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Next-Generation Micromanipulator for Computer-Assisted Laser Phonomicrosurgery

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Abstract— **This paper describes a new motorized laser micromanipulator created for computer-assisted laser laryngeal microsurgeries. This new device is based on a single tip/tilt fast steering mirror driven by a parallel kinematics mechanism, which is shown to improve previous laser micromanipulator designs by offering highly accurate motorized laser aiming control from a small, simple, and robust system created for real operating settings. The integration of this new device to a previously developed assistive surgical system is also described, including the new calibration model implemented to enable precise laser beam control from the live microscope video displayed on a computer screen. High system accuracy is demonstrated by the results of trajectory following experiments, which reveal an average RMSE of only 0.06 mm over an 8.5 mm diameter circular path. These numbers are also shown to favorably compare to those obtained with a traditional laser micromanipulator, evidencing a 70% error reduction when using the new system. In addition, experiments under higher optical magnification (40x instead of 16x) demonstrate even better accuracy results, proving the new system is highly scalable and indicating it has the potential to greatly improve laser microsurgery quality and safety.**

I. INTRODUCTION

LASERS form an increasingly common tool for precision treatment of pathological conditions on delicate and vital human organs. Laser phonomicrosurgery, which involves a suite of complex surgical techniques for the treatment of minute abnormalities in the vocal cords, is one such example. This important organ can be affected by a range of malignant and benign pathologies, including cancer, cysts, polyps, and reactive lesions [1]. In these cases a CO_2 surgical laser is commonly used to perform the precise ablation or cutting procedures involved in the pathology treatment. Accurate laser aiming is extremely important since preserving healthy tissue while completely removing the pathology is a major goal to minimize surgical impact on voice quality [2].

Traditionally, laser aiming during phonomicrosurgery is performed using a manual laser micromanipulator device connected to a surgical microscope. The typical operating distance is 400mm and the surgical site can be as small as 1mm (adult vocal folds measure between 11 and 21mm [3]). This means that laser control within a minuscule area is performed from 400mm away by the hands of the surgeon, who has to be highly trained, skillful and careful during the procedures. Surgical safety is an issue here, and so are the ergonomics of the operative setup and the controllability of the laser micromanipulator.

Research towards improving laser phonomicrosurgeries has recently produced motorized laser scanners such as the commercial *AcuBlade* and the *SoftScan Plus R* [4], [5]. These devices improve surgical outcome by offering a range of pre-programmed laser scan patterns. However, the surgeon is still required to precisely position these patterns on the surgical site using a traditional type of laser micromanipulator.

An alternative way to eliminate this last problem has been described by Giallo, who proposed a joystick-controlled surgical system based on the motorization of a traditional manual laser micromanipulator [6]. Unfortunately, their prototype suffered from design and fabrication issues, pointing to the need for further research into medical micro-mechanisms.

Yet another approach that has been investigated for improving laser laryngeal surgeries consists in the use of the daVinci Surgical Robot (Intuitive Surgical Inc.) in conjunction with a flexible CO_2 laser fiber [7], [8]. This was shown possible, but once again research conclusions stressed the need for enhanced laser aiming precision, resolution and

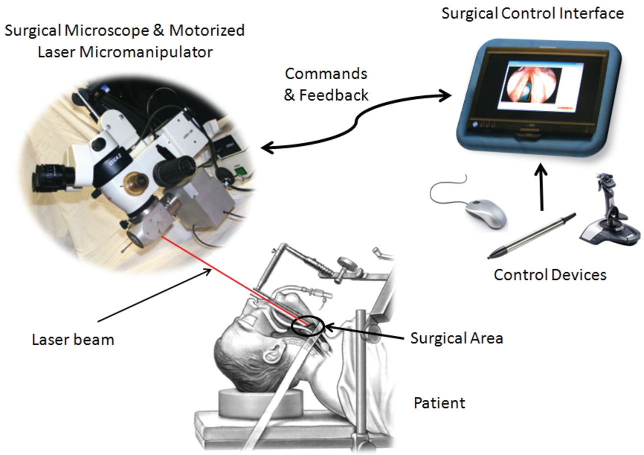

Fig. 1. The computer-assisted system for laser laryngeal microsurgery: Surgical control is performed from a computer station, which offers an ergonomic operating setting and added safety via a mixed-reality environment. Surgeon commands are processed and sent to a motorized laser micromanipulator, which controls the laser beam in real-time with micrometer accuracy. Patient drawing copied from [11].

