

Scoping Document

Introduction

A critically ill patient is admitted with acute respiratory distress. Examination reviews a critically narrowed subglottic airway (section of the throat below the vocal cords) consistent with laryngeal stenosis, as shown in Figure 1 (tightening of the voice box). Standard procedures would require a tracheostomy, creating an opening in the airway to place a breathing tube (Figure 1), and can take years for endoscopic or reconstructive procedures to widen the airway (Holinger 1982). While lifesaving, endoscopic procedures require repeated visits to the hospital and invasive reconstructive procedures with long postoperative care (Maresh et al. 2014).

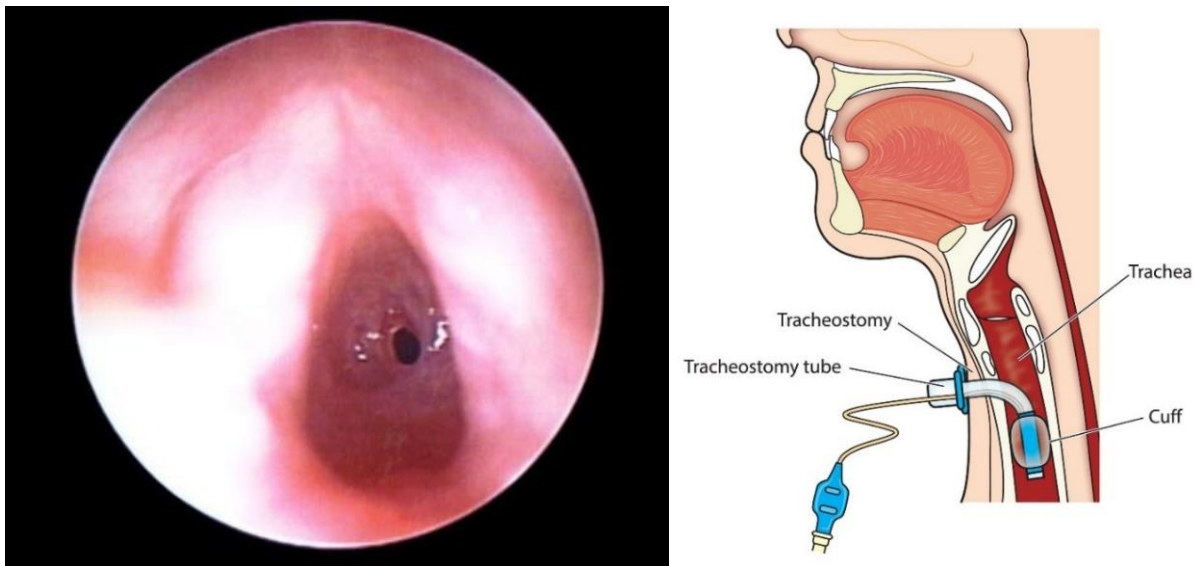


Figure 1: Left: View of a 4-month-old infant with grade 3 subglottic stenosis (Subglottic Stenosis in Children 2025)

Right: Diagram of tracheostomy. ("Tracheotomy | Definition & Facts | Britannica," n.d.)

However, the introduction of CO₂ lasers has proven to be an effective way to treat laryngeal stenosis without the need for a tracheostomy (Duncavage et al. 1985; Holinger 1982). CO₂ lasers enable the physician to create precise incisions with minimal damage to surrounding tissues. Beyond treating stenosis, CO₂ lasers have been applied to remove laryngeal tumors (Niemz 2019), avoiding the need for open partial laryngectomy, a procedure that opens the larynx to remove the tumor. The success of CO₂ lasers in such challenging laryngeal cases stems from a unique set of properties that offer distinct advantages over traditional surgical procedures.

Introduction to Laser Surgery

Fundamentals of Surgical Lasers

A laser's surgical effectiveness is dictated by its specific physical properties. While the CO₂ laser excels in laryngeal surgery, it is just one of several classes of medical lasers with surgical applications. CO₂ lasers are effective for precise tissue vaporization. Others, such as Argon lasers, are effective for coagulation (heating tissue to seal blood vessels), while KTP lasers (potassium titanyl phosphate) are versatile and have varied purposes (Azadgoli and Baker 2016). Each of these lasers emits electromagnetic radiation, imparting thermal, non-ionizing energy. As the electromagnetic radiation is absorbed, this energy is converted into heat that can cut tissue, ablate surfaces (remove matter), or cauterize blood vessels.

