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Laser-Guided CT Intervention using Flexible Laser Bow

Abstract: Laser bow systems are used for intervention guidance by steering laser rays. Such systems have shown applications in biopsy, nasal surgeries, drainage, pain therapy. In this paper, we introduce an image-based laser guided CT intervention. Instead of relying on traditional laser bow rigidly mounted to the CT scanner, our approach performs registration making use of a patient tracker in image as well as CT data to find the orientation of laser bow with respect to the CT data. The image is acquired by a camera rigidly connected to the laser bow. The proposed approach allows movability to the laser bow system without compromising on accuracy. Using camera allows real-time view of the intervention and can be used for futuristic applications.

Keywords: Laser-guided, CT intervention, Flexible laser bow, Image-guided, Biopsy.

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1 Introduction

Guided interventions have proven to be useful in biopsy, nasal surgeries, drainage, tumour, and pain therapy. To allow such interventions, planning is performed on pre-surgically acquired CT or x-ray data. The state-of-the art laser guided systems like Atlas 3D-LNS allows the surgeon to perform planning on CT data and guide the surgical intervention by a laser beam. Based on the planned position of intervention and medication application the laser orientation and CT table translation (on which the patient lies) is computed. Existing systems allow laser illumination in the laser bow system plane only, so the CT table translation is required to compensate for

the lack of out of plane motion of the laser beam. Existing laser-guided systems require the laser bow to be fixed with respect to the CT, possibly only by firmly mounting it to ceiling in the CT room. The fixed laser bow makes sure that the CT plane is always parallel to the laser plane, an installation overhead required to allow planning without rotational difference.

To allow more control of the intervention, pre-surgical data should be manipulatable especially in 3D. Such ease of handling of pre-surgical data can be obtained by performing registration with a known or controllable coordinate system. This requires a registration element which can be identified in CT data and is visible and, therefore, accessible in an alternate coordinate system. Often the alternate coordinate system is a camera, which can see the registration element and identify it using some unique key points. Previously, camera images have been used to register ENT CT data for surgical intervention [1], [2]. In their work the facial skin surface served as a natural registration element.

Figure 1: Example patient tracker used for CT to camera registration having an XOX structure and an approximate size of 10x10 cm.

In this work, we propose a flexible laser bow system, housing a color+depth (RGB-D) camera. The camera gives additional degree of freedom to the laser bow system. This is made possible by placing a patient tracker (Fig. 1) as a registration element on the region of intervention. After acquiring the pre-surgical CT data, the patient is then imaged by the RGB-D camera. The patient tracker which has high CT number can be easily detected in the CT DICOM data, as well its unique line and ellipse features help it to be identified in the camera image. The patient tracker detected in the two coordinate systems allows computing CT to camera coordinate

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system transformation. The camera which is firmly mounted to the movable laser bow system, can be calibrated to obtain camera to bow coordinate system transform. The two transforms can be combined to obtain the CT to laser bow system transform. This transformation is applied to the CT data before planning the intervention. The planning which was previously possible only in the CT plane (to which the laser bow plane needed to be parallel) can now be performed in the laser bow plane.

2 Setup

The proposed approach requires the additional setup of RGB-D camera to be firmly mounted to the laser bow, near the laser source (Fig. 2). The camera should be mounted to allow the patient tracker to be visible in the central region of the camera image.

Figure 2: The laser-bow system movable relative to the CT device.

3 Method

The relation between the CT and the flexible bow is established by a two-stage process using the RGB-D camera like the Intel RealSense D400 series. First, the changeable orientation of the CT and the camera coordinate system is established using a registration element visible in CT as well as camera image, detailed in Section 3.1. Then, the fixed orientation of the camera with respect to the laser bow is utilized to obtain a calibration transformation detailed in Section 3.2. Concatenation of both transforms provides the complete transform from CT coordinates to laser-bow coordinates.

3.1 Patient Tracker Registration

Patient tracker acts as a link between CT data and camera image registering the two data sources with each other. Fig. 3 outlines the registration algorithm. The patient tracker is acquired in CT data and the similarly it is acquired from the camera image. The tracker features in the two systems are detected based on their properties in the two data sources. In the CT data, the tracker is detected based on its CT number which is distinctly higher than the human muscles. This allows intensity-based segmentation of patient tracker in the CT data, resulting in patient tracker points. This set of 3D points denotes patient tracker point cloud in CT coordinate system.