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scanning capabilities.

Our current research also involves laser phonomicrosurgery, aiming at providing accuracy, safety, better ergonomics, and reduced training period for these procedures. This has already resulted in the development of a computer-assisted system for laser laryngeal microsurgery, which was introduced in [9] and is schematized in Fig. 1. The premise here is to improve these procedures through: 1) the design of a new motorized laser micromanipulator featuring high speed and high accuracy; 2) the creation of new interfaces for intuitive and easy laser control from a computer station; 3) the creation of a mixed-reality operating environment including virtual features for increased surgical safety; and 4) the automation of cutting and ablation procedures based on a new intraoperative planning software.

Previous research results presented in [9] demonstrated all of these ideas in the laboratory setting. However, when the new system was connected to a real CO_2 surgical laser in the operating room, a couple of issues with the developed motorized laser micromanipulator surfaced. These included high sensitivity to the incoming laser beam alignment, and variable laser focal distance within the scan area. Therefore, the research presented here focuses on resolving these issues through a new laser micromanipulator design.

The first part of this paper analyses the issues encountered with our previous laser micromanipulator and presents possible solutions to render that system functional. Then, the reasoning for a redesign of the micromanipulator is explained and the new system is presented. That is followed by a description of the new system calibration model, and by initial validation experiments. Finally, the paper concludes with remarks about further system improvements and future research directions.

II. ISSUES WITH THE LINEAR LASER MICROMANIPULATOR

The previous motorized laser micromanipulator developed for our computer-assisted phonomicrosurgery system was based on mirrors set on two perpendicular linear axes, which created the required two-dimensional laser scanning area as illustrated in Fig. 2(a). This configuration was shown to facilitate system calibration and to make both the aiming resolution and the calibration parameters independent of the target distance. In addition, this system was driven by fast linear ultrasonic motors featuring absolute encoders, which enabled high speed operation (up to 180 mm/s) and high positioning accuracy (1 µm). However, experimentation with this device in the operating room exposed two issues with its design.

The first problem observed was related to the micromanipulator robustness against small changes in the incoming laser beam alignment. In this case, it was noticed that small angulations of the laser beam away from the system's central optical axis could cause it to miss the optical output port. This was not a problem in the laboratory, where the laser source was perfectly aligned and rigidly attached the micromanipulator. However, when using a surgical CO_2 laser system, this poor robustness became an issue because the laser beam arrives to the micromanipulator via an articulated arm with 7 degrees of freedom, which causes small variations in the final laser beam direction according to its configuration.

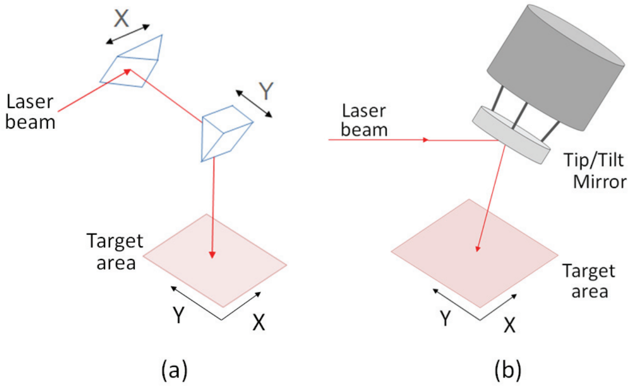

Fig. 2. Working principle of the two different laser micromanipulator designs: (a) Laser scanning based on the linear motion of two mirrors; (b) Laser scanning based on a single tip/tilt fast steering mirror.

A possible solution to this first issue could be to rigidly fix the articulated laser arm in a specific good configuration; one that would ensure correct laser beam alignment inside the micromanipulator. However, this would involve constraining or modifying other surgical devices, which is not the current intent of this research.