Each class of laser has its own unique uses. Vaporizing lasers, such as CO₂ lasers, have a high extinction coefficient in water (how strongly they absorb the laser), resulting in a decrease in intensity with depth. In surgery, this limits the penetration of soft tissue and minimizes thermal damage (Rubinstein & Armstrong, 2010). Meanwhile, KTP lasers use a particular wavelength and are strongly absorbed by hemoglobin and melanin (Keller, 1992). This makes KTP lasers useful for ablating both soft and hard tissues while being focused specifically on the target tissue, keeping the surrounding tissue largely unaffected (Lee et al. 2022). This is particularly utilized for ear surgeries (Lee et al., 2022). Argon lasers are effective for coagulating blood-rich tissues because their wavelength is well-absorbed by such tissue. However, they tend to produce radial tissue damage, which limits their use in delicate areas (Nanni, 1997). While each type of laser has its own niche, CO₂ lasers are often the ideal option for sensitive areas, as seen in laryngeal surgery.

The effectiveness of a given laser type is also dependent on how the laser beam is delivered. There are three primary forms of laser delivery: articulated arms, fiber optics, and free beam. Examples of two of these delivery methods are shown in Figure 2. Articulated arms consist of a series of mirrors mounted on rotating holders, enabling high adaptability to various environments. However, they can easily be misaligned, resulting in unwanted effects on the tissue (Verdaasdonk & Swol, 1997). Optical fibers offer a physically flexible delivery system, providing better access to hard-to-reach tissue with minimal invasiveness (Burgess et al., 2010). However, the laser beam will immediately diverge upon exiting the fiber optic, limiting the control of the spot size (diameter of the beam at the focal point) of the laser (Lee et al. 2022). In most clinical applications, fibers are typically steered manually through endoscopes or rigid scopes but have historically suffered from lower accuracy compared to free beams. This makes them well-suited for minimally invasive procedures where precision is less critical. Free beam delivery, by contrast, utilizes micromanipulators to align optical fibers with precision. However, most free-beam systems also require a direct line of sight to the target tissue, restricting the applicability of minimally invasive surgeries. A study comparing fiber optics and free beam

delivery found that the mean operating time for free beam laser delivery is longer than that for fiber optics, with no statistically significant differences in the outcomes (Chang et al., 2017).

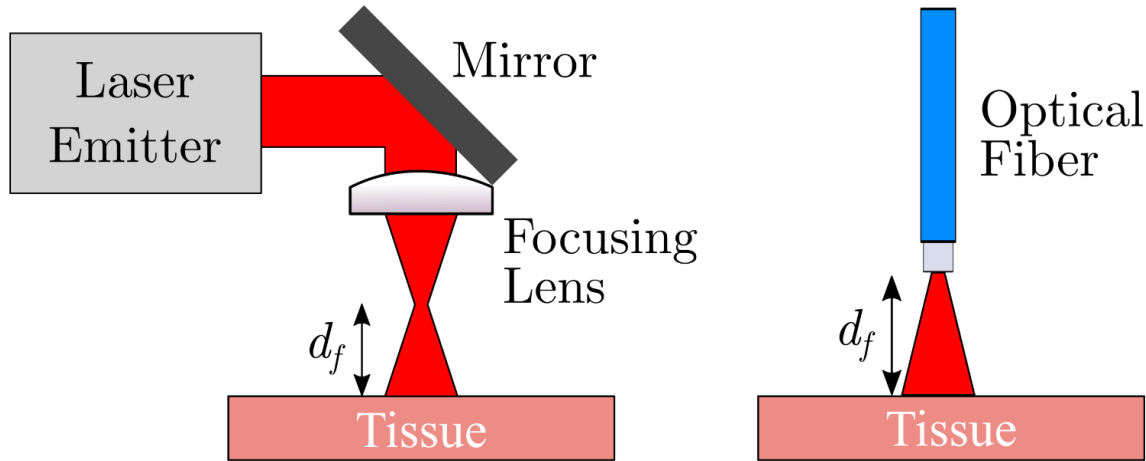


Figure 2: Different delivery methods. Free beam laser (left) and fiber optic (right) (Pacheco et al. 2023)

The tradeoffs between laser types and delivery systems are crucial, as they can all influence surgical accuracy, efficiency, and patient outcomes. To conduct an operation using laser technology, the proper combination of laser type and delivery method must be selected beforehand. The numerous combinations of these aspects of laser surgery devices, along with their associated advantages and disadvantages, enable lasers to be utilized in a wide range of procedures across various surgical fields.

Advantages and Applications of Surgical Lasers

Surgical lasers possess a number of advantages over conventional techniques, stemming from their unique physical properties discussed above. These advantages have made lasers increasingly valuable across multiple surgical specialties. Advantages include high precision, controlled ablation depth, reduced bleeding, minimal invasiveness, and reduced infection risk.

