PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

Comparison of tablet-based strategies for incision planning in laser microsurgery

Andreas Schoob, Stefan Lekon, Dennis Kundrat, Lüder A. Kahrs, Leonardo S. Mattos, et al.

Andreas Schoob, Stefan Lekon, Dennis Kundrat, Lüder A. Kahrs, Leonardo S. Mattos, Tobias Ortmaier, "Comparison of tablet-based strategies for incision planning in laser microsurgery," Proc. SPIE 9415, Medical Imaging 2015: Image-Guided Procedures, Robotic Interventions, and Modeling, 94150J (18 March 2015); doi: 10.1117/12.2081032

SPIE.

Event: SPIE Medical Imaging, 2015, Orlando, Florida, United States

Comparison of tablet-based strategies for incision planning in laser microsurgery

Andreas Schoob[a], Stefan Lekon[a], Dennis Kundrat[a], Lüder A. Kahrs[a], Leonardo S. Mattos[b], Tobias Ortmaier[a]

[a]Leibniz Universität Hannover, Institute of Mechatronic Systems, Hanover, Germany
[b]Istituto Italiano di Tecnologia, Department of Advanced Robotics, Genoa, Italy

ABSTRACT

Recent research has revealed that incision planning in laser surgery deploying stylus and tablet outperforms state-of-the-art micro-manipulator-based laser control. Providing more detailed quantitation regarding that approach, a comparative study of six tablet-based strategies for laser path planning is presented. Reference strategy is defined by monoscopic visualization and continuous path drawing on a graphics tablet. Further concepts deploying stereoscopic or a synthesized laser view, point-based path definition, real-time teleoperation or a pen display are compared with the reference scenario. Volunteers were asked to redraw and ablate stamped lines on a sample. Performance is assessed by measuring planning accuracy, completion time and ease of use. Results demonstrate that significant differences exist between proposed concepts. The reference strategy provides more accurate incision planning than the stereo or laser view scenario. Real-time teleoperation performs best with respect to completion time without indicating any significant deviation in accuracy and usability. Point-based planning as well as the pen display provide most accurate planning and increased ease of use compared to the reference strategy. As a result, combining the pen display approach with point-based planning has potential to become a powerful strategy because of benefiting from improved hand-eye-coordination on the one hand and from a simple but accurate technique for path definition on the other hand. These findings as well as the overall usability scale indicating high acceptance and consistence of proposed strategies motivate further advanced tablet-based planning in laser microsurgery.

Keywords: laser surgery, surgeon interface, performance assessment, usability

1. DESCRIPTION OF PURPOSE

Medical lasers have been introduced to advance surgical techniques dedicated to the field of microsurgery. One remarkable application is laser phonomicrosurgery for contact-less treatment of disorders on the vocal folds (e.g. tumors). The operation is performed with a micro-manipulator attached to the surgical microscope in order to remove the lesion by manually steering the laser under direct line-of-sight conditions. Defining proper incision paths requires training and high dexterity. Thus, current and prospective systems for laser surgery demand for more sophisticated intra-operative planning concepts. An early development of an intuitive interface is dedicated to laser-assisted laparoscopic surgery.[1] Laser control is simplified by employing familiar hand writing skills facilitating accurate tissue ablation. Such a tablet-based approach has also been considered in endoscopic laser surgery of the larynx.[2] More recently, a computer-assisted virtual scalpel was developed using a motorized micro-manipulator operated with a pen display for planning in the live view.[3] The latter approach demonstrates that tablet-based interfaces are superior in precision, control and ergonomics compared to state-of-the-art micro-manipulator solutions.

