µRALP and beyond: Micro-technologies and systems for robot-assisted endoscopic laser microsurgery

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Abstract

Transoral laser microsurgery is the current gold standard technique for the treatment of diseases in delicate structures such as the larynx. However, the operations require large surgical expertise and dexterity, and face significant limitations imposed by available technology, such as the requirement for direct line of sight to the surgical site, restricted access, and relatively long operative distances. All of these factors can severely affect surgical quality, which is critical to the patient's survival and post-treatment quality of life. To change this status quo, the European project µRALP proposed a complete redesign of the surgical setup through the development of micro-technologies and systems for robot-assisted endoscopic laser microsurgery. This paper reviews the achievements and key contributions of this project, whose primary target application was phonomicrosurgery, i.e., the challenging surgical treatment of vocal cords. The paper starts by presenting µRALP's motivations and rationale, which leads to the introduction of robotics as an enabling technology for improved surgical site accessibility, visualization and management. Then, the goals and achievements of the different research areas that

composed the project are presented, including an overview of results achieved beyond and independently of µRALP. This includes research in micro-robotic laser steering, flexible robotic endoscopes, augmented imaging, assistive surgeon-robot interfaces, and cognitive surgical systems. Innovations in each of these areas are shown to provide sizable progress towards more precise, safer and higher quality transoral laser microsurgeries. Yet, major impact is really expected from the full integration of such individual contributions into a complete clinical surgical robotic system, as illustrated in the end of this paper with a description of preliminary cadaver trials conducted with the integrated µRALP system. Overall, the contribution of this paper lays in outlining the current state of the art and open challenges in the area of robot-assisted endoscopic laser microsurgery, which has important clinical applications even beyond transoral operations.

1 Introduction

Lasers form an increasingly common tool for precision treatment of pathological conditions on delicate and vital human organs. One example is transoral laser microsurgery (TOLMS), which involves the use of a surgical laser and challenging surgical techniques for treating abnormalities in the glottis and supraglottic regions (Steiner and Ambrosch, 2000).

TOLMS is the current gold-standard technique for phonomicrosurgeries, i.e., the surgical treatment of the vocal cords (Rubinstein and Armstrong, 2011). These are delicate operations that require high surgical precision. However, they are currently performed with very limited technological support, so large surgical dexterity and expertise is needed. The consequence is that the quality of such surgeries relies completely on the dexterity and capabilities of the operating surgeon, who must control the surgical tools with micrometric precision to both eradicate the disease and minimize damage to healthy tissue. If not performed well, phonomicrosurgery can have a large impact on the quality of life of the patient, as it can affect both phonation and deglutition (Presutti, 2010).

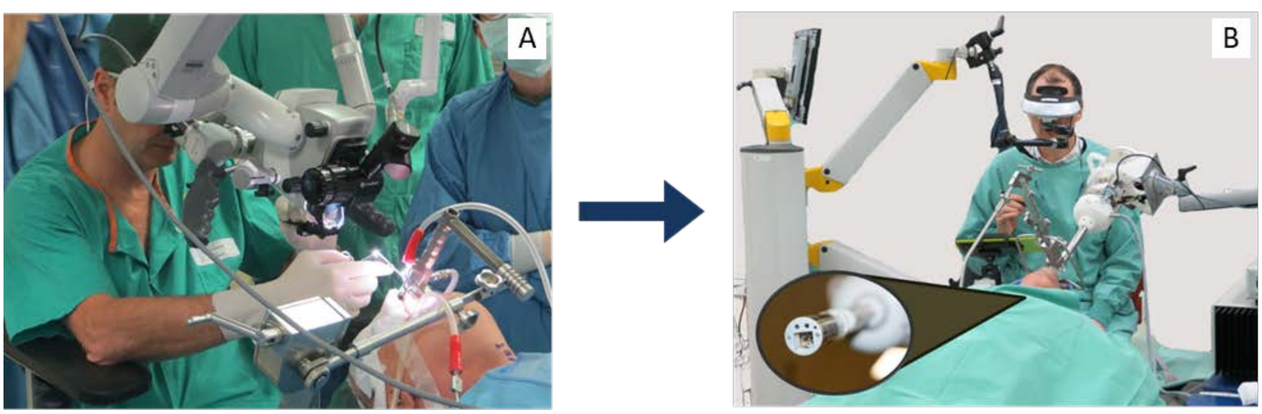


Fig. 1. µRALP achievement: complete redesign of the traditional free-beam laser phonomicrosurgery surgical setup (A) to enhance surgical safety, accuracy and quality through a novel endoscopic robot-assisted laser phonomicrosurgery system (B).

Performing TLM currently requires the use of a laryngoscope to provide both visualization and access to the surgical site, which is located deep down the throat of the patients. The laryngoscope is basically a metal tube that is inserted through the mouth of the patient to provide this required operative channel. It allows the use of an external microscope and specialistic surgical tools. As Fig. 1 shows, the surgeon operates through the laryngoscope while using a microscope, a laser micromanipulator and long microsurgical forceps.

The ergonomics of the current TLM setup is also sub-optimal, complicating the achievement of high precision surgical tasks. In addition, other difficulties include the fact that the laser beam is controlled manually from the outside the patient's body, from a comparatively large range from the surgical site (typically 400mm). This results in a stringent requirement for direct line-of-sight for laser control, imposing limits on the types of patients that can benefit from this state of the art treatment due to their specific anatomy [Peretti et al. 2016]. Furthermore, the long operating range causes laser aiming accuracy and consistency problems, increasing the need for extensive surgeon training.

Considering this context, the European project µRALP proposed a complete redesign of the TLM surgical setup and pursued the development of a new flexible endoscopic system for robot-assisted laser phonomicrosurgery. The result was the creation of an advanced micro-surgical robotic system through research on novel robotic endoscopes and precision micro-robotic end effectors, which allowed relocating the imaging sensors and the laser actuator closer to the surgical site. In addition, research in real-time cancer imaging, surgeon-robot interfaces, cognitive controllers, augmented-reality and assistive teleoperation contributed to improve the surgical site visualization, the controllability of the surgical tools, and the precision of the operations.

µRALP was a three-year project executed in the period between 2011 and 2015. It involved five European institutions: three engineering institutions and two hospitals. The project was coordinated by the Italian Institute of Technology (IIT, Genoa, Italy) and included the University of Franche-Comté (UFC, Besançon, France), the Leibniz University (LUH, Hannover, Germany), the University Hospital of Besançon (UHB, Besançon, France) and the University of Genova (UNIGE, Genoa, Italy).

The engineering advancements and scientific contributions of µRALP are reviewed in this paper, together with further developments in the area achieved beyond the end of the project. This leads to an outline of the current state of the art and open challenges in the area of robot-assisted endoscopic laser microsurgery.

2 µRALP project context and objectives

Back in 2011, a number of clinical devices were already available for laser surgery, including optical scalpels and manual laser micromanipulators commercialized by Deka, KLS Martin, Lumenis, OmniGuide and other companies (see Fig. 2). Now, a decade later, these are still the same devices available commercially for TLM. However, as mentioned above, the control of such devices relies completely on the dexterity and skills of the operating surgeon, who has to go through a long training process to acquired the expertise needed for precision operations such as phonomicrosurgery. Furthermore, ergonomic issues such as sub-optimal surgeon hand support and the need to operate while looking through a microscope, lower the accuracy and aggravate consistency problems that affect these delicate surgeries.

