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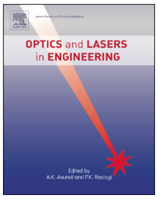

Color-encoded distance for interactive focus positioning in laser microsurgery

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ABSTRACT

This paper presents a real-time method for interactive focus positioning in laser microsurgery. Registration of stereo vision and a surgical laser is performed in order to combine surgical scene and laser workspace information. In particular, stereo image data is processed to three-dimensionally reconstruct observed tissue surface as well as to compute and to highlight its intersection with the laser focal range. Regarding the surgical live view, three augmented reality concepts are presented providing visual feedback during manual focus positioning. A user study is performed and results are discussed with respect to accuracy and task completion time. Especially when using color-encoded distance superimposed to the live view, target positioning with sub-millimeter accuracy can be achieved in a few seconds. Finally, transfer to an intraoperative scenario with endoscopic human *in vivo* and cadaver images is discussed demonstrating the applicability of the image overlay in laser microsurgery.

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1. Introduction

Surgical interventions dedicated to delicate anatomical organs often require microscopic observation while manipulating tissue with microinstruments. A noteworthy clinical application is transoral laser microsurgery for contact-less treatment of benign or malignant disorders on the vocal folds [1]. If surgical treatment is indicated, TLM is considered as standard intervention utilizing a surgical laser with a micromanipulator attached to a stereo microscope facilitating a magnified view onto the target. Resection of the lesion is achieved by manually steering the laser over a long distance and under direct line-of-sight conditions. Even though instrumentation for laser surgery has been steadily improved, the quality of surgical outcome strongly depends on the surgeon's dexterity and amount of training. Thus, recent advances in laser surgery address novel user interfaces and operating setups [2,3], endoscopic laser systems with integrated beam deflection [4–6], vision-based laser control [7,8], and online estimation of laser incision depth [9].

In addition to precise control of the laser beam direction, efficacy of the ablation process depends on accurate laser focus positioning particularly for interventions on delicate anatomical structures. An example is the resection of a vocal fold nodule as shown in Fig. 1a. Ensuring an optimal laser configuration does not only contribute to improved incision quality but also to minimized collateral thermal damage to the vocal fold ligaments that are just a few hundred micrometers below the topmost epithelium layer and thus, probably at the base of the nodule [10]. However, establishing consistent distance between laser focus and tissue surface is challenging. Stereo vision can address this limitation by introducing depth perception to the intraoperative scenario. Associated stereopsis derived from the visual information of the two eyes provides spatial comprehension of the surgical scene. Unfortunately, one cannot accurately estimate absolute distances solely from visual inspection neither in the mono nor in the stereo view. Further advanced methods for computation of depth information as well as appropriate visualization techniques are required.

Once three-dimensional information of the image data is available, proper visualization can be addressed by color-encoded distance. A promising approach is superimposing color-gradients, denoted as chromadepth, to the live view. The refraction of visible light, *i.e.*, hues ranging from red (780 nm, close scene objects) via orange, yellow, green to blue (450 nm, farther objects in the scene), leads to different focuses within the human eye and thus facilitates depth perception without the need of eyeglasses [11]. Less distraction from shading is achieved by pseudo-chromadepth reducing the gradient to only the two hues red and blue. An example application is discussed for angiography and identification of stenosis as well as aneurisms in cerebral vessel structures. Spatial relationship of the blood vessels is visualized by applying

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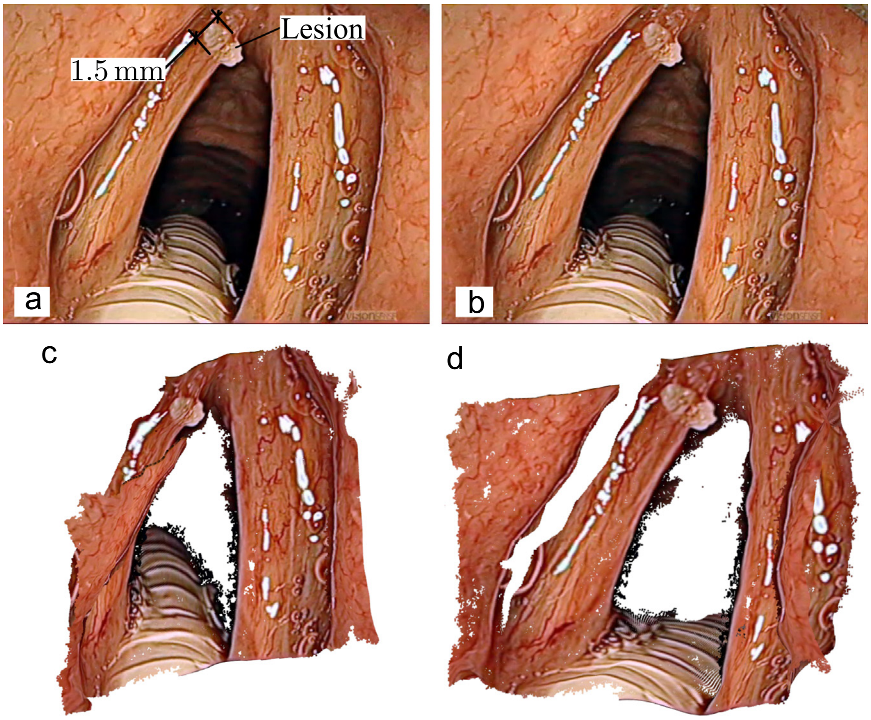