The second problem that surfaced during the operating room trials was related to the surgical laser focus on the target area. This, in fact, is a very important parameter to determine the laser beam effect on the targeted tissue: a highly focused beam can produce a fine cut, whereas a defocused beam can be used for shallow tissue ablations. The problem identified in this case was that the linear laser micromanipulator produces variations in the optical path length between the focusing optics and the target due to its operating principle. This, in turn, directly impacts the focal distance of the system. Furthermore, this problem becomes increasingly significant as the surgical area grows because the changes in optical path length are directly proportional to changes in the scanning mirrors position. In our linear

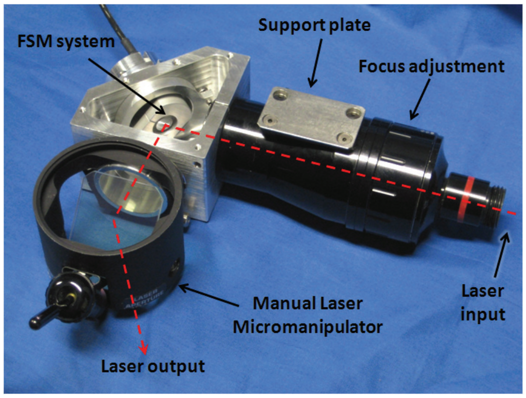

Fig. 3. The new laser micromanipulator system based on a single fast steering mirror (FSM) device.

micromanipulator prototype, which offered a surgical wide of 11x11 mm, the optical path length could change up to 22 mm from one extreme of the surgical field to another, causing significant changes in laser beam focus on the target.

This second issue can possibly be solved by incorporating of a motorized focusing system and associated controller to adjust the laser focus in synchronism with the scanner position. However, this would require a fast focusing system to cope with the rapid changes in focal distance produced by the micromanipulator, which can reach approximately 255 mm/s.

III. THE NEXT-GENERATION LASER MICROMANIPULATOR

Although the modifications suggested above could have rendered the linear laser micromanipulator functional with the surgical CO_2 laser system, we opted to redesign this system to make it smaller, simpler, and more robust at real operating settings. The new laser micromanipulator is based on a single fast steering mirror driven by a parallel kinematics mechanism, as illustrated in Fig. 2(b). This configuration offers increased robustness in terms of laser alignment since it uses only one mirror, and eliminates issues related to variable laser focal distance by manipulating the laser beam through mirror rotations only.

A picture of the new laser micromanipulator is shown in Fig. 3. This system was designed to use the S-334 fast steering mirror (FSM) from PI GmbH, which was identified as a commercial device that perfectly fitted our application needs. The S-334 is a miniature tip/tilt mirror system featuring differentially driven piezo actuators and built-in absolute position sensors. It offers high speed operation (1KHz resonant frequency) and 100 mrad optical beam deflection in closed-loop control. In addition, it guarantees 10 µrad optical beam deflection resolution with 10 µrad repeatability on both axes. Considering the typical operating distance of 400 mm, these values convert to a 40x40 mm surgical range, 4 µm resolution, 4 µm repeatability, and maximum speed in the order of 10 m/s.

The new laser micromanipulator was also designed to allow microsurgeries to be performed in the traditional way, i.e., with a traditional manual system. This was achieved by adding a traditional laser micromanipulator to the output port of the new FSM system, as seen in Fig. 3. This configuration provides the necessary optics for coaxial microscope visualization and laser actuation; improves safety since operations can be performed manually in case of electric system failure; and increases the surgical range of the new device with the extra manually controlled mirror. In the prototype shown in Fig. 3 the manual laser micromanipulator used was the *Unimax 2000* from Reliant Laser Corp.

After finalizing the prototype development, this new motorized laser micromanipulator was integrated to our computer-assisted laser phonomicrosurgery system, as Fig. 4 shows. This system was introduced in [9] and offers a novel interface for improved safety, controllability and ergonomics of the surgical setup. It uses assistive teleoperation techniques that enable, for example, tremor suppression and increased manual aiming resolution through optical magnification and motion scaling. In addition, it offers the option of defining virtual safety regions for laser operation, which are used to automatically switch off the laser in case it is aimed at a point outside those regions. Finally, the system's control software also allows the programming scan patterns for the laser beam, which further improves surgical safety and effectiveness.

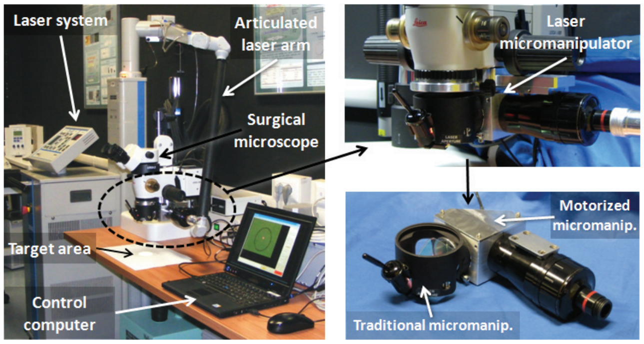

Fig. 4. The complete system for computer-assisted laser phonomicrosurgery showing: the surgical CO_2 laser system with its articulated arm; the microscope and laser micromanipulator system; and the surgical control computer.