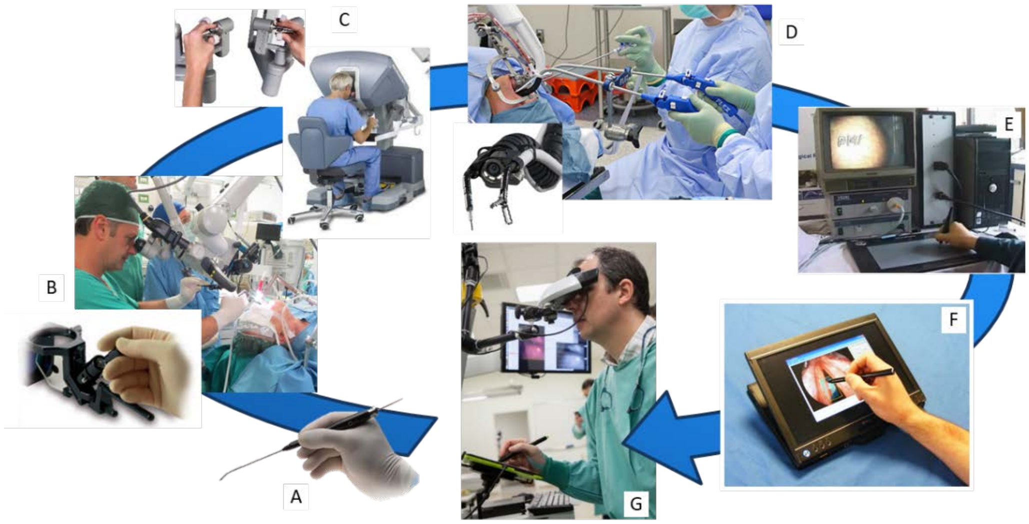


Fig. 2. User interfaces for laser surgery: (A) Elevate ENT handpiece, an optical scalpel commercialized by OmniGuide Surgical. (B) EasySpot Hybrid, a manual laser micromanipulator by DEKA for surgical microscopes. (C) Intuitive Surgical's da Vinci system and (D) Medrobotics Flex robotic system, both of which can include an optical fiber for laser surgeries. (E) K.U. Leuven's interface for robot-aided laser surgery based on a graphics tablet. (F) IIT's Virtual Scalpel interface based on a tablet PC. (G) µRALP's Virtual Microscope and tablet-based laser controller.

Nonetheless, the recognition that interfaces (and human factors) play a major role in the success and quality of laser surgeries has driven research into augmenting the surgeons' capabilities with new surgical systems such as teleoperated robotic devices. In addition, the creation of hollow core optical fibers capable of transmitting CO_2 laser power has enabled, for example, research into the use of surgical robots, such as the *da Vinci* system (Intuitive Surgical Inc., USA), for laryngeal laser procedures. This possibility was first explored by Solares and Strome (2007), and later by Desai et al. (2008), who have coupled such optical fibers to the *da Vinci*'s tool tip and used it for laryngeal surgeries. This idea was successfully demonstrated by both groups, and later corroborated by others using also other robotic systems, such as the Flex robot launched by Medrobotics Corporation (USA) in 2014 (Lang et al. 2017). However, the conclusions of such studies continue to emphasize the need for new robotic technologies to improve access, laser aiming precision, and ablation quality for delicate operations in the glottic region. Current robotic instruments are still too large for deep laryngeal interventions, limiting their effective use to the oral cavity, pharynx and supraglottic regions.

By the time the µRALP project started, research towards new robot-assisted laser surgery systems included the work of Tang et al. (2006) at K.U. Leuven, and Mattos et al. (2011) at the IIT. Their research resulted in the creation of writing-based interfaces for controlling laser aiming in robot-assisted laser surgeries, which demonstrated potential for bringing greatly enhanced precision, controllability, safety, and ergonomics for laser microsurgeries. However, similarly to the traditional laser microsurgery setups, both systems were still limited by the need for direct line-of-sight from the outside of the patient to the operative field.

Therefore, µRALP was focused at advancing such state of the art in laser phonomicrosurgeries, specially through the elimination of limitations regarding the access to the surgical site and the need for establishing an operative direct line-of-sight from the outside of the patient's body. For this, the project concept included the creation of a novel teleoperated surgical system based on a micro-robot laser micromanipulator and a custom flexible endoscope, which could bring novel imaging and surgical technologies close to the surgical site. Furthermore, to augment the surgeons' capabilities, the project also aimed at creating a novel ergonomic and information-rich surgeon-machine interface, including augmented visualization, intuitive controllers and assistive cognitive systems. The ultimate goal was to bringing unprecedented levels of accessibility and precision to laser microsurgeries to allow operations not previously possible with existing technology.

To realize this concept, µRALP focused on accomplishing the following objectives:

- *Micro-robotic laser micromanipulator*: The engineering of a dexterous micro-robotic end-effector for precise laser power delivery in minimally invasive surgeries. This system should control the surgical laser steering from the immediate vicinity of the surgical site.
- *Flexible robotic endoscope*: The development of a novel endoscopic system providing the appropriate degrees of freedom for effective access and visualization of all possible phonomicrosurgery sites.
- *Surgical interface*: The creation of an intuitive and information-rich augmented reality man-machine interface for assisted teleoperation of the robotic system, including real-time surgical guidance based on pre- and intraoperative surgical plans. This goal involved the design of:
    - An assistive teleoperation interface able to achieve the required control system performances and support informed decisions by the surgeon
    - A laser visual servoing system able to demonstrate accurate laser aiming control
    - An augmented reality surgical interface demonstrating accurate preoperative image registration
- *Cancer tissue visualization*: The study and development of micro-optomechatronic technologies and computer vision methods for intraoperative real-time cancer tissue visualization, to support the intraoperative definition of surgical margins.
- *Cognitive controller*: The creation of a cognitive system capable of learning and predicting the changing characteristics of the surgical site during laser procedures, to improve laser-tissue interaction quality and safety.

To pursue these objectives, µRALP was subdivided into parallel research and technological development work packages, whose results achieved within and beyond the end of the project (also by other research groups) are discussed in the next sections.

3 Micro-technologies and systems for robot-assisted endoscopic laser microsurgery

The research leading to the µRALP system demonstrator shown in Fig. 1 included parallel efforts towards the design, development, assessment and integration of its subsystems. Such subsystems focused on the different objectives outlined above, i.e., the creation of: 1) a micro-robotic system to steer the laser beam; 2) a flexible robotic endoscope to bring the imaging sensors and surgical instruments close to the surgical target; 3) optical technologies and computer vision methods for real-time cancer tissue imaging; 4) teleoperation and surgeon-robot interfaces; 5) augmented reality for enhanced surgical awareness and control; and 6) cognitive systems for safety supervision and autonomous operations.

3.1 Micro-robotic laser micromanipulator

The concept driving the design and development of this device is presented in Fig. 3. The goal of the micro-robot is to serve as the end-effector of a new endoscopic system for laser phonomicrosurgeries, allowing accurate laser aiming by providing high resolution motions and fast response times. The micro-robot was also designed to allow teleoperation and automatic control based on visual servoing methods, to enable high-accuracy operations. The design specifications for the creation of the micro-robot included the robot size (diameter ≤ 10 mm), mobility (laser deflection range ≥ 30º) and laser aiming accuracy (≤ 100 µm).

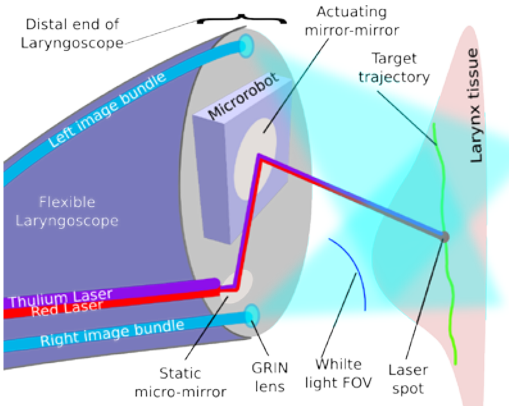
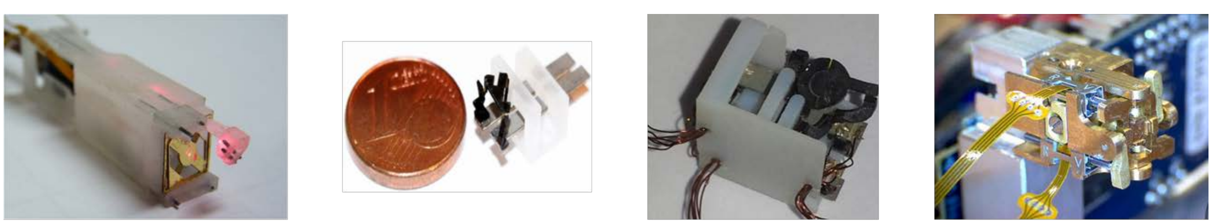


Fig. 3. Schematic view of micro-robotic laser micromanipulator concept.