Fig. 1. Left (a) and right (b) endoscopic view of vocal folds comprising a lesion on the left vibratory edge. Reconstructed surface is shown from two different perspectives (c, d).

pseudo-chromadepth to the normalized distance [12]. A similar technique uses a virtual mirror that can be moved in the three-dimensional image data set. The two-dimensional projection of voxels representing the vessel structure is mapped onto color for improved perception of vasculature ordering [13].

In the context of neurosurgical interventions, perceptibility of potential nerve-vessel contacts can be improved indicating neurovascular compression syndromes. To achieve this, related distances are computed and color-encoded with a gradient ranging from red (near) to yellow (far) whereas potential contacts are rendered in dark gray [14]. In combination with optical tracking, chromadepth visualization can successfully be applied for intraoperative guidance in neurovascular surgery [15].

In the field of laparoscopic surgery, registration of stereo and ultrasound images facilitates to display the distance to risk structures located in the liver within the live endoscopic view [16]. A similar approach combining stereo-endoscopic surface reconstruction with preoperative tumor segmentation is discussed for resection planning in partial nephrectomy. In detail, a probabilistic augmented reality framework is deployed to draw the surgeons' attention to uncertainties in the tumor localization [17].

Aforementioned visualization techniques have in common that the color-coding context is assumed to be static since user interaction does not affect the distance relation of considered anatomical structures and modalities. In contrast to that, treatment planning characterized by manual positioning tasks can benefit from visual feedback on success or failure of the user interaction. A recent study related to treatment planning in total hip joint replacement surgery successfully demonstrates visual guidance for implant positioning. Superior performance is achieved when deploying visual cues such as chromadepth color-coding, colored axial slices or oriented elastic glyphs [18]. Application of complex rendering like the elastic glyph concept to endoscopic surgery should be treated with caution. On the one hand, superimposing distance information should not obstruct the surgical view unnecessarily in order not to impede intraoperative planning, tissue handling and depth perception. On the other hand, image noise and depth computation inaccuracies might have a stronger impact on such a rendering. Compared to well established chromadepth, this could result in visual discomfort.

Regarding laser microsurgery, we recently proposed methods for focused laser ablation and visual augmentation based on surface information and laser-to-camera registration [19]. This contribution further advances this approach by addressing manual focus positioning of a laser that has a limited focal range and workspace. Based on laser-to-camera registration, computed tissue surface is virtually intersected with the laser workspace in order to provide visual feedback during focus positioning. Three visualization concepts are presented that were preliminarily evaluated for two subjects [20]. In this contribution, the performance is measured and discussed for an extended user study with ten subjects. Regarding quantitative assessment, methods described in this paper are investigated on a custom surgical laser system with an attached stereo camera. Qualitative results are obtained from laryngeal *in vivo* and cadaver sequences. Latter have been acquired with the laser endoscope for phonomicrosurgery [5,6,8].

2. Materials and methods

In the following, we describe the experimental setup for interactive focus positioning. Subsequently, required work flow steps consisting of stereo-based surface estimation, laser-to-camera registration and real-time image overlay in the live view are presented (see Fig. 2a). Finally, the study design for user performance assessment is detailed.

2.1. Experimental setup

As shown in Fig. 2b, the setup comprises an Er:YAG laser (module DPM-15, Pantec Engineering AG, Ruggell, Liechtenstein), a galvanometer-based three-axis scanning unit (VarioScan and

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