However, aforementioned studies are mainly based on image processing on monoscopic camera data. Thus, we recently proposed methods for incorporating tissue surface information into intra-operative incision planning.[4] Based on registration of laser to camera and stereo image processing, highly accurate incisions are achieved by automatic laser positioning and focus adjustment. In other words, laser is activated only if tissue surface is located inside the focal range of the laser. Furthermore, introduced depth information facilitates real-time

Address all correspondence to: Andreas Schoob, E-mail: andreas.schoob@imes.uni-hannover.de, Telephone: +49 (0)511 762 17846

Medical Imaging 2015: Image-Guided Procedures, Robotic Interventions, and Modeling, edited by Ziv R. Yaniv, Robert J. Webster III, Proc. of SPIE Vol. 9415, 94150J
 · doi: 10.1117/12.2081032

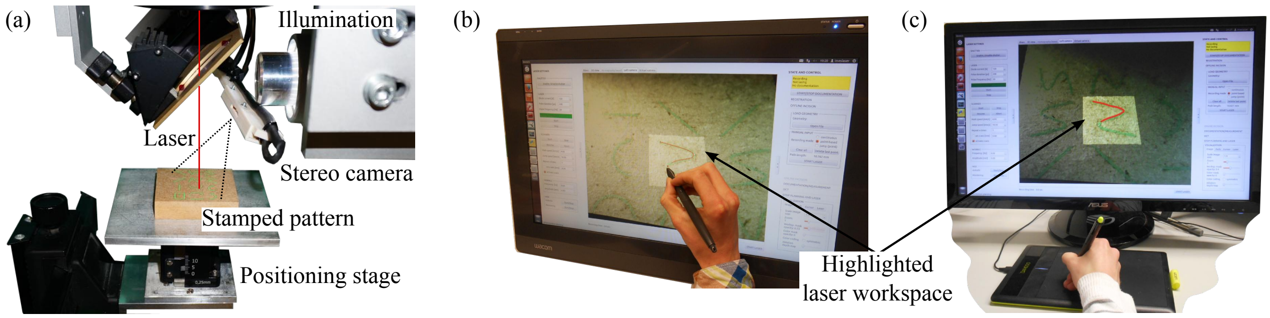

Figure 1. The surgical laser setup with stereo camera and stamped pattern in (a) is operated either with (b) a pen display or (c) a graphics tablet and a (2D/3D) monitor.

augmented reality in a mono, a stereo or even a virtual view from laser's perspective. For instance, aforementioned focus range is highlighted to the live view computed from the intersection of tissue surface and laser scanning workspace.

In this contribution, we present a comparative study of six tablet-based concepts for visualization and incision planning in laser microsurgery. User trials on path tracing of curves stamped to tissue substitutes are discussed with respect to accuracy, completion time and ease of use. In this context, laser ablations are performed with a surgical laser while observing the scene with registered stereo camera. For both, path planning and adjunct visualization different devices are analyzed.

2. METHODS

The setup is shown in Fig. 1a and comprises an Er:YAG laser (DPM-15, Pantec Engineering AG, Liechtenstein), a galvanometer based three-axis scanning unit with a resolution of 2 µm (VarioScan and HurryScan, SCANLAB AG, Germany) and focusing optics.[5] The laser spot can be positioned in a three-dimensional, cubic workspace of 10 mm in each direction. Stereo images are acquired with two miniature camera modules having an image definition of 640×480 pixels and a baseline of 5 mm. Planar pattern-based calibration is applied to estimate camera intrinsic and extrinsic parameters while assuming the pinhole model with radial and tangential distortion.[6] Laser and stereo camera are arranged non-coaxially while illumination with a cold light source is aligned to laser's optical axis. Scene is visualized either monoscopic, stereoscopic or as synthesized laser view.[4] For stereoscopic visualization and thus, depth perception of observed scene, a 3D monitor (VG278, ASUS, Taiwan) and active shutter glasses (3D Vision 2, NVIDIA, Santa Clara, CA, USA) are used. As illustrated in Fig. 1b and 1c, our framework enables incision planning with a writing interface on a pen display or a graphics tablet (Bamboo CTH-470 and DTU-2231, Wacom Co., Ltd., Japan). Laser interface, image acquisition and processing are implemented in a framework based on the open source Robot Operating System (ROS) as high-level control layer.[7]

In order to compute scene depth, a parallelized, census transform-based similarity measure is implemented.[8] Applying known camera calibration, images are rectified simplifying correspondence search of pixel positions in the left and right image. Triangulation of those points to object space provides an estimate of observed surface with respect to the camera coordinate frame. Depth computation facilitates laser-to-camera registration and thus, synthesis of a virtual view from laser's perspective and focusing of arbitrary laser trajectories onto tissue surface that is located inside the cubic workspace.[4] As depicted in Fig. 1b and 1c, the intersection of surface and laser workspace is also highlighted in the live image providing visual feedback if tissue is properly positioned close to laser focus. Any incision that is planned image-based is mapped to its corresponding three-dimensional trajectory. Then, path following of the laser spot is achieved with integrated scanning unit for lateral beam deflection and axial focus adjustment.