During µRALP, four solutions were proposed for the micro-robotic laser micromanipulator. These are presented in Fig. 4 and included a hybrid piezoelectric compliant mechanism (Rabenorosoa et al., 2014), two different piezoelectric smart composite microstructures (Lescano, 2015), and a solution based on conventional clockwork technology (HorloBot).



(A) (B) (C) (D)

Fig. 4. Micro-robotic laser micromanipulators developed during µRALP: (A) Squipabot; (B) PIBOT, (C) Micro Agile-Eye, (D) HorloBot.

The PiBot and the Micro Agile-Eye piezoelectric smart composite microstructure robots were proposed to satisfy the stringent system requirements by combining the following principles:

- The use of piezoelectric cantilevers allows the achievement of very high positioning resolution (submicrometric).
- The use of several piezoelectric actuators and the lever principle can amplify displacements.

- A parallel kinematic structure allows high miniaturization of the structure while maintaining the range of displacements and of velocities offered by the piezoelectric actuators.
- The use of a 5R (for micro Agile-Eye) and 2 RUS (for the PiBot) parallel kinematic structures allows transforming linear displacements into angular displacements for laser scanning with conservation of the high velocity capability.
- The use of smart composites microstructures (SCM) fabrication process can allow microfabrication of the whole piezoelectric microrobot with minimized complexity. The principle consists in machining first the structure in planar form, then folding this in order to obtain the 3D structure.

The HorloBot micro-robot was developed based on conventional clockwork solutions. Developments here involved undergraduate students at Lycée E. Faure in Morteau and resulted in the creation of a working prototype using linear micromotors.

The Squipabot was the micromechatronic laser micromanipulator finally integrated in the µRALP endoscope. This device was selected for its simple fabrication and assembly methods, and for its higher technology readiness level (TRL) for integration with the other µRALP systems. The Squipabot is based on the use of conventional mechanisms and MEMS technology. More precisely, it is a combination of a compliant micro-fabricated silicon structure (deformable mirror) with innovative linear micromotors, used to actuate the two decoupled and high range (up to 45°) tilting stages with high accuracy (Renevier et al., 2017). Details of this micro-robot are shown in Fig. 5.

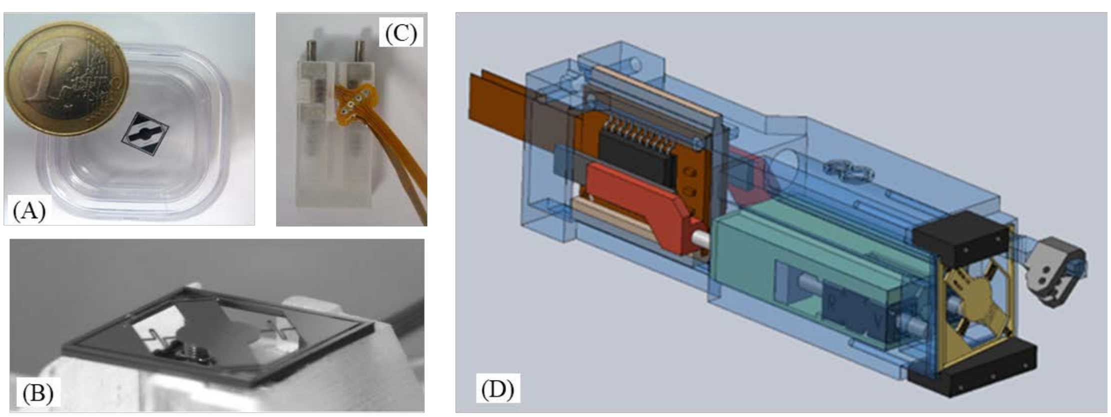


Fig. 5. Details of µRALP's Squipabot micro-robotic laser micromanipulator: (A) and (B) the deformable micromirror (MEMS). (C) the linear piezoelectric microstages. (C) CAD model of the assembled microrobot.

The Squipabot featured integrated high-resolution magnetic position sensors to determine, in real-time, the position of the linear stages and, consequently, the position of the beam deflection micro-mirror. All components (linear micromotors, MEMS mirror, sensors, laser fiber, fixed mirror, electrical wires) were assembled and packaged in a 3D printed housing. The entire integrated micro-robot (depicted in Fig. 4) measured 9 mm x 11 mm x 42 mm. It successfully satisfied the performance requirements by demonstrating closed-loop trajectory following root-mean-square (RMS) errors in the order of 80 µm, laser deflection velocity up to 95 °/s, and control loop frequency up to 40 Hz.

Beyond the end of µRALP, project partners continued the research towards higher TRL and alternative technological solutions for the micro-robotic laser micromanipulator. These efforts resulted, for example, in the creation of a magnetically actuated laser scanner for endoscopic microsurgery (Acemoglu et al., 2019), which demonstrated open-loop accuracy below 1.4 mrad (90 µm at 30 mm working distance) for scanning frequencies up to 15 Hz. This device, depicted in Fig. 6, is based on the creation of a local magnetic field to bend a cantilevered laser fiber in a controllable fashion. It was originally based on the use of a standard silicon optical fiber with 300 μm core diameter, but was subsequently enhanced to use a waveguide for CO_2 lasers. This allowed demonstrating higher quality tissue ablations when compared to the bare waveguides currently in clinical use, enabling both reduced carbonization levels and narrower ablation craters (Acemoglu and Mattos, 2018). The concept of this device was later extended to allow closed-loop control of the scanning fiber, demonstrating promising results towards a system with higher robustness and accuracy (Mohammadbagherpoor et al. 2019).

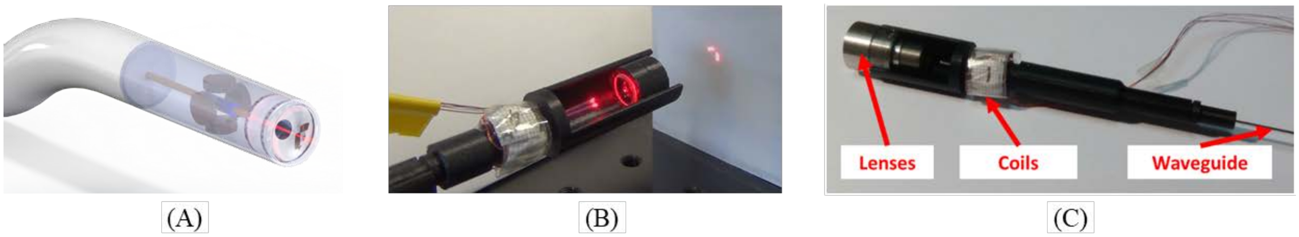


Fig. 6. Magnetically actuated laser scanners for endoscopic microsurgery: (A) Concept. (B) Prototype based on a standard silicon optical fiber. (C) Prototype based on a CO_2 laser waveguide.

Other prototypes proposed beyond μRALP to steer laser fibers for microsurgery include biocompatible conducting polymer continuum robots (Chikhaoui et al. 2018), tiny flexible steerable instruments to be used through the tool channel of clinical endoscopes (O'Brien et al. 2019), and a cable-driven parallel robotic system for phonosurgery (Zhao et al., 2020). Finally, a millimeter-scale tip/tilt laser scanning system based on a micro-mechatronic structure actuated by piezoelectric beams has been proposed for transoral robotic surgery, demonstrating a field of view of 10 mm x 20 mm and scanning speed up to 7 m/s from an 11 mm diameter device (Bothner et al., 2019). This device was subsequently further miniaturized to a diameter of 6 mm and improved to cover a 18 mm x 18 mm workspace (York et al., 2021). Images of such systems are presented in Fig. 7.

