. This would enable PDT treatment dosage to be determined with greater accuracy. Works are ongoing to build a miniaturized device that moves the light source and camera via a fiber-optics bundle commonly used for endoscopy with increased accuracy.

Keywords

pleural photodynamic therapy; PDT; chest contour; chest cavity geometry

1. Introduction

In order to improve treatment techniques for pleural photodynamic therapy (PDT), it is necessary to develop a way to provide real-time feedback of the pleural cavity geometry. Previously, the cavity space could only be determined once at an initial time. However, the cavity space undergoes change throughout the course of treatment. A laser system may be used to develop a device to produce real-time feedback of the cavity geometry. In order to

implement this idea, a laser source coupled with a hologram was use in conjunction with a camera with auto-focusing abilities.

2. Methods And Calculations

Data collection involves a calibration procedure to determine the laser source-to-camera shift. Using the calibration plane template and shifts from that template, we are able to reconstruct the surface of an arbitrary surface.

2.1 Algorithm

The underlying algorithmic principle of the device is based on the idea of parallax. First, it is important to determine the shift between the laser source and the camera. All following calculations depend on an accurate measurement of the laser-camera shift. Two known calibration planes are used to determine the shift value. These two planes are set up to be parallel and at two known distances away from the camera. Using a MATLAB script, we determine the location of corresponding points of the pattern from the two images. Then the differences in the x- and y-directions are used to calculate the shift. Since there are multiple points in the pattern that can be used, the shift value is optimized through a minimization procedure. The value with the smallest error is used as the laser-camera shift throughout the following calculations.

The mathematical algorithm for determining the laser-camera distance is given by equations (1) through (12) and Figure 1. By using two of these equations in a system, we can find the values of the shift of the camera from the laser. Each value of dx is given by the i^{th} coordinate of the two calibration planes ($x1$ and $x2$). The system of equations is given by looking at two different sets of points from the calibration planes. The i^{th} and j^{th} points should be chosen so that any the difference in x and y are not too small. If the values are too small, there is a greater error in calculation. The system of equations is given in equations (13) through (19). The equations presented describe the method to determine the x -shift and z -shift. A similar calculation can be done for the y -shift. Since there are multiple pairs of points to use to determine this shift, a minimization method is used to determine the optimal value for the shift. This greatly reduces any error there could be in measurement.

$$\tan\theta_x = \frac{x2}{z1} \quad (1)$$

$$\theta_x = \tan^{-1} \frac{x2}{z1} \quad (2)$$

$$dx = x1 - x2 \quad (3)$$

$$\cos\theta_x = \frac{z2}{r} \quad (4)$$

$$r = \frac{z_2}{\cos \theta_x} \quad (5)$$

$$\frac{dx}{a - b \tan \theta_x} = \frac{r - z_1 / \cos \theta_x}{r - b / \cos \theta_x} \quad (6)$$

$$\frac{dx}{a - b \tan \theta_x} = \frac{z_2 / \cos \theta_x - z_1 / \cos \theta_x}{z_2 / \cos \theta_x - b / \cos \theta_x} \quad (7)$$

$$\frac{dx}{a - b \tan \theta_x} = \frac{z_2 - z_1}{z_2 - b} \quad (8)$$

$$dx \cdot z_2 - dx \cdot b = z_2 \cdot a - z_2 \cdot b \cdot \tan \theta_x - z_1 \cdot a + z_1 \cdot b \cdot \tan \theta_x \quad (9)$$

$$dx \cdot z_2 = a(z_2 - z_1) + b(dx - z_2 \cdot \tan \theta_x + z_1 \cdot \tan \theta_x) \quad (10)$$

$$dx \cdot z_2 = a(z_2 - z_1) + b\left(dx - z_2 \cdot \frac{x_2}{z_1} + z_1 \cdot \frac{x_2}{z_1}\right) \quad (11)$$

$$a(z_2 - z_1) + b\left(dx - \frac{x_2 \cdot z_2}{z_1} + x_2\right) = dx \cdot z_2 \quad (12)$$

$$A = z_2 - z_1 \quad (13)$$

$$B = dx - \frac{x_2 \cdot z_2}{z_1} + x_2 \quad (14)$$

$$C = dx \cdot z_2 \quad (15)$$

$$aA_i + bB_i = C_i \quad (16)$$

$$aA_j + bB_j = C_j \quad (17)$$

$$a = \frac{C_i B_j - B_i C_j}{A_i B_j - B_i A_j} \quad (18)$$

$$b = \frac{C_i - aA_i}{B_i} \quad (19)$$

After determining the shift between the laser and the camera, we can use a similar algorithm to reconstruct an arbitrary scene. Equations (20) through (29) and Figure 2 describe this method. One of the two calibration plane from the first part is used as the “calibration template.” All of the data points collected from the images from the surface of interest is referenced to this calibration template.

