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Safe Teleoperation based on Flexible Intraoperative Planning for Robot-Assisted Laser Microsurgery

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Abstract— **This paper describes a new intraoperative planning system created to improve precision and safety in teleoperated laser microsurgeries. It addresses major safety issues related to real-time control of a surgical laser during teleoperated procedures, which are related to the reliability and robustness of the telecommunication channels. Here, a safe solution is presented, consisting in a new planning system architecture that maintains the flexibility and benefits of real-time teleoperation and keeps the surgeon in control of all surgical actions. The developed system is based on our virtual scalpel system for robot-assisted laser microsurgery, and allows the intuitive use of stylus to create surgical plans directly over live video of the surgical field. In this case, surgical plans are defined as graphic objects overlaid on the live video, which can be easily modified or replaced as needed, and which are transmitted to the main surgical system controller for subsequent safe execution. In the process of improving safety, this new planning system also resulted in improved laser aiming precision and improved capability for higher quality laser procedures, both due to the new surgical plan execution module, which allows very fast and precise laser aiming control. Experimental results presented herein show that, in addition to the safety improvements, the new planning system resulted in a 48% improvement in laser aiming precision when compared to the previous virtual scalpel system.**

I. INTRODUCTION

ROBOT assistance is increasingly growing in the operating room and, at the same time, the application areas of surgical robots have been quickly expanding [1]. Robots are now helping surgeons not only achieve unprecedented levels of performance on various fields of surgery, but also pioneer new procedures [2]. This is the case of microsurgeries, i.e., surgeries involving very small and delicate tissues or organs that require the aid of a microscope.

Robot-assisted microsurgery is rapidly growing and being adopted in specialties such as plastic surgery, otolaryngology, urology, gynecological surgery, ophthalmology, and others. In these cases, lasers are often part of the surgical tool sets. Lasers afford high precision and can be used to perform delicate ablation and cutting procedures [3]. An example is the use of CO_2 lasers in phonomicrosurgery [4], which involves a suite of complex otolaryngological surgical techniques for the treatment of minute abnormalities in the larynx. Accurate laser aiming is extremely important in this case since preserving healthy tissue while completely removing the pathology is a major goal to minimize surgical impact on voice quality [5].

However, robot-assistance in laser microsurgery is still in its infancy, counting with only a few commercial devices such as the commercial AcuBlade [6] and the SoftScanPlusR [7]. These devices enable improved surgical outcomes by offering motorized laser scanners featuring pre-programmed scan patterns. Yet, as the traditional manually actuated laser micromanipulators, they are installed on the surgical microscope and require direct manual control by the surgeon. As a result, laser microsurgeries still suffer from major problems related to bad ergonomics, hand-eye coordination and aiming precision; and surgical outcomes are still highly dependent on the dexterity and experience of individual surgeons.

New robot-assisted laser microsurgery systems are highly desired to address the problems above by providing improved precision, controllability, safety and ergonomics. For this reason, our recent research efforts have focused in this area and a new teleoperated laser microsurgery system has been developed [8]. This system is controlled from an intuitive and ergonomic teleoperation interface using the virtual scalpel mode, which allows surgeons to perform operations using a stylus directly over the live video of the surgical site. The system was shown to offer great improvements in terms of laser aiming precision and safety, and to allow very long distance telesurgery, e.g. over the internet [9].

On the other hand, as other teleoperated systems, the virtual scalpel microsurgical system is subject to delays or other disruptions in the communication channel between the surgeon interface and the local system controller responsible for driving the laser beam. This is especially serious in the case of long-distance telesurgery with the surgeon controlling in real-time both the laser aiming and its activation. In this case, communication problems may cause errors and undesired actions, posing a serious safety issue [10].

A solution to this problem is the creation of an intraoperative surgical planning system as proposed in this paper. Here, a new real-time planning system for robot-assisted laser microsurgery is described and evaluated. This new system maintains the flexibility and benefits of real-time teleoperation, and keeps all surgical actions under full surgeon control. Moreover, by enabling fast and precise automatic laser scanning control, it improves the quality of operations [11] and eliminates performance limitations due to the duality between speed and precision in manual operations [12]. As presented herein, in addition to the safety improvements, the new planning system also enabled a large increase in laser aiming precision when compared to the