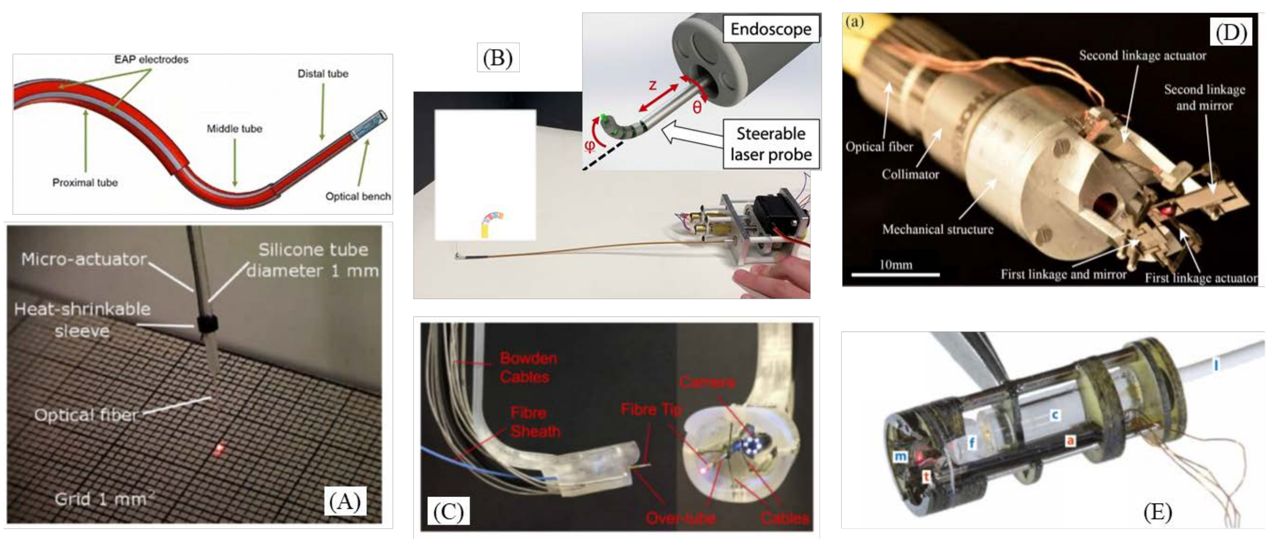


Fig. 7. Further devices created to steer a surgical laser beams: (A) A biocompatible conducting polymer continuum robot (Chikhaoui et al. 2018). (B) A flexible steerable instrument (O'Brien et al. 2019). (C) A cable-driven parallel robotic system (Zhao et al., 2020). (D) A millimeter-scale tip/tilt laser-steering system (Bothner et al., 2019). (D) Microrobotic laser steering system (York et al., 2021).

3.2 Flexible robotic endoscope

The specific objective of this device was to provide a robotic structure to deploy, support, position and properly orient the imaging and laser steering systems to allow effective laser microsurgery. This required the creation of a device with the appropriate size, operative channels and degrees of freedom to access the larynx and all possible surgical sites.

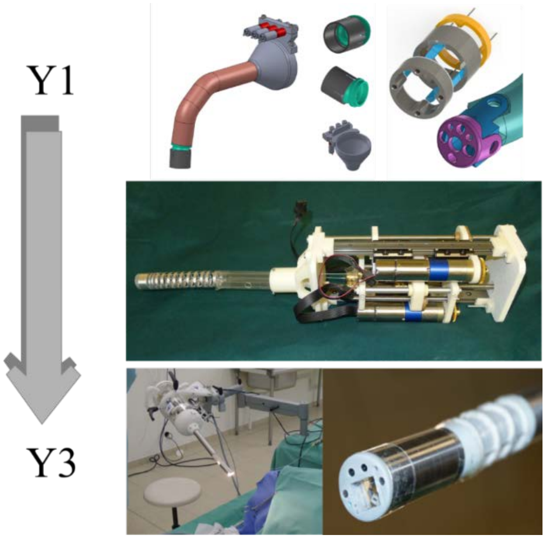


Fig. 8. Development stages of µRALP's flexible robotic endoscope within the 3-year project.

The development of this endoscopic system was an iterative process strongly influenced by results of adjunct research and cadaver trials. As presented in Fig. 8, the design evolved to adapt to demands identified throughout the µRALP project. The final device consisted of following components: a distal tip (housing a stereo imaging system, illumination fibers, the Squipabot, and laser focusing optics), one bendable and extendable continuum segment, one solely bendable continuum segment, a rigid shaft and an actuation unit (Kundrat et al., 2015).

The endoscope's actuation unit provided manual and motorized actuation for the two consecutively attached continuum segments. Actuation was based on spindle driven carriers, which were attached to NiTi rods and wires connected to both segments and guided through the rigid shaft. Each segment was actuated by three rods and wires. Manual actuation was connected to the first segment and allowed for in-plane bending (1 DoF). Intraoperative positioning of the Squipabot was achieved with the second continuum segment. The flexible and leak-tight continuum segments were manufactured individually by silicone casting. The flexible segments were rigidly connected to the distal tip and rigid shaft. Three motors actuated the spindle-carrier system, enabling bending in two DoF (pan-tilt) and extension of the segment. Another DoF was achieved by manually rotating the actuation unit inside the customized interface.

Control of the endoscope's actuation system was implemented on a BeagleBone Black embedded Linux device. A customized extension was designed to connect the motors directly to the RS232 interface and power supply. Customized ROS modules provided low and high level interfacing with the µRALP control framework. Kinematics of the actuated continuum segment were derived considering the novel variable length of segments (Kundrat et al., 2015).

As detailed in (Kundrat et al., 2019), direct and inverse kinematics were available, as well as Jacobian formulation for velocity mappings. This enabled control of the endoscope directly from image space based on the stereoscopic imaging information. The adjustment of the distance between the endoscopic tip and the tissue surface was implemented to allow laser focusing and a maximum radiant exposure on the tissue. In this regard, a visual servoing loop was implemented obtaining depth information from stereo triangulation and applying proportional control to adjust the length of the continuum segment to a desired distance from the tissue surface. This feature enabled precise positioning for laser focus adjustments.

The endoscope distal tip provided central alignment for the Squipabot. In order to obtain an overlapping workspace, the imaging sensors and illumination light guides were circumferentially aligned and inclined with respect to the laser beam steering micro-robot. Optical fibers and electrical cables were routed within the endoscope in order to be protected during intraoperative handling.

The robotic endoscope design also considered different approaches for stabilizing the system with respect to the patient. The decision to use a commercial manually lockable positioning arm was taken after preliminary cadaver experiments, since it demonstrated proper support while being readily available. This support consisted of two parts: a serial kinematics arm and a custom interface to the endoscope unit. The custom interface added two additional degrees of freedom to the supporting system, facilitating intraoperative handling. In addition, the access to the laryngeal anatomy was facilitated by the use of commercial mouth retraction device, allowing improved dexterity for inserting the µRALP endoscope through mouth and oropharynx to finally reach the laryngopharynx (see Fig. 9).

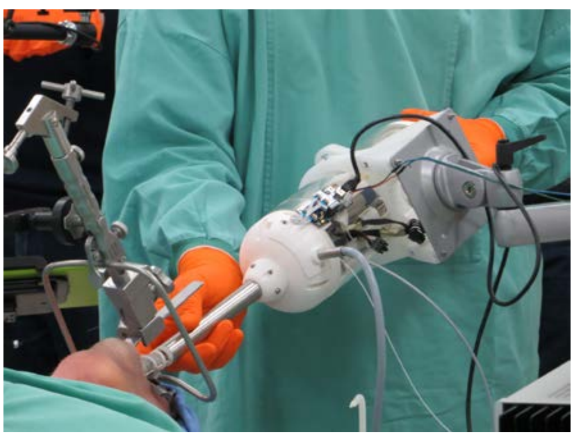


Fig. 9. Initial rough positioning of µRALP's flexible robotic endoscope was performed manually with the support of a passive lockable holder and a standard mouth retraction device.

Beyond the end of µRALP, efforts continued towards the realization of a robotic endoscope with higher TRL. This included the integration of a high power laser into the system and mechanism enhancements for higher robustness and performance. Non-contact soft tissue ablation was demonstrated using a Er:YAG laser (2.94 µm wavelength), delivered using a GeO_2 solid core fiber and appropriate laser focusing optics (Kundrat et al., 2016). Subsequently, a new 5 DOF continuum robotic endoscope composed of two segments with 11 mm outer diameter and a large inner lumen of 5.75 mm was designed and fabricated monolithically. The system featured multiple rigid guidance elements connected to bellow-shaped flexible sections to enable bending, extension, and compression of the structure, which demonstrated bending up to 90° and elongation of up to 80% from its initial length. These capabilities were instrumental to allow the demonstration of assistive and autonomous technologies for laser focus adjustments (Kundrat et al., 2019).