$$\tan\theta_x = \frac{xS}{z1} \quad (20)$$

$$\theta_x = \tan^{-1} \frac{xS}{z1} \quad (21)$$

$$dx = x1 - xS \quad (22)$$

$$\frac{dx}{a - b \tan\theta_x} = \frac{r_x - z1/\cos\theta_x}{r_x - b/\cos\theta_x} \quad (23)$$

$$r_x \cdot dx - \frac{dx \cdot b}{\cos\theta_x} = r_x \cdot a - r_x \cdot b \cdot \tan\theta_x - \frac{a \cdot z1}{\cos\theta_x} + \frac{b \cdot z1 \cdot \tan\theta_x}{\cos\theta_x} \quad (24)$$

$$r_x \left(dx - a + b \cdot \frac{xS}{z1} \right) = \frac{dx \cdot b}{\cos\theta_x} - \frac{a \cdot z1}{\cos\theta_x} + \frac{b \cdot xS}{\cos\theta_x} \quad (25)$$

$$r_x = \frac{dx \cdot b - z1 \cdot a + xS \cdot b}{(\cos\theta_x) \left(dx - a + b \cdot \frac{xS}{z1} \right)} \quad (26)$$

$$X = r_x \cdot \sin\theta_x \quad (27)$$

$$Y = r_y \cdot \sin\theta_y \quad (28)$$

$$Z = r_x \cdot \cos\theta_x = r_y \cdot \cos\theta_y \quad (29)$$

2.2 Device

The current device is composed of a motor and encoder, a laser source, a hologram to produce the pattern, and a camera with auto-focusing abilities. The motor rotates the laser and camera combination to get a scan of the cavity of interest.

The motor and encoder is controlled by custom-made software to rotate the laser-camera device. The laser-camera device will move to the angle that is inputted into the software. At each angle location, a picture is taken of the laser pattern on the surface. In order to

reconstruct the contour of a chest phantom, an image was taken at small angle intervals. The device will move angles that are less than 1° .

3. Results and Discussion

The laser source to camera shift is determined with an average uncertainty of $\sim 2\text{mm}$. The process incorporates multiple points from the calibration images and finds the optimal x -, y -, z -shift. A summary of the error in these values is in Table 1. It is critical to determine the source-camera shift accurately for the reconstruction of the contour. There is a larger error with the 20cm calibration due to a less focused image. Focusing is essential in accurately determining the position of the points in the laser pattern.

The laser scanning device was used to create a contour plot of a chest phantom. The data was then compared with the CT scan data of the chest contour to determine its accuracy. A reconstructed contour is plotted in Figure 4. The current device has a limited span in its operating range in the z -direction due to the size of the device and camera lens. Furthermore, the number of data points collected in that range is limited by the hologram pattern. The data can be collected at angle intervals of less than 1° . The average error between the CT scan of the phantom and the reconstructed contour using the new device is within 2mm. The operating range (distance from device to unknown surface) for this average error is between 15cm and 35cm, which is adequate for the purposes of this device. At large distances, there is greater uncertainty with the precise location of the laser pattern points, and at smaller distances, the images are not focused. Any larger disagreement between the CT data and the laser data may be caused by the movement of the device during the image collection for different angles. Figure 5 is a general view of the 3D reconstruction, while Figure 6 shows just the yz -plane. The larger disagreement between the CT contour data and the laser scan data is due to movement of the device during the scan.

4. Future Work

To improve this method and make it possible for implementation during pleural PDT, it is necessary to make the device much smaller. It is also important to improve the resolution of the contour acquired with the device. Current plans are to implement a fiber optic bundle and projection system. Furthermore, the data collection time will be greatly reduced with an optimized automatic pattern detection method.

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Figure 1.

Schematic diagram for calibration planes. The two calibration planes at known distances are used to determine the shift from the laser source to the camera. The above figure shows the diagram for the x and z planes, but this can be done in a similar manner for the y plane.

Figure 2.

Schematic diagram for the algorithm to determine an arbitrary surface. Using a known calibration template at a distance of zI , the distance to an arbitrary plane can be determined at points that correspond to points in the calibration plane. The diagram is shown for the x and z planes, but a similar diagram can be drawn for the y plane.

Figure 3. Current scanning device. The wide angle lens attachment is to capture more of the laser pattern in one picture at close distances. The motor axis is in line with the camera lens.

Figure 4. Custom-made motor controlling software. The motor will rotate to the angle specified (in degrees).

Figure 5. CT scan data (blue lines) overlay with laser scan data (red circles). This set of data was collected at 5° intervals. The numerical values of the axes have units of cm.

Figure 6.
CT scan data (blue lines) overlay with laser scan data (red circles) in the yz -plane.

Laser Source-Camera Shift. Using various calibration planes at known distances, the source-camera shift was determined using a fitting code. The values are absolute and percentage variations for the x , y , and z -directions.

Table 1

Distance to Surface	x (cm)	y (cm)	z (cm)	$\frac{\Delta x}{x}$ (%)	$\frac{\Delta y}{y}$ (%)	$\frac{\Delta z}{z}$ (%)
20cm	0.027	0.002	0.033	1.07	0.19	1.99
25cm	0.015	0.005	0.016	0.61	0.45	1.00
30cm	0.016	0.004	0.013	0.66	0.41	0.80