In this study, user trials on incision planning with described setup are discussed. For each proposed strategy, ablations are performed on tissue substitutes, i.e., medium density fiberboards, with 13 stamped, green colored straight lines and curves (see Fig. 2a). Reference strategy is defined by path planning in the mono camera view. In this case, incisions are planned by continuously drawing a curve on the graphics tablet while moving cursor on the screen maps the user input to the live image. Obtained path is characterized by a vector of M points (see Fig. 2b). Deploying same interface, we acquire further results from using the stereoscopic visualization and synthesized laser view. In contrast to continuous drawing, we propose a method with point-based planning by concatenating straight line segments to quasi curved shapes. Subsequent to defining a point P_k, potential partial path is spanned to and moving with current cursor position as shown in Fig. 2c. Next point P_{k+1} is set by the user as connecting line between P_k and P_{k+1} that fits best to desired trajectory, i.e., to underlying stamped curve. Compared to continuously planning, required user inputs via the tablet are significantly reduced ($N \ll M$).

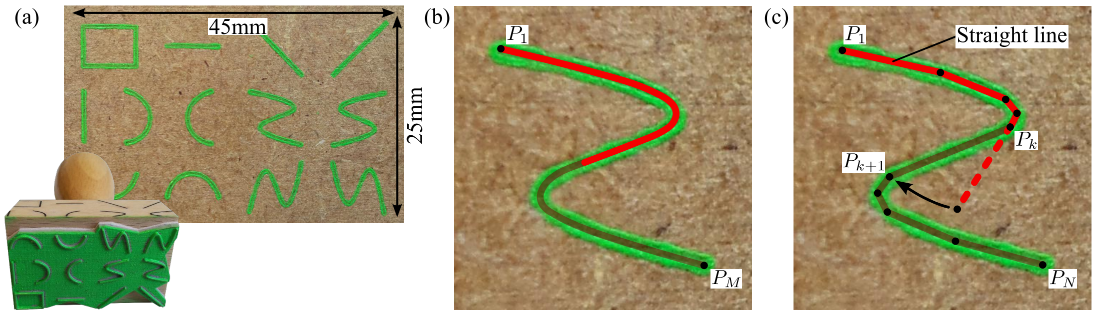

Figure 2. Stamp and corresponding green lines for path tracing experiments are shown in (a). Incision planning can either be performed by (b) continuous or (c) point-based path drawing with stylus and tablet. In the latter case, planned incision is concatenated by straight line segments of user-defined length.

Investigating the impact of hand-eye-coordination, another strategy deploys aforementioned pen display and continuous path drawing in the mono view. Compared to separating input device and display, the tablet and visualized pattern are within the same field of view. Thus, the user can keep an eye on both, planned incision line and moving tip of the stylus. Hence, more accurate planning is expected. In contrast to aforementioned strategies, a further concept consists of simultaneous path drawing and ablation using the mono view and the graphics tablet. Regarding this kind of real-time teleoperation, improper movement of the stylus instantaneously leads to irreversible and inaccurate laser ablation. As additional option, planned incisions can be corrected by using the eraser of the stylus before activating the laser (except for real-time teleoperation).