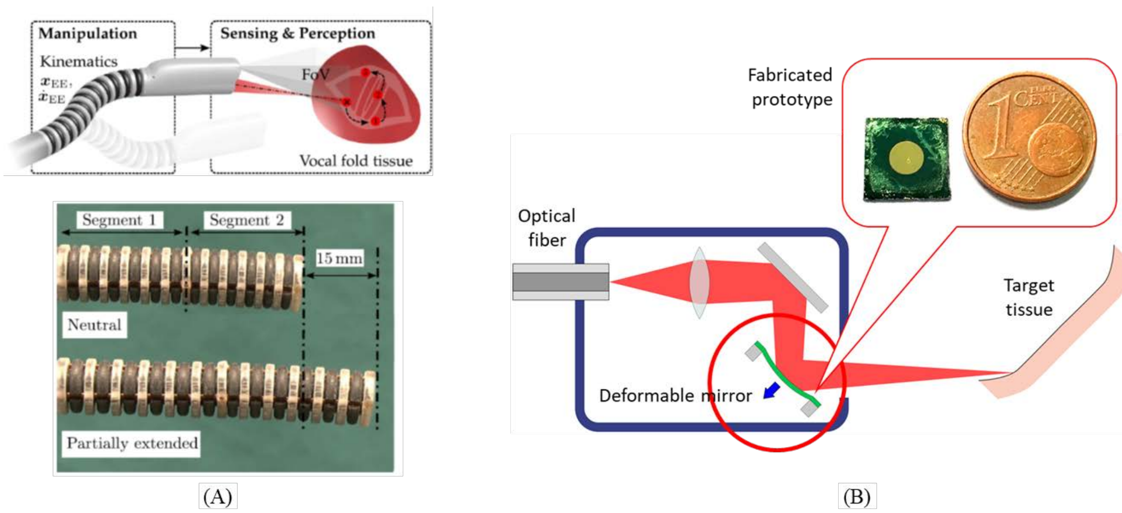


Fig. 10. (A) Advanced version of a flexible robotic endoscope for non-contact laser surgery (Kundrat et al., 2019). (B) High power laser auto-focusing system based on a hydraulically actuated MEMS varifocal mirror (Geraldes et al., 2019).

The realization that high power laser focusing is critical for the precision and quality of endoscopic laser microsurgeries also lead to parallel research into micro-opto-electromechanical systems (MOEMS) for this purpose. This included the development of a 3 × 4.24 mm hydraulically-actuated MEMS varifocal mirror able to provide laser beam defocusing over 60 diopters. The device proved to be appropriate for use with high power surgical lasers (including CO_2 lasers) and enabled the implementation of an auto-focusing system with focal length ranging from 15 mm to 140 mm (Geraldes et al., 2019).

3.3 Cancer tissue visualization systems

The goal here was to create new technologies to support the detection of tumors and the intraoperative definition of surgical margins. This was pursued through research and development of optical technologies and computer vision methods for enhanced real-time visualization of cancer tissue, which led to the development of a dual imaging system for the acquisition of stereoscopic white-light and fluorescence images.

The white-light imaging system was specifically designed for high-speed imaging to enable visual servoing of the laser beam controlled by the Squipabot. It was based on the use of two imaging bundles of 50,000 fibers each, providing monochrome stereo images with a 720×576 pixels resolution at up to 1000 frames per second (fps). The system's field of view was 15 mm in diameter at a 25 mm working distance. This corresponded to a pixel resolution of approximately 13 µm/pixel.

The fluorescence imaging system was based on the same fiber bundles and an additional fluorescence excitation laser. Optical filters were used outside the endoscope body to select the wavelengths of interest. The system was able acquire 10 fluorescence images per second (10Hz), which were automatically co-registered and with the same 720×576 pixels resolution as the white-light images.

The realization of this dual imaging system demonstrated a new hardware for hyperspectral augmented-reality visualization of the surgical field. Figure 11 shows a picture of this system integrated to the µRALP endoscope tip and sample images acquired with it at 600 fps, which presented satisfactory resolution, contrast and field of view.

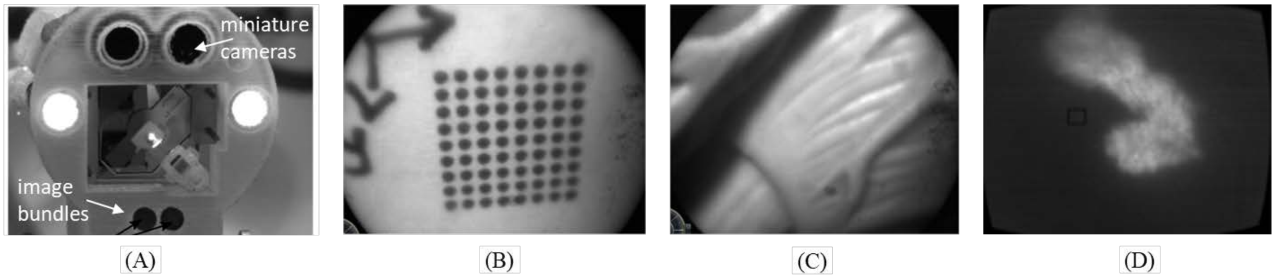


Fig. 11. (A) the µRALP endoscope tip with integrated dual imaging system. (B) and (C) white-light images acquired at 600fps. (D) Fluorescence image acquired with the same imaging bundle.

In addition to the development of new hardware for cancer imaging, µRALP also involved research on computer vision methods for automatic detection and classification of laryngeal tumors based on narrow-band imaging (NBI) endoscopic videos. Around 2011, clinical studies were starting to establish correlations between the characteristics of the laryngeal mucosal microvascular network and different cancer types (Ni et al., 2011). Therefore, the automatic recognition of microvascular patterns was deemed as a promising technology to assist in cancer detection and surgical margins definition.

Initial research on this topic focused on detecting and classifying blood vessel patterns based on anisotropic filtering, morphological analysis, and statistical analysis of extracted metrics such as blood vessels' thickness, tortuosity, and density (Barbalata and Mattos, 2016). The method reached an overall classification accuracy of 84.3% during a preliminary assessment, proving the feasibility of the approach. This motivated further research in the area, including the development of machine learning methods for laryngeal tissue classification based on NBI texture analysis (Moccia et al., 2017), which achieved a median recall of 98% on a well-balanced dataset built from endoscopic videos of 33 patients.

3.4 Teleoperation and surgeon-robot interfaces

The specific goals here were to design and implement the software and hardware infrastructures for the complete integration of the µRALP system, and to develop novel user interfaces for intuitive, precise, and ergonomic teleoperation of such system.

Initial efforts focused on a comprehensive assessment of the Virtual Scalpel system involving expert and novices ENT surgeons (Mattos et al., 2014). This system, shown in Fig. 2, allowed the use of a stylus to control the steering and activation of the surgical laser beam directly from a touch-screen monitor, where real-time video of the surgical site was displayed. Results demonstrated the Virtual Scalpel could augment the surgeons' skills by providing a highly intuitive control interface able to eliminate the hand-eye-foot coordination issues that affect the standard laser microsurgery systems used clinically. This translated into significantly enhanced laser aiming accuracy and controllability assessed through a quantitative analysis of trajectory following errors.

However, feedback from the surgeons also highlighted the need for stereoscopic visualization of the surgical site for proper depth perception during the delicate laser microsurgeries. Therefore, the Virtual Scalpel system was redesigned to provide such visualization. This lead to the development of the Virtual Microscope concept (Deshpande et al., 2014), in which a stereoscopic head-mounted display (HMD) was used to simulate a standard surgical microscope, and a graphics tablet was used as the input device for controlling the laser beam. Results here demonstrated similar performance enhancements as Virtual Scalpel system in terms of laser control accuracy and usability, with the extra benefits of allowing 3D visualization and augmented reality features. Therefore, this was the surgeon interface selected for the µRALP system (Fig. 12).