Calibration of this new computer-assisted surgical system is essential for enabling the automatic operation and the virtual safety functionalities mentioned above. In this case, the calibration process was modified from the one presented in [9] because of differences in the actuators' work principle. Here, the laser beam is controlled from a fixed point in space rather than from a translating point, so a new model for mapping target space coordinates to the actuator space was derived. This is described in the next section.

IV. SYSTEM CALIBRATION

The method implemented for system calibration is responsible for determining the parameters of the affine transformation that maps image space coordinates (i.e.,

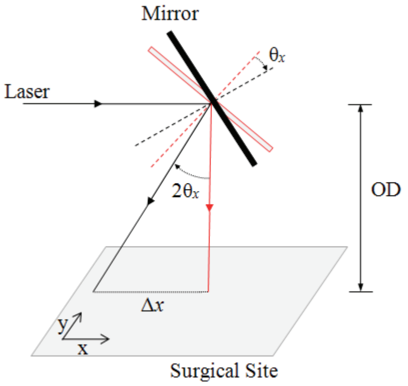

Fig. 5. Schematic for modeling the laser beam displacement from micromanipulator mirror rotations. The parameter OD is the operating distance.

points in the live video presented on the computer display) to target space coordinates. This transformation consists of translation, rotation, zoom and shear [10]:

$$X' = AX + B = \begin{bmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{bmatrix} \begin{bmatrix} \alpha & 0 \\ 0 & \gamma \end{bmatrix} \begin{bmatrix} 1 & \beta \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} + \begin{bmatrix} x'_0 \\ y'_0 \end{bmatrix} \quad (1)$$

However, the first step to use this mapping is to convert the actuator coordinates (mirror rotations) into linear displacements on the target area. This is done according to the diagram shown in Fig. 5, from which the following equation is established:

$$\Delta x = OD \cdot \tan(2\theta_x) \quad (2)$$

A similar equation is assumed for Δy, with the parameter OD (operating distance) being clearly the same for both axes.

With these equations defined, the system calibration procedure consisted of two parts: Acquisition of calibration points, and calculation of the space transformation parameters. The first part was performed in a semi-automatic fashion and used the laser system's low-power visible aiming beam. In this case, the laser micromanipulator was automatically positioned at five different known coordinates and the operator was requested to click on the laser spot seem on the live video. These user inputs provided estimates for the laser spot coordinates in the video coordinate frame, which were subsequently refined by custom image processing software that computed the real geometric center of the laser spot image. The information collected in this first phase was then used to compute the desired space transformation parameters using a least squares error minimization method.

V. VALIDATION EXPERIMENTS

The new laser micromanipulator system, its control, and the implemented calibration method were assessed by preliminary validation experiments. These tests focused on acquiring laser aiming accuracy metrics, and were based on trajectory following experiments. In this case, the target trajectory consisted of a circle with 8.5 mm in diameter printed on a piece of white paper. This target was placed under the surgical microscope, which was set to a 16x magnification. This experimental configuration was selected for consistency with prior extensive sets of trials conducted with the linear laser micromanipulator.

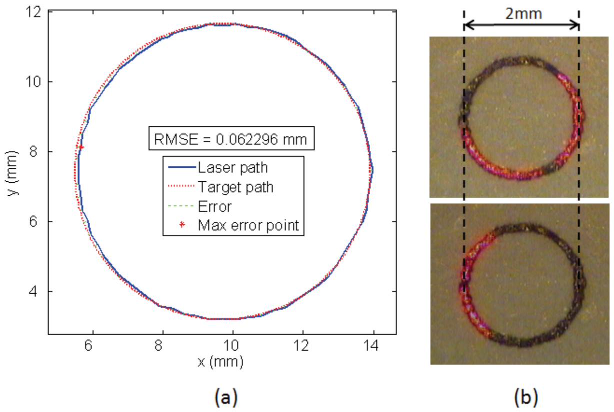

Fig. 6. Circular trajectory following experiments: (a) Sample result from an 8.5mm diameter target; (b) Pictures from a fast scan of a 2mm diameter target, from which no observable error could be measured.