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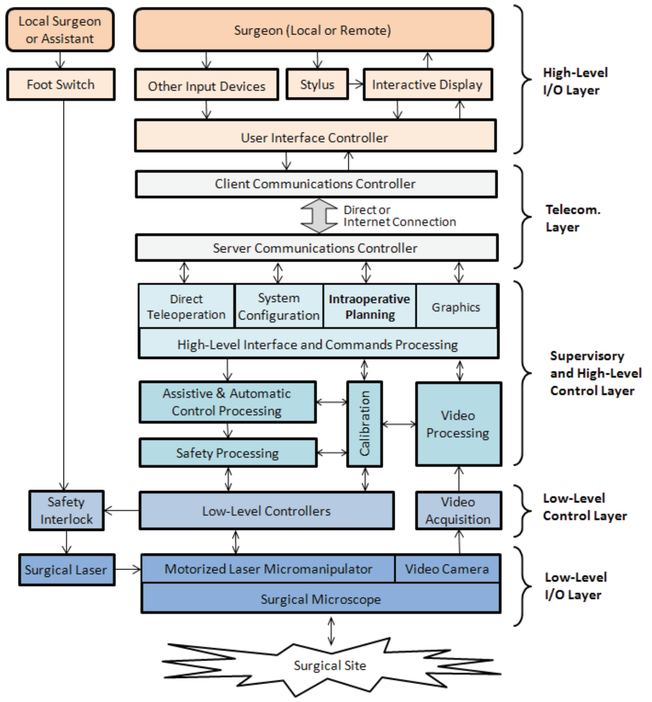


Fig. 1. The robot-assisted laser microsurgery system architecture.

virtual scalpel results, indicating it is a successful addition to our laser microsurgery system.

II. SYSTEM ARCHITECTURE

The new intraoperative surgical planning system is based on the robot-assisted laser microsurgery system developed at the IIT [8]. This system allows precise surgical laser aiming and activation from an intuitive teleoperation interface using the virtual scalpel concept. In this case, control is performed using a stylus directly over the live video of the surgical field displayed on a tablet or even on a remote smart device (over the internet). A brief summary of this system's architecture is described below.

A. *Hardware architecture*

The microsurgical system's hardware architecture includes the following devices: the IIT's custom laser micromanipulator; a surgical microscope with built-in video camera (Leica M651); a CO_2 surgical laser system (Zeiss Opmilas 25); and one tablet PC (Dell Latitude XT2). At this time, all high-level control and processing functions are managed by the tablet PC, which offers connectivity to a range of user input devices and also internet sockets that allow long-distance tele-cooperation.

The IIT laser micromanipulator used in this research is based on a single tip/tilt fast steering mirror and offers, at a typical 400mm operating range, a 40x40 mm surgical range, 4 µm resolution, 4 µm repeatability, and maximum speed in the order of 10 m/s [13]. This device is fitted to the surgical microscope and connected to the laser system to precisely control the surgical laser beam displacements on the surgical area.

For safety reasons, the high-power CO_2 laser beam is enabled by a local footswitch, i.e., physically located near the

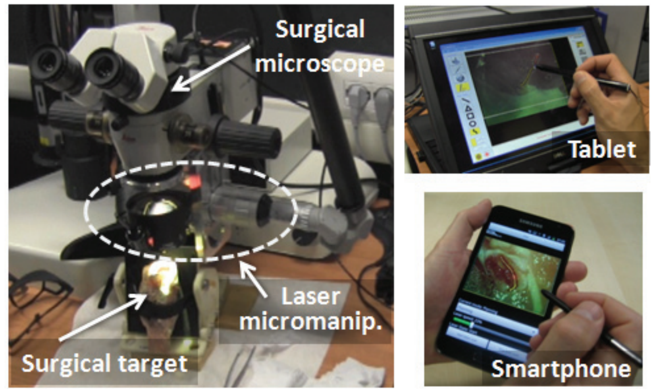


Fig. 2. The experimental setup and two teleoperation interfaces: A tablet computer and a smart device. Both of these interfaces handle the virtual scalpel function and the intraoperative planning mode for safe telesurgery.

laser source. In addition, the laser system features a low-power HeNe visible laser that is coincident to the CO_2 laser beam and is always turned on. This laser is used for aiming, and is thus called aiming laser.

B. *Control architecture*

As illustrated in Fig. 1, within the microsurgical system's control architecture the surgeon generates high-level commands to: (a) guide the laser beam aiming; (b) control the CO_2 laser activation; (c) define virtual operating regions for the laser; and (d) define custom laser scan patterns for automatic execution. All of these commands are processed at the control computer, where they go through safety analysis and are subsequently converted to low-level commands. These, in turn, are forwarded to low-level controllers, which precisely drive the laser micromanipulator and control the surgical laser activation.