Aforementioned six tablet-based strategies for laser incision planning and visualization are summarized and assigned with abbreviations for further reference:

- Continuous path planning on graphics tablet using mono (MV), virtual laser[4] (LV) or stereo view (SV) with subsequent laser ablation
- Point-based path planning on graphics tablet using mono view (PB) with subsequent laser ablation
- Continuous path planning on graphics tablet using mono view with real-time laser ablation (RT)
- Continuous path planning on pen display (PD) with subsequent laser ablation

In this study, six non-expert subjects with a background in medical engineering were asked to plan laser ablations with proposed interface. Aforementioned strategies were performed randomly counterbalancing learning effects. In order to provide equal conditions to left and right-handed participants, stamped curves were mirrored, rotated and duplicated (see Fig. 2a). Freehand path tracing of stamped lines was performed from any direction. Subsequently, planning was analyzed with respect to the root mean square error (RMSE) and maximum distance error (MDE) between desired and executed laser trajectory. In this context, image-based path detection is achieved by color thresholding and subsequent thinning of both the stamped and ablated patterns.[9] Additionally, completion time required for drawing and ablation is measured. Adequate laser power is set to achieve clearly visible cuttings (diode current: 120 A, pulse duration: 220 µs, pulse frequency: 50 Hz). Stereo camera is positioned at a distance of 37 mm with respect to sample surface.

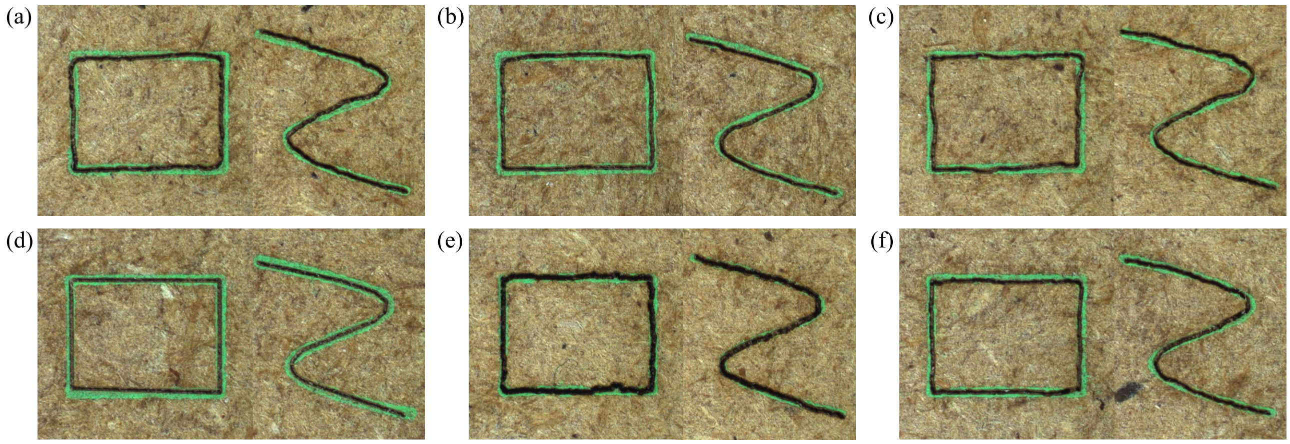

Figure 3. Exemplary laser incisions (black lines) tracing stamped curves (green lines) when deploying strategy (a) MV (mono view, tablet), (b) LV (laser view, tablet), (c) SV (stereo view, tablet), (d) PB (point-based, tablet), (e) RT (real-time, tablet), and (f) PD (pen display). Shown microscopic photographs were acquired subsequently to the trials of the same user.

Usability is assessed by carrying out the After Scenario Questionnaire (ASQ) subsequently to each performed strategy and finally conducting the System Usability Scale Questionnaire (SUS) rating the overall tablet-based planning framework. The ASQ consists of hypotheses for assessing user satisfaction, i.e., the ease of use and the amount of time to complete the task in a scenario.[10] Scoring is defined by seven-point Likert scale (1 - strongly disagree, 7 - strongly agree). In other words, high rating correlates with increased user satisfaction of considered criterion. Furthermore, the user can add comments. Applying the SUS, which is based on five-point Likert scale (1 - strongly disagree, 5 - strongly agree), gives a maximum score of 100.[11] A score of 70 defines average rating whereas a score of below 50 indicates unacceptable system usability.