Figure 3: Registration of RGB-D camera and CT data using patient tracker.

In the RGB-D camera data, the patient tracker detection starts from the image. First, the rough tracker position in the camera image is identified by template search. In this region, the patient tracker pixels are identified by its distinct features, like lines and ellipse. The 2D pixels of the patient tracker can be “deprojected” (as it is called in the technical language of the RealSense cameras software library provided by Intel) to 3D points providing the depth information of the RGB-D camera.

Then the patient tracker points are extracted from the 3D point clouds in the two co-ordinate systems. These point sets can be registered with each other using iterative closest point [3] algorithm which results in an affine transformation matrix. This matrix defines transformation from the CT coordinate system to the camera coordinate system.

3.2 Laser Calibration

Figure 4: The three-coordinate system (CS) and planar plates used for calibration purpose.

Once the relation between the CT and the camera has been established using patient tracker matching, the relation between the camera and laser system needs to be established. The laser beam device moves in a controlled and well-calibrated manner in the bow system. In our work it does not require any attention but is used as given. The laser bow device is enhanced by the RGB-D camera being firmly mounted to the bow. So, the relation between the camera and the laser bow system has to be computed by a calibration. This geometric relationship between laser bow and camera holds constant, until the either of the two devices is moved relative to the other. For the calibration procedure, a set of 3D points in the operational volume of the laser bow is illuminated by the laser beam and observed by the RGB-D camera. Comparable to spatial resection of a pinhole camera, where pairs of view rays and 3D points are used to estimate the exterior orientation of the camera, pairs of laser beam directions and 3D points are used to estimate the laser bow's pose in the camera coordinate system. The illuminated 3D points are observed in 3D by the RGB-D camera.

Fig. 4 shows the setup for laser calibration, where the coordinates system axis XYZ is illustrated by colour red, green and blue (RGB) respectively. The laser beam device is moving along the laser bow allowing rotations such that the laser ray is always a straight line through the circular bow. To obtain the set of 3D laser-illuminated points, the laser beam device is steered to position and angular settings giving a ray, i.e., a straight line in the laser-bow co-ordinate system. The two planar calibration plates, as shown in Fig. 4, are catching the laser beam rays thereby generating 3D points. Those are imaged by the RGB-D camera and automatically detected. The extracted 2D pixels are deprojected to obtain the 3D point in camera coordinate system.

Figure 5: Illustration of the three laser angles (ρ : ρ , ϕ : ϕ , τ : τ).

The corresponding laser co-ordinate system data is a set of three laser angles defining a straight line: ρ defining the angular motion of the laser beam device along the bow around z-axis and origin of the laser bow co-ordinate system (Fig. 5 top), ϕ being the rotation of the laser beam against the direction to the origin of the laser bow co-ordinate system in the laser bow plane, and τ being the deflection of the laser beam out of the laser bow plane (Fig. 5 bottom). The set of laser angles and 3D points is used to compute the transformation. In the software implementation, we make use of the Ceres library [4] non-linear least-squares optimization to obtain the final estimate of the transform.

4 Results and Discussion

In practice, the laser bow vs. camera calibration is established once, in a preparatory procedure, and kept fixed until the camera is moved with respect to the laser bow. For treatment, the patient is prepared and equipped with the patient tracker, and the CT data is acquired. While the patient resides on the CT's table, he/she is transported into the operational volume of the laser bow. Then the tracker is imaged with the camera, and the CT data is transformed to laser bow co-ordinates.

The calibration's Ceres solver adjustment results in RMS distance errors of 0.65 ± 0.02 mm in direction of ϕ angle and 0.0010 ± 0.0002 mm in direction of τ angle.

Imagery of a patient is acquired with patient tracker. The tracker 3D point clouds in CT as well as camera data are registered to obtain CT to camera transform. This transform when combined with the laser calibration transform results in the complete CT to bow coordinate system transform. The planning is then performed on this transformed data. Accuracy investigations resulted in a distance error of the laser beam passing by the planned point of intervention of 2 ± 0.5 mm. This illustrates the validity of the newly developed system.

The camera after being used for registration sits idle on the laser bow system. For future works, this camera can be used for more interactive intervention guidance systems.

Author Statement

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