This control architecture was designed for safety and thus guarantees the surgeon is always in control of the surgical laser. During virtual scalpel operation, for example, the stylus contact with the display controls both the laser aiming and its activation. This means the laser is immediately disabled when the stylus and display are no longer in contact. In other control modes, e.g. teleoperation through a joystick, a physical control button is configured to command the surgical laser activation/deactivation. However, surgeon commands can be blocked by the system as a result of the safety analysis. An example is the use of virtual operating regions to automatically turn off the laser if it enters a forbidden area.

The safety features of this control structure affect the low-level laser activation control via a safety interlock system featuring two inputs and an AND control logic. One input comes from the control computer and the other from the mentioned footswitch. This adds yet another safety check to the system, guaranteeing the laser will only be turned on if commands coming from the software are enabled locally by the footswitch.

C. *User Interfaces and Teleoperation*

The IIT's robot-assisted laser microsurgery system offers four different teleoperation modes: *virtual scalpel*; *teach*; *planning*; and *joystick/joypad* control. The first three are of interest here and are based on the use of an interactive pen

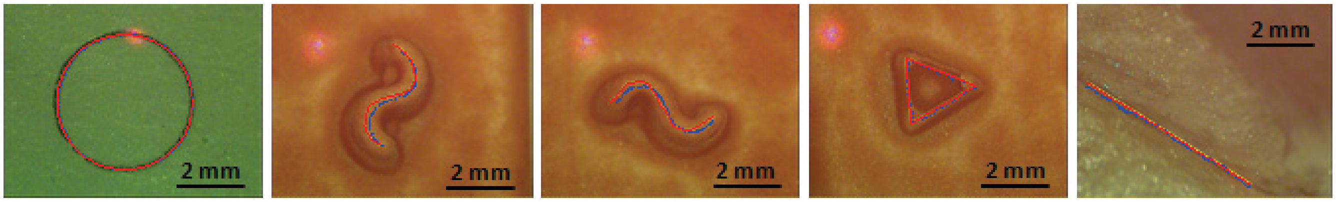


Fig. 3. Precision evaluation targets used during the experiments under 40x magnification: Intraoperative plans are drawn in red and the blue dots represent the actual laser spot coordinates determined by image processing. (a) 4mm circle printed on paper; (b) Vertical s-shaped 3D plaster structure; (c) Horizontal s-shaped structure; (d) Triangle structure; (e) Chicken thigh.

display, e.g. a tablet or a smart device (Fig. 2). In these modes, the interaction of the stylus with the live surgical field video displayed on the device generates high-level commands that are used to precisely guide the laser beam. This control requires identification of the mapping parameters for real-time coordinate transformations between the video and the target coordinate frames, which is done via system calibration as described in [13].

III. Intraoperative Planning

In virtual scalpel mode, as previously mentioned, the stylus controls simultaneously and in real-time both the laser aiming and its activation. In the intraoperative planning mode, however, laser motions and CO_2 laser activation are automatically controlled by the system, based on surgical plans defined, verified, and approved by surgeon.

In this mode, surgical plans are created directly on the live surgical video using graphics overlays, which are drawn using the stylus and assistive graphics functions. For example, the surgeon can define cutting or ablation laser scan patterns with the help of a range of graphics shapes, including: line, triangle, rectangle, ellipse, and freehand drawing. In addition, these shapes and drawings can be easily edited in real-time, allowing their precise positioning over the desired target and, consequently, precise planning of the desired surgical action.

Once the desired laser scan pattern has been defined in image space, it is forwarded to the main system controller, where it goes through safety analysis and generates the low-level control commands as described in section II.

This planning system provides the surgeon with a fast and simple way to plan surgical actions intraoperatively. It also allows inspection and safe execution of these plans with simple button clicks. After the desired scan pattern is defined, it is executed using only the low-power visible laser. This gives instantaneous visual feedback to the surgeon, who can perform a final inspection, edit the plan if necessary, and then command the plan execution.

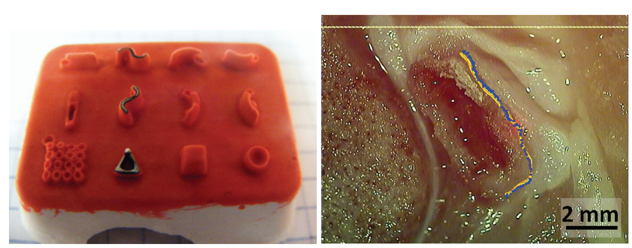
IV. Safe Plan Execution

In the developed laser microsurgery system, surgical plans can be created using any of the available teleoperation interfaces, i.e., local or remote computer, or smart device. In any case, the plan to be executed is transmitted to the main system controller located in or near the operating room. There it is automatically processed and later executed following separate surgeon commands.