3. RESULTS

Laser-to-camera registration was performed once before all trials and quantified by a median ablation error of below 75 µm.[4] Subsequently, asked subjects performed laser incisions with provided interfaces. Exemplary cuttings obtained from the same user are illustrated in Fig. 3. Even though trials on path tracing were applied to all curves on stamped pattern, in some cases subsequent image-based ablation detection failed. Thus, those data sets had to be excluded from conducted 468 incisions (78 per strategy). For instance, experiments with the pen display (PD) resulted in a reduced number of 72 measurements (see Table 1). Regarding quantitative analysis, Kolmogorov-Smirnov test reveals that some of the data sets do not meet the assumption of normality. However, sample sizes and variances are similar and thus, we apply non-parametric Wilcoxon rank-sum test (significance level $p = 0.05$) to compare the outcomes of reference strategy MV with the other concepts. In this context, Fig. 4 illustrates obtained ablation errors and completion times in the form of box plots.[12] So-called interquartile range (IQR) comprises data points between the 25th and the 75th percentile and is defined by the bottom and top of the box, respectively, while the error median is represented by the notch. The upper whisker includes data within 1.5 times the IQR of the upper quartile, whereas the lower whisker contains data within

Table 1. Path tracing results with medians of the root mean square error (RMSE), maximum distance error (MDE) and completion time. Significance of comparison with MV is given in brackets (p-value).

	MV	LV	SV	PB	RT	PD
Detected ablations	78	74	75	77	75	72
RMSE [mm]	0.110	0.124 (0.03)	0.120 (0.02)	0.084 (1e-6)	0.099 (0.12)	0.089 (5e-4)
MDE [mm]	0.288	0.305 (0.31)	0.297 (0.08)	0.216 (3e-6)	0.260 (0.45)	0.222 (2e-4)
Completion time [s]	26.0	28.7 (0.48)	29.0 (0.13)	27.6 (0.28)	17.8 (7e-6)	23.1 (0.17)

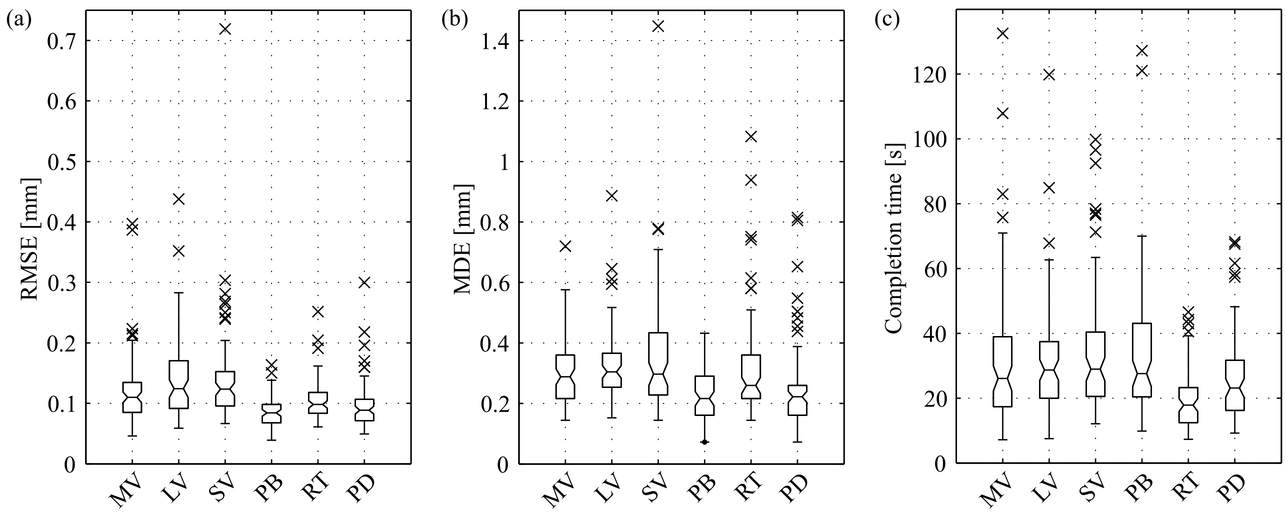

Figure 4. Box plots of path tracing results with the (a) RMSE, (b) MDE, (c) completion time per pattern. Significance (p-value) of comparison with MV is given in Table 1.

1.5 times the IQR of the lower quartile. Values are marked as outliers by a cross ($\times$) if not included between the whiskers.