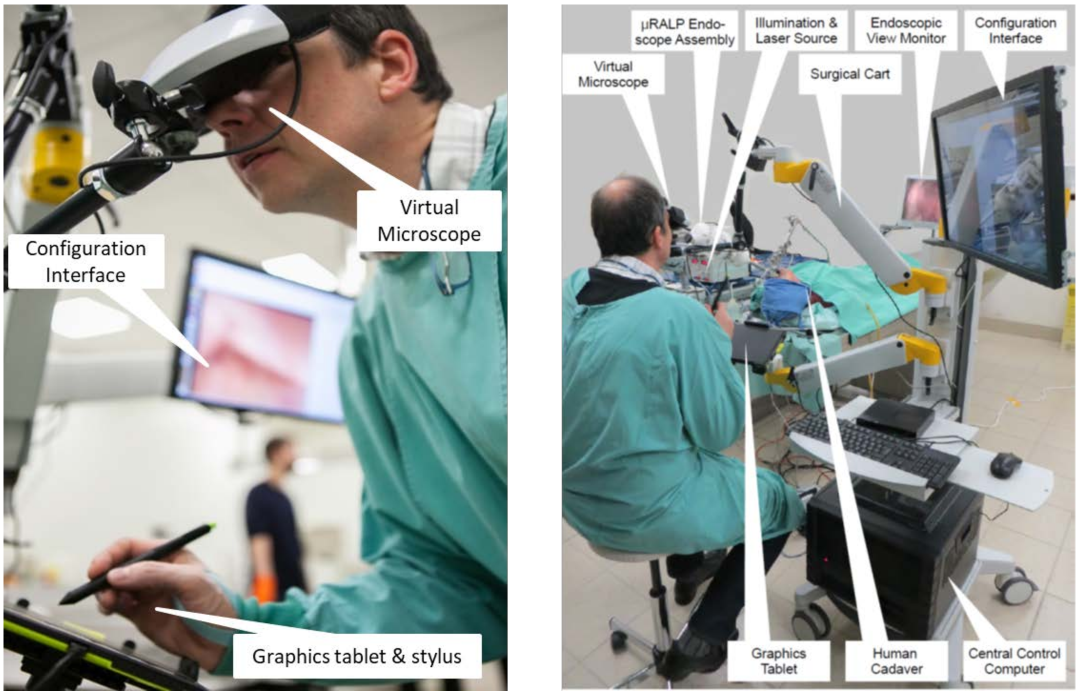


Fig. 12. The µRALP teleoperation interface and its components.

Overall, the final µRALP surgeon interface was composed of the following main elements:

- Input Interface: A graphics tablet was used for laser aiming control. Buttons on the stylus were used for the definition of intraoperative plans and for system configuration changes.
- Visualization Interface: The system included three visualization devices:
    - Virtual Microscope: This component provided real-time stereoscopic visualization of the video streams produced by the endoscope's imaging system. The 3D videos were displayed on a high-definition immersive stereoscopic display fixed to the µRALP surgical cart with an adjustable arm.
    - Configuration Interface: A touchscreen monitor was used for system configuration, operating mode selection, alarm messages, and as a supplementary display for surgical site visualization.

  - Endoscopic View Monitor: An additional monitor was used to display the real-time endoscopic video for the surgical team in the operating room. It also served as a visualization aid during the manual insertion and rough positioning of the µRALP endoscope near the surgical site.

- Surgical Cart: A cart was used to integrate and organize the different parts of the surgical system into a single rack-style configuration. It provided housing and support for the system's control computer, graphics tablet, virtual microscope, and configuration touchscreen monitor. It was designed to be easily rolled in and out of operating rooms and reconfigurable to match the surgeon requirements.

Controlling the complete µRALP surgical system from the surgeon interface required full software and hardware integration and real-time operations. This was implemented following the architecture presented in Fig. 13. The software components included: Input command processing; Image acquisition, processing, and display; Visual servoing for closed-loop laser control; Image registration and 3D reconstruction; Augmented reality processing and display. The hardware components included: Micro-robotic laser micromanipulator (Squipabot); Robotic endoscope; Illumination; Endoscopic cameras; Visualization devices.

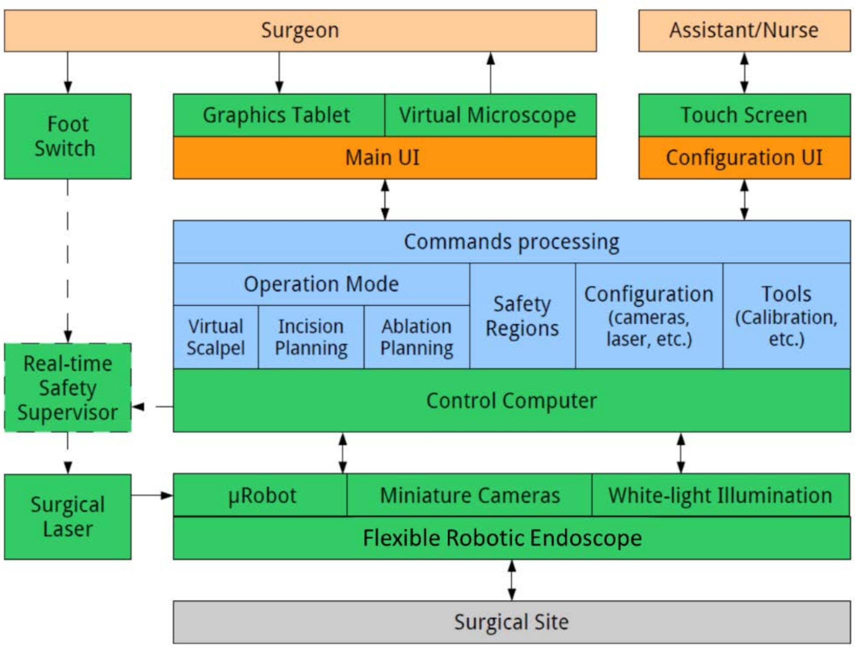


Fig. 13. The µRALP surgical system architecture.

When using the µRALP system, the surgeon was in full control of the operation. Nonetheless, different components assisted in the execution of surgical tasks. These provided the following assistive features:

1. Virtual Scalpel: Real-time laser aiming control using the stylus and tablet interface.

2. Intraoperative Planning: The stylus could be used to define virtual scan patterns in the surgical field, allowing the planning of incisions or ablation regions for subsequent automatic execution (Fig. 14).

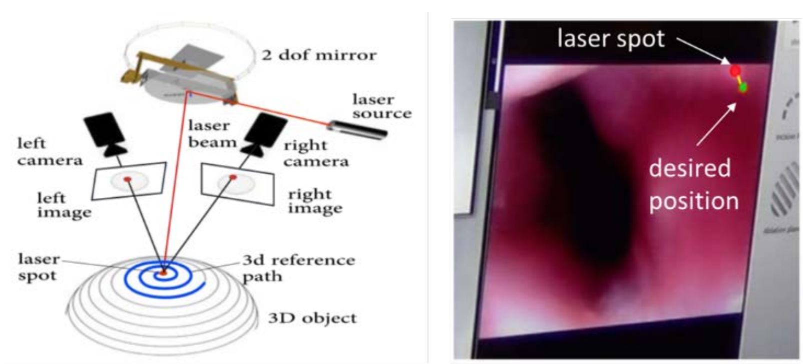
3. Predictive Safety: The stylus could also define safe and forbidden virtual regions in the surgical field, which were used as virtual fixtures to automatically enable or disable the high-power surgical laser.

(A) Incision planning (B) Ablation planning (C) Safe region definition

Fig. 14. Examples of intra-operative planning of incisions paths, ablation patterns, and safety regions based on graphic overlays. The high-power surgical laser was only enabled within the defined safe region.

Accurate automatic execution of surgeon-defined intraoperative plans was pursued through research on novel laser visual servoing methods. This resulted in the development of two methods, called epipolar and trifocal visual servoing. The epipolar method used one of the embedded cameras and Squipabot's actuated mirror as a virtual camera to implement a weakly calibrated controller able to accurately follow paths in a 3D scene (Andreff et al., 2013). This method was also shown to enable decoupling path following from velocity profile control, offering advantages in terms of laser-tissue interaction control (Seon et al., 2015).

The trifocal visual servoing method used the two endoscopic cameras and the actuated mirror (virtual camera) to construct a three-view imaging system and then use the trifocal constraint to design a robust and accurate controller (Andreff and Tamadazte, 2016). This method was shown to simplify the eye-to-hand visual control law of the pan-tilt laser, avoiding the need for a strong Euclidean calibration of the system and for interaction matrix inversions. At the same time, it provided good performance, achieving an RMS error of 1.20 pixels in trajectory tracking tasks during cadaver trials with the µRALP system.