A first surgeon command sets the laser scan speed and starts the plan execution in a continuous loop to create the laser scanning motion. At this point only the aiming laser is on, allowing the surgeon to visually inspect the final laser path and confirm the accuracy of the automatic controller. In addition, the surgeon can adjust the scan speed at any time using a slide bar implemented on the graphical user interface. If necessary or desired, he/she can also cancel the plan execution. In fact, when an edited or new plan arrives at the main system controller, the current plan is automatically canceled and substituted by the new one.

Finally, after approving the surgical plan, the surgeon commands the activation of the CO_2 laser to actually realize the surgical action. This is done through a pushbutton on the user interface, which sends the laser activation command to the main system controller on every communication cycle until it is depressed. On the controller side, the laser is turned on upon arrival of the activation command, and a safety timer with 100ms period is restarted every time a new laser activation command is received. The laser is then automatically turned off if no activation command is received in a communication cycle, or if the next communication package takes more than 100ms to arrive at the main controller.

Alternatively, the surgeon can command the CO_2 laser activation for a precise amount of time. In this case, the command includes a parameter describing the number of milliseconds to keep the laser on, after which it is automatically switched off. For safety reasons, activation time is currently limited to 1 second. If extended exposure time is needed, the surgeon can submit additional laser activation commands, which is done by a simple button click on the user interface.



(a) (b)

Fig. 4. (a) Plaster targets created for aiming precision experiments. The results of intraoperative plans executed using the CO_2 surgical laser are shown by the burn marks along the top edges of the three shapes used during the trials. (b) Piece of a chicken thigh used for experiments, with the yellow line showing the defined surgical plan and the blue dots marking actual laser aiming spots during the computer-controlled scan process.

TABLE I. PRECISION ASSESSMENT VIA CIRCLE TRACING TRIALS[a]

Microscope Magnification	*Target Circle Diameter*	*RMSE ± S.D.*[b]	*Maximum Absolute Error*
6x	8.5	0.103 ± 0.060	0.320
10x	8.5	0.086 ± 0.058	0.350
16x	8.5	0.053 ± 0.026	0.123
25x	4	0.037 ± 0.021	0.094
40x	4	0.025 ± 0.017	0.080
16x (virtual scalpel)	8.5	0.110 ± 0.394	n/a

a. All values are given in millimeters [mm].
b. S.D. is the standard deviation of the errors.

TABLE II. PRECISION ASSESSMENT USING 3D TARGETS[a]

Target description	*Mag.*	*RMSE ± S.D.*[b]	*Maximum Absolute Error*
Plaster; vertical S struct.	40x	0.093 ± 0.041	0.156
Plaster; horizontal S struct.	40x	0.081 ± 0.048	0.188
Plaster; triangle structure	40x	0.044 ± 0.024	0.085
Chicken; straight line path	40x	0.064 ± 0.037	0.170
Chicken; randon path	25x	0.072 ± 0.041	0.185

a. All values are given in millimeters [mm].
b. S.D. is the standard deviation of the errors.

V. INTRAOPERATIVE PLANNING EXPERIMENTS

Evaluation of the new intraoperative planning system was performed through a series of experiments designed to measure the achievable laser aiming precision in different scenarios. For comparison with the virtual scalpel control mode, which was evaluated in [8], the initial experiments consisted of circle tracing trials. In this case, two target paths were printed on a piece of white paper using a 0.12 mm line width: One circle with 8.5 mm diameter and another one with 4 mm diameter. These were used to evaluate the laser aiming precision under five different microscope magnifications, as presented in Table I.

A second set of experiments was conducted to evaluate the developed surgical planning system using 3D precision aiming targets. These consisted of small 3D plaster structures with millimeter-size features, as shown in Fig. 3 and Fig. 4. In this case, 40x microscope magnification was used and the desired target paths were defined as the top edge of three 3D structures: A triangle, a horizontal s-shaped curve, and a vertical s-shaped curve.

Finally, a third set of experiments evaluated the new system in a more realistic scenario, using a chicken thigh as model. Here, two target paths were tested: one straight line defined on the tissue under 40x magnification, and a second following the edges of an anatomical detail under 25x magnification. In this last case, the surgical plan was defined using the freehand drawing mode (see Fig. 4).