As listed in Table 1, experimental results of reference strategy MV are quantified with RMSE, MDE and completion time medians of 0.11 mm, 0.288 mm and 26 s, respectively. Deploying the laser (LV) or stereoscopic view (SV) is less accurate (RMSE of 0.124 mm and 0.120 mm, respectively, $p \leq 0.03$) whereas path tracing with point-based planning (PB) or the pen display (PD) significantly increases ablation accuracy by approx. 25 %. Corresponding RMSE medians are measured with 0.084 mm (p = 1e-6) and 0.089 mm (p = 5e-4), respectively. This observation is underlined by significantly decreased MDE medians ($p \leq$ 2e-4). Regarding real-time teleoperation (RT), observed increase in ablation accuracy does not reach statistical significance compared to MV ($p > 0.05$). But in contrast to the other strategies, completion time is reduced drastically (17.8 s, p = 7e-6) since planning and laser cutting are performed simultaneously.

Quantitative results are emphasized by conducted After Scenario Questionnaire (ASQ). In especially for strategy PB, a score of 6.67 out of seven indicates a superior ease of use compared to MV while suggesting a reduced task completion time (see Fig. 5). Similar user feedback (scoring > 6) is provided for PD demonstrating improved hand-eye-coordination compared to MV. However, a few subjects claimed that in some situations the target visualized on the pen display was occluded by their writing hand. Thus, tracing the remaining path

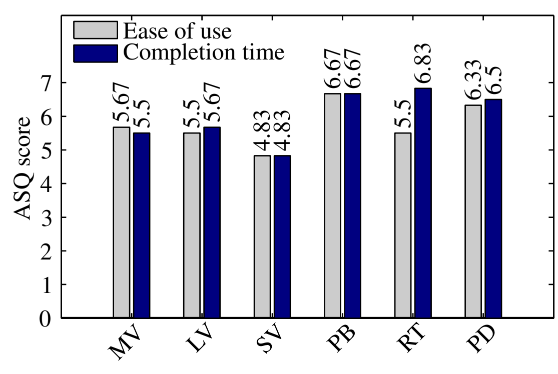

Figure 5. Results of After Scenario Questionnaire (ASQ) describing overall satisfaction regarding criteria ease of use and completion time. High scoring correlates with increased user satisfaction if considered criterion.

became more difficult. As already observed in prior quantitative measurements, real-time planning (RT) is well accepted by involved users due to the short amount of time that is required for planning and laser cutting (scoring of 6.83). Regarding scenario SV, reduced ease of use and thus, lower acceptance is revealed for our current implementation with active shutter glasses. Here, a score of only 4.83 coincides with observed decrease in ablation accuracy. Moreover, visualization LV was rated as good as strategy MV in terms of completion time and ease of use, even in the presence of slight jittering of the scene due to image noise that affects synthesizing the live laser view.

Regarding overall usability assessed with the SUS, proposed tablet-based planning framework was rated with an average score of 86.25 demonstrating high acceptance and consistence among involved subjects.

4. DISCUSSION AND CONCLUSION

In this contribution, a comparative study on six tablet-based strategies for incision planning in teleoperated laser microsurgery is presented. Results clearly demonstrates that, even when making use of a tablet and familiar hand writing, significant differences exist between proposed strategies. Although all strategies provide sub-millimeter accuracy, highly accurate planning is achieved with concepts PD and PB (lowest RMSE and MDE) while no significant difference is indicated in completion time. Regarding stereoscopic view, we found that most of the participants were not familiar with this visualization technique or noticed visual discomfort when observing the scene with active shutter glasses. Proper distance to the screen or the required amount of vergence-accommodation has to be taken into account more individually. An alternative solution is provided by deploying head-mounted 3D displays.[13]

Furthermore, one has to fully exploit human hand writing skills considering strategies beyond continuous path drawing with the stylus. This is achieved with point-based planning (PB) that outperforms reference strategy MV with respect to accuracy and ease of use. This is potentially due to the fact that path definition with the stylus is simplified by concatenating straight line segments. This approximation approach reduces the number of required user inputs and thus, the cognitive load. In this context, future work will focus on optimizing proposed planning framework and conducting experiments with an increased number of subjects targeting further validation of observed outcomes.