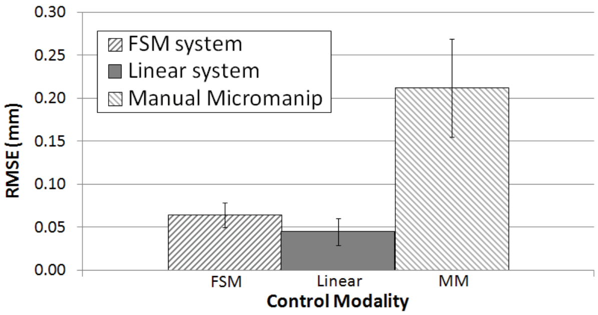

Fig. 7. Comparative graph of average trajectory following RMSE achieved on the 8.5 mm diameter circular target by the different laser control devices.

Execution of the validation experiments started with the system calibration, followed by the definition of a circular laser path perfectly matching the real target seen on the live video. This last step was performed with the help of graphics functionalities built into the developed control interface, which facilitate the drawing, editing and repositioning of standard 2-D shapes over the displayed video. Subsequently, the experiments continued with the activation of the automatic laser control routine to move it along the defined path, and a video of this entire process was recorded. Finally, measurement of the trajectory following root-mean-squared-error (RMSE) for each trial was performed offline by processing the recorded videos.

A total of 10 experiments were performed according to this scheme, with the system being recalibrated each time. The obtained results presented an average trajectory following RMSE of 0.0638 ± 0.0143 mm, demonstrating only a minor mismatch between the desired and the achieved laser targets. These results prove that the new laser micromanipulator and the implemented calibration process are reliable and precise. A sample result from one of the trials is presented in Fig. 6(a). That figure also shows pictures from a similar set of experiments conducted with a 2 mm target circle under 40x magnification, which demonstrated great system scalability and perfect targeting at reduced scales (no measurable error could be observed in those cases).

A comparison of the results obtained here with those from

TABLE I
RESULTS FROM PATH FOLLOWING EXPERIMENTS

Control Mode	RMSE
Automatic – FSM Micromanipulator	0.0638 ± 0.0143 mm
Automatic – Linear Micromanipulator	0.0445 ± 0.0155 mm
Manual – Traditional Micromanipulator	0.2119± 0.0570 mm

the linear laser micromanipulator system and from the traditional manually-controlled micromanipulator is presented in Fig. 7 and summarized in Table I. This data shows that the accuracy of the new FSM laser micromanipulator is slightly inferior to that of the previous linear system, which may indicate the need for a better calibration model if an increase in accuracy is desired. Nevertheless, the FSM system was proven vastly superior to the traditional manually controlled laser micromanipulator in terms of achievable accuracy, which is readily seem from the 70% reduction in the measured trajectory following RMSE.

VI. CONCLUSION

This paper presented the next-generation laser micromanipulator device created for our computer-assisted laser phonomicrosurgery system. This new device is based on a single tip/tilt fast steering mirror and improves previous laser micromanipulator designs by offering highly accurate motorized laser aiming control from a small, simple, and robust system created for real operating settings.

The integration of this new device to the assistive surgical system and its new calibration model were also presented. The final system setup was then evaluated through trajectory following experiments, which demonstrated an average trajectory following RMSE of only 0.0638 mm over an 8.5 mm diameter circular target. In addition, this was shown to compare very favorably to the results obtained with the traditional laser micromanipulator system, evidencing a 70% reduction in the trajectory following RMSE. This indicates that the new laser microsurgery system has potential to greatly improve surgical safety. Furthermore, trajectory following experiments under higher magnification (40x) and using a smaller target path (2 mm diameter circle) demonstrated excellent results, proving the new system is highly scalable and capable of higher accuracy as the optical magnification increases. This result suggests that, given enough magnification, the new laser micromanipulator system can approach its mechanical accuracy value of 4 µm at a 400 mm operating distance.

The technology advances presented here are now in the process of being evaluated jointly by surgeons and engineers using phantoms and ex-vivo pig larynxes as models. The current aim is to characterize the new system in real operating conditions through a scientific assessment of its safety, accuracy and effectiveness. Results from this phase are expected to be positive and clear the way for clinical trials. On the other hand, research towards improving the user interface and the augmented reality assistive system will continue, possibly incorporating pre-operative data for the creation of an information-rich surgical environment.

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