Each evaluation experiment started with the positioning of the target element under the microscope, which was followed by focus adjustment and calibration of the robotic system. Then, a surgical plan matching the desired target path was drawn by the operator using the tablet teleoperation interface. Once completed, the surgical plan was executed using the aiming laser only, and a video of the experiment was recorded using the microscope camera. Each video encompassed 10 automatic executions of the entire surgical plan. These were analyzed offline using a custom laser tracking software that computes the root-mean-squared-error (RMSE) on trajectory tracing tasks [8]. The computed precision values are summarized in Table I and Table II, and examples of processed videos are shown in Fig. 3 and Fig. 4.

An analysis of the data in Table I shows that the robot-assisted laser microsurgery system is highly scalable, resulting in increased precision as the microscope magnification is increased. Furthermore, the data demonstrates the intraoperative planning system can produce very accurate surgical actions. In fact, the achieved precision values correspond approximately to the accuracy of the laser spot tracking software, which presents an average error around 1 pixel at the lowest microscope magnification and around 2 pixels at 40x due to the increased size of the 0.4 mm aiming laser spot on the video images.

Similar observations can be made examining the data in Table II. Here, slightly larger RMS errors were recorded, but these were comparatively very small: Errors in these trials corresponded to values between 11 and 23% of the aiming laser spot size. The main cause of this small performance degradation comes from the robotic system calibration procedure, which assumes the target area is planar. However, when the target presents a 3D shape, some parts of it are located at slightly different distances from the laser scanner than the calibration plane, and are hit by the laser beam slightly before or after than forecasted. Nevertheless, this is not a major problem in laser microsurgery because the microscope objectives have a short focal depth, i.e., only target areas laying at short distances from the microscope's focal plane are clearly imaged. This means that during a procedure most of the surgical area lays at the microscope's focal plane, as assumed by the system calibration.

Tables I and II also present the maximum absolute errors recorded during the experiments. As expect, these are larger than the RMS errors, but continue to be small when compared to the size of the aiming laser spot. This demonstrates that the automatic laser controller is precise and effective in executing surgical plans, thus able to guarantee a high safety level for the new intraoperative surgical planning system.

VI. CONCLUSION

In this paper we have introduced and evaluated a new intraoperative planning system for improved precision and safety in teleoperated laser microsurgeries. The new planning system integrates to the IIT's robot-assisted laser microsurgery system, allowing the definition of surgical actions via drawings created directly over live surgical video displayed on local or remote control interfaces. This intuitive process is complemented by the fact that the surgical plan is completely and safely transmitted to the local system controller, where it goes through safety analysis and waits for separate surgeon commands for verification and execution.

Here, the developed planning system was shown to offer a very flexible and easy way to define, verify and safely execute surgical actions. It increases the safety of telesurgical procedures by: 1) Allowing initial visualization and inspection of the virtually defined surgical plan directly on the target tissue using a low-power visible aiming laser; 2) Allowing real-time editing of the surgical plan or its instant replacement with a new plan; 3) Offering very precise and fast laser scanning motions, which are essential to minimize thermal damage to surrounding tissue; 4) Allowing precise control of the laser scan speed and CO_2 laser activation time, which together can define the resulting characteristics of the laser procedure; 5) Realizing automatic control of the scanner and laser locally, at the main system controller; and 6) Implementing an interlock system and requiring the use of a footswitch to locally enable the CO_2 laser.

The new planning system was evaluated through experiments presented herein and demonstrated very high precision laser aiming control from a tablet teleoperation interface. In a circular trajectory tracing task, its use resulted in a root-mean-squared-error (RMSE) 48% smaller than that obtained with our previous virtual scalpel control mode. Moreover, the new system was shown to improve the virtual scalpel system in terms of: 1) robustness and safety against telecommunications delays or disruptions; 2) capacity for very fast and precise laser scan motions; and 3) capacity to precisely control the CO_2 laser activation time.

Nevertheless, the performed experiments have shown that further system improvements are still possible. For example, the combined control of the laser scanning speed and CO_2 laser activation time can be used to produce predictable outcomes on tissue, allowing automatic control of surgical parameters such as incision length and depth. In addition, the system's aiming precision in 3D surfaces (natural tissue) can be further improved, for example, with the development of a laser visual servoing system capable of eliminating the small residual errors of the current open-loop control.

In the future, trials and system evaluations should also include the use of the surgical CO_2 laser to generate metrics in real tissue and move the system development to clinical trials. At that point, our new microsurgical system is expected to not only prove its efficiency, but also to show evidence that it allows a reduction in surgical time due to its flexible, precise and fast scanning capabilities.

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