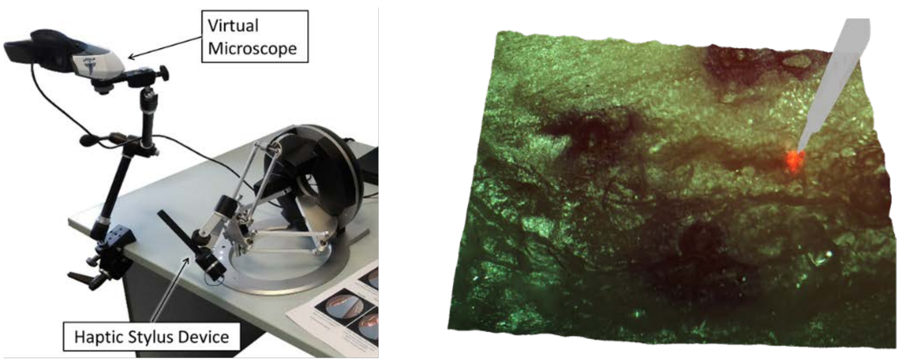


(A) (B)

Fig. 15. (A) Schematic view of a trifocal laser visual servoing system with two cameras. (B) Intraoperative scene during laser virtual servoing on the vocal cord of a cadaver.

Research beyond the end of µRALP continued the efforts towards fast, accurate and robust laser visual servoing, leading to the development of a new path following method incorporating trifocal constraint (Tamadazte et al., 2018). This method ensures accurate 3D control of laser spot displacements in unknown environments while exhibiting good robustness with respect to the calibration and measurement errors and scene variations. In addition, it allows perfectly decoupling the laser spot velocity from the path shape.

Furthermore, continued research towards surgeon interfaces with improved usability, intuitiveness, and laser control performance led to the development of the Haptic Laser Scalpel system (Olivieri et al., 2017). This new control interface brought the sense of haptics to contactless laser surgeries, enriching the surgeon experience and allowing the exploitation of active constraints and guidance techniques to significantly enhance laser control accuracy both in static and dynamic environments. This was realized by exploiting stereoscopic visualization and real-time 3D reconstruction to create a virtual haptic surface representing the real surgical site, which could be explored using a commercial haptic device. This same device was also used to control the steering of the surgical laser beam, allowing the co-location of the haptic feedback and the laser spot seen on the target tissue.



(A) (B)

Fig. 16. The Haptic Laser Scalpel, developed to bring the sense of haptics to contactless laser surgeries. (A) Surgeon interface. (B) 3D visualization of the surgical site with an augmented reality haptic scalpel avatar.

3.5 Augmented reality systems

The research focus here was on enhancing intraoperative surgical planning and visualization by means of stereoscopic methods. This included the development of methods for planning laser incisions in 3D, for assessing and controlling the laser focus, and for creating image overlays based on information from the tissue surface and from the laser.

One of the main achievements in this area regarded real-time intraoperative acquisition of tissue surface information (see Fig. 17). For this, a fast 3D reconstruction method providing sub-pixel accuracy at up to 25 frames per second was developed based on stereo image processing (Schoob et al., 2016). This corresponded to a reconstruction accuracy below 1 mm when using the µRALP endoscope, which featured a stereo imaging system with working distance between 20 and 30 mm. Furthermore, the method included robust techniques for outlier rejection and for handling radiometric illumination changes, as these naturally occur in the tube-like larynx.

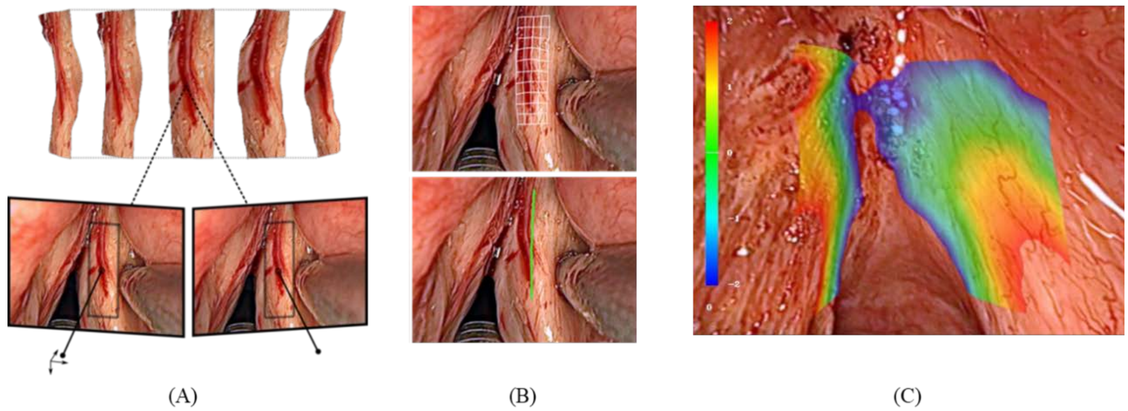


Fig. 17. Real-time stereoscopic methods for (A) 3D reconstruction, (B) intraoperative incision planning and visualization, and (C) laser focus adjustment.

Image-based assistance to the surgical workflow was achieved by incorporating the extracted tissue surface information in the definition and visualization of surgical plans. For this, a new method for visual augmentation and three-dimensional feedback was developed. The method included real-time registration of the laser workspace on the live stereoscopic view, enabling accurate registration of laser incision plans with a maximum error of 0.2 mm (Schoob et al., 2016).

Tissue surface information was also used to produce a synthetic laser view, which was exploited in the implementation of assistive and automatic laser focusing methods (Schoob et al., 2015). This included an intuitive framework for interactive laser focus positioning, which used color-coded image overlays to highlight regions in the surgical site under proper laser focusing (Schoob et al., 2016b). The system was shown to allow manual positioning of the laser focal plane on the target tissue with an accuracy of 0.4 mm within seconds.

Research beyond the end of µRALP continued the development and enhancement of these assistive systems for endoscopic laser surgey, introducing extensions able to compensate for tissue motion and tracking inaccuracies such as inconsistent feature matching and drift. The enhanced framework proved to be suitable for online ablation control in laser microsurgery, enabling accurate execution of laser incision paths defined by the surgeon even in the presence of tissue motions and deformations (Schoob et al., 2017). The system demonstrated real-time operation and highly accurate soft tissue tracking performance, providing tracking errors below 0.05 mm and path ablations with RMS error below 0.21 mm in dynamic conditions. Subsequently, it was also integrated into the controller of a new robotic endoscope for non-contact endolaryngeal laser surgery, enabling both assistive and autonomous laser focus adjustments (Kundrat et al., 2020).

3.6 Cognitive surgical systems

The development of cognitive systems within µRALP aimed at providing safety supervision and autonomous operations to further improve the safety, quality, and precision of laser microsurgeries. This led to research towards the modeling and control of laser-tissue interactions, which are critically important in delicate tissue sparing operations such as laser phonomicrosurgery. In fact, after the complete eradication of malignancies, a secondary major clinical goal in this case is the preservation of healthy tissue to maintain key larynx functionalities and enable good post-treatment vocal quality.

From a research and technology development perspective, this clinical requirement translates into the need to perform precise and clean laser cuts on the soft laryngeal tissue, avoiding carbonizations and thermal damage to surrounding healthy tissue. In addition, the depth of laser ablations should be properly controlled, to avoid damaging underlying tissue layers.

Satisfying these needs requires controlling the laser-tissue interaction process. This was pursued within µRALP not only through laser focus control and laser scanning capabilities as discussed above, but also through the development of cognitive systems to model and control the laser-tissue interactions in real-time. Initially, tissue temperature dynamics under high-power laser irradiation was studied and reliably modeled using nonlinear regression based on Gaussian basis functions (Pardo et al., 2015). This knowledge was then used to generate real-time estimates of the thermal state of soft tissues during laser ablation, proving the approach was suitable to produce feedback for automatic laser incision control (Pardo et al. 2014).