To conclude this study, prospective interfaces for laser surgery require an optimal setting of visualization and interactive planning mode in order to achieve high performance. For instance, we believe combining the pen display approach (PD) with point-based planning (PB) has potential to become a powerful planning strategy because of benefiting from improved hand-eye-coordination and from a simple but accurate technique for path definition. As a result, PD would not suffer from covering the display with the writing hand since the stylus can be released during planning of longer path segments. These findings, including the high usability scale, motivate further advanced tablet-based planning in laser microsurgery.

ACKNOWLEDGMENTS

The research leading to presented results has received funding from the European Union Seventh Framework Programme FP7/2007-2013 Challenge 2 Cognitive Systems, Interaction, Robotics under grant agreement μRALP - n^o 288663.

REFERENCES

[1] Tang, H.-W., Brussel, H. V., Sloten, J. V., Reynaerts, D., De Win, G., Cleynenbreugel, B. V., and Koninckx, P. R., "Evaluation of an intuitive writing interface in robot-aided laser laparoscopic surgery," *Comput. Aided Surg.* **11**(1), 21–30 (2006).

[2] Patel, S., Rajadhyaksha, M., Kirov, S., Li, Y., and Toledo-Crow, R., "Endoscopic laser scalpel for head and neck cancer surgery," *Proc. SPIE 8207, Photonic Therapeutics and Diagnostics VIII* , 82071S (2012).

[3] Mattos, L. S., Deshpande, N., Barresi, G., Guastini, L., and Peretti, G., "A novel computerized surgeon-machine interface for robot-assisted laser phonomicrosurgery," *Laryngoscope* **124**(8), 1887–1894 (2014).

[4] Schoob, A., Kundrat, D., Kleingrothe, L., Kahrs, L., Andreff, N., and Ortmaier, T., "Tissue surface information for intraoperative incision planning and focus adjustment in laser surgery," *Int J Comput Assist Radiol Surg* **10**(2), 171–181 (2015).

[5] Fuchs, A., Schultz, M., Krüger, A., Kundrat, D., Diaz Diaz, J., and Ortmaier, T., "Online measurement and evaluation of the Er:YAG laser ablation process using an integrated OCT system," *Proc. Annual Conference of the German Society for Biomedical Engineering (BMT)* , 434–437 (January 2012).

[6] Zhang, Z., "A flexible new technique for camera calibration," *IEEE Trans. Pattern Anal. Machine Intell.* **22**(11), 1330 – 1334 (2000).

[7] Quigley, M., Gerkey, B., Conley, K., Faust, J., Foote, T., Leibs, J., Berger, E., Wheeler, R., and Ng, A., "ROS: an open-source robot operating system," *IEEE International Conference on Robotics and Automation (ICRA) - Workshop on Open Source Robotics* (May 2009).

[8] Schoob, A., Podszus, F., Kundrat, D., Kahrs, L., and Ortmaier, T., "Stereoscopic surface reconstruction in minimally invasive surgery using efficient non-parametric image transforms," *Proc. 3rd Joint Workshop on New Technologies for Computer/Robot Assisted Surgery (CRAS)* , 26–29 (2013).

[9] Zhang, T. Y. and Suen, C. Y., "A fast parallel algorithm for thinning digital patterns," *Commun ACM* **27**(3), 236–239 (1984).

[10] Lewis, J. R., "Psychometric evaluation of an after-scenario questionnaire for computer usability studies: the ASQ," *SIGCHI Bull.* **23**(1), 78–81 (1991).

[11] Brooke, J., "SUS - a quick and dirty usability scale," *Usability Evaluation in Industry* **189**, 194 (1996).

[12] McGill, R., Tukey, J. W., and Larsen, W. A., "Variations of box plots," *Am Stat* **32**(1), 12–16 (1978).

[13] Deshpande, N., Ortiz, J., Caldwell, D., and Mattos, L., "Enhanced computer-assisted laser microsurgeries with a virtual microscope based surgical system," *IEEE International Conference on Robotics and Automation (ICRA)* , 4194–4199 (2014).