Subsequent research focused on the modeling, online estimation and automatic control of the laser incision depth in soft tissues. This resulted in the development of a model able to estimate, in real-time, the depth of laser ablations with RMS error of 0.1 mm for depths ranging up to 1.4 mm (Fichera et al., 2015). This model was then used in a robotic laser microsurgery system to enable both autonomous laser incision depth control along cutting trajectories and autonomous ablation of tissue volumes (Fichera et al., 2015b). Finally, these controllers were extended to allow regulating the laser energy density along the incision path, demonstrating that target depths could be achieved within ±60 µm error range (Acemoglu et al., 2017).

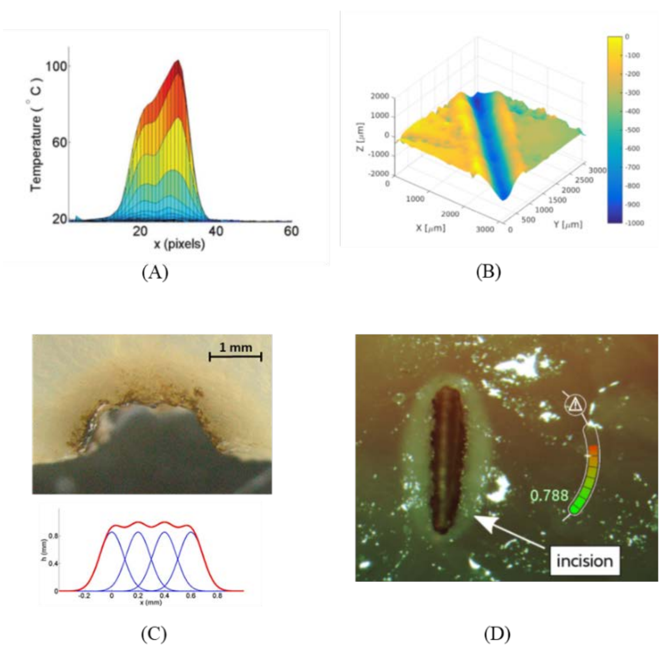


Fig. 18. Results from research on cognitive modeling and control of laser-tissue interactions. (A) Real-time estimate of superficial tissue temperature during high-power laser scanning. (B) Autonomous laser incision depth control along incision paths. (C) Autonomous tissue volume vaporization by laser ablation. (D) Augmented reality gauge for displaying the laser incision depth progression in real-time.

The developed laser-tissue interaction models and controllers were also integrated into µRALP interface to provide assistive functions during surgery. For instance, methods to provide real-time feedback on the laser incision depth to the surgeon were researched. These included the use of an augmented reality gauge to display the incision depth progression (Fichera et al., 2015), and of kinesthetic and vibrotactile haptic feedback to inform the user when a target depth was reached (Fichera et al., 2016). Both systems were shown to significantly enhance the laser incision depth control capabilities of the users during preliminary trials.

3.7 µRALP system integration and cadaver trials

After 3 years of intense research work, the µRALP project concluded with the complete integration of the surgical system and tests in human cadavers. The final system consisted of two main parts: The µRALP endoscope and the µRALP teleoperation interface, as depicted in Fig. 19. The cadaver experiments were instrumental for obtaining performance metrics regarding the complete system and all of its sub-components in a realistic surgical scenario. This experience highlighted the benefits of an integrated solution for robot-assisted endoscopic laser microsurgery, with each system component contributing to enhance surgical precision and quality. It also allowed the acquisition of important clinical feedback, which guided the research and development of the technologies beyond the end of the project as detailed above.

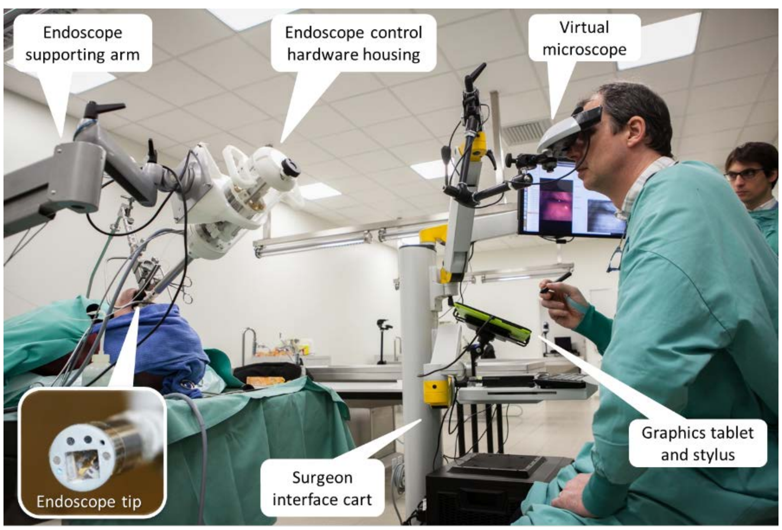


Fig. 19. The integrated µRALP surgical system prototype under evaluation in a human cadaver.

4 Conclusion

This paper reviewed the technological advancements and scientific contributions achieved within and beyond µRALP, a collaborative European project that aimed at bringing unprecedented levels of accessibility, precision and quality to endoscopic laser microsurgeries. The range of technologies developed to achieve these goals included flexible robotic endoscopes, micro-mechatronic robotic systems for laser steering, cancer tissue visualization systems, surgeon-robot interfaces, stereoscopic methods for enhanced teleoperation and automatic control, and cognitive surgical systems. Individually, each of these technologies proved to bring incremental levels of improvement towards the project goals. However, major impact is expected to come from their full integration into a complete clinical surgical robotic system, as preliminarily experienced during cadaver trials with the final µRALP prototype.

Specifically, the research contributions reviewed in this paper were shown to allow significant advances in:

- Medical continuum robot design, with the introduction of novel concepts for patient-friendly and surgeon-acceptable continuum robots with large central lumen and adjustable length.
- Medical micro-mechanisms, with new methodology for designing out-of-plane micro-fabricated mechanisms with high range of motion, and novel devices for high power laser focusing and steering.
- Surgeon-robot interfaces, with novel methods for intuitive robot control, intraoperative planning, and automatic operations leading to sizable improvements in the precision and safety in laser microsurgeries.
- Three-dimensional vision and control, with novel solutions for 3D reconstruction of the surgical scene allowing large improvements in surgical robot control, intraoperative planning and in the quality of laser incisions through adaptable laser focusing.
- Cancer tissue visualization, with a new approach for fiber-based endoscopic hyperspectral imaging and image processing methods for the automatic detection and classification of laryngeal tumors.
- Cognitive surgical system, with new methods for the modeling and control of laser-tissue interactions enabling autonomous depth control during incisions and volume ablations.

At this current point in time, research continues towards improving the TRL of endoscopic laser microsurgery technologies created within and beyond µRALP. This includes further miniaturization of the robotic devices to expand their clinical indications, and the elimination of system limitations such as the lack of endoscopic tissue manipulation capabilities during laser ablation. Nonetheless, it is clear that the technologies reviewed in this paper have the potential to bring many benefits to patients, surgeons, hospitals, and the public healthcare system in general. For example, once they reach clinical use, more patients will qualify for transoral laser microsurgeries and benefit from enhanced surgical precision and quality compared to the current state of the art. Surgeons will benefit from a more intuitive surgical setup and from robotic assistance, which will enable them to better plan and execute delicate interventions. Finally, hospitals will see less complications and revision surgeries, increasing customer satisfaction and, at the same time, contributing to lower healthcare costs.

It is also clear that the new knowledge and the new technologies described herein are applicable to a wide range of microsurgery interventions, both laser and otherwise. This expands the impact of the reviewed research beyond the specific application in robot-assisted endoscopic laser microsurgery.

5 Data Availability Statement

The laryngeal images dataset used for the development and assessment of cancer detection methods can be found in Zenodo [https://zenodo.org/record/1003200#.X6LLjVNKhTY].

6 Author Contributions

The Author Contributions section is mandatory for all articles, including articles by sole authors. If an appropriate statement is not provided on submission, a standard one will be inserted during the production process. The Author Contributions statement must describe the contributions of individual authors referred to by their initials and, in doing so, all authors agree to be accountable for the content of the work. Please see here for full authorship criteria.

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8 Supplementary Material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/...

μRALP video

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10 Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.