Lasers' fine spot size allows for "highly accurate targeting" of specific tissue, resulting in intricate procedures minimally impacting surrounding tissue in comparison to standard tools such as hand-operated scalpels (Kumar et al. 2024). This is especially beneficial in procedures affecting delicate parts of the body, such as the eyes, brain, or near-critical nerves, which are common targets for laser surgery procedures (Kumar et al., 2024). For example, CO₂ lasers used in delicate laryngeal and oral surgeries need high accuracy to avoid extraneous tissue damage of the laryngeal folds and vocal cords (Rubinstein and Armstrong 2011). The spot-size accuracy of lasers in general, combined with the high extinction coefficient of lasers such as CO₂ lasers, can significantly decrease excess tissue damage during a procedure (Rubinstein and Armstrong 2011).

Lasers can also provide simultaneous cutting and coagulation to limit bleeding. The heat from the laser energy can coagulate blood vessels while cutting the tissue, which cauterizes the

wounds during the surgical process (Kumar et al. 2024). This is particularly vital for treating patients with bleeding disorders or those receiving anticoagulants (blood thinners) (Khalkhal et al., 2019). An example of this coagulation is shown in Figure 3. The coagulating effects combined with the accuracy of laser technology make lasers far safer for operating in areas with highly vascularized tissue (Nanni 1997). This property is especially present in Argon lasers, as described earlier, as they are used in procedures on blood-rich tissue, such as vascular lesions, where coagulating any excess blood can make a significant difference in the blood loss for a patient (Nanni 1997).

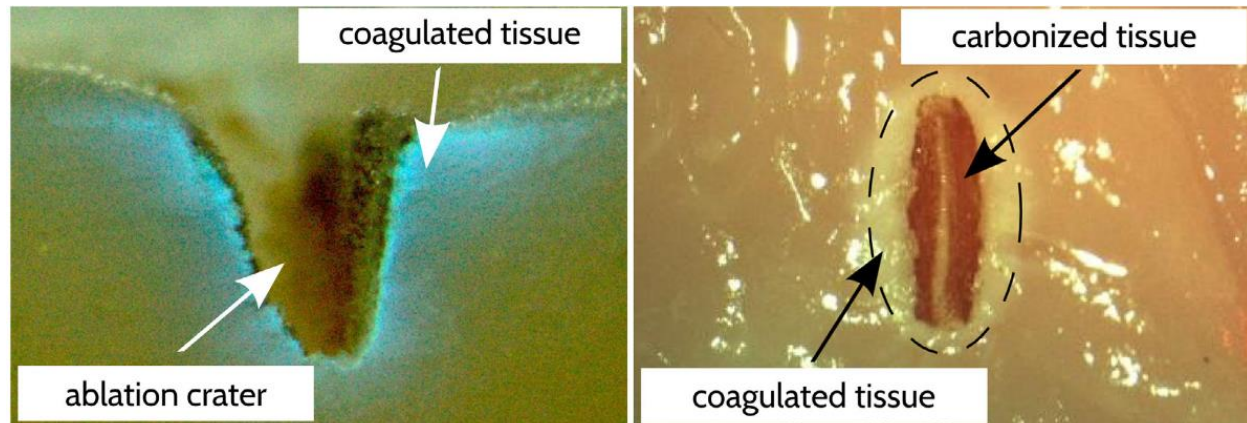


Figure 3: Ablation of tissue using laser. (Lee et al. 2022)

Laser procedures are often less invasive than traditional surgical methods. With smaller operating spaces and minimal incisions, laser surgeries result in “less scarring and quicker healing times” for patients. The heat generated on the tissue also often sterilizes the treatment area, thereby lowering the risk of infection and complications for patients. These factors improve “surgical outcomes and patient satisfaction” throughout a wide range of procedures across medical fields that utilize laser technology (Kumar et al. 2024). In the case of laryngomicrosurgery, a common larynx operation, the laser-based operation requires no incisions. It allows the surgeon to guide the laser through the mouth and effectively vaporize abnormal tissues with higher performance and better outcomes than traditional methods (Zhang et al. 2015).

When paired with appropriate procedures, the advantages of laser technology in surgery translate to minimized post-operative pain, a quicker return to daily life, and fewer complications (Kumar et al. 2024; Khalkhal et al. 2019). These improvements make procedures safer, more predictable, and result in higher satisfaction. However, the specific applications of laser technology are not uniform across all contexts (Kumar et al. 2024). Understanding distinctions between laser systems is crucial for determining how lasers can be effectively applied across various surgical specialties. These specialties include fields such as fetoscopy, urology, laryngology, ophthalmology, otology, neurology, and others. (Lee et al. 2022; Shokrollahi et al. 2004). A longer list of fields and procedures is presented in Appendix A.

The chosen delivery method and laser class often determine the feasibility and safety of a laser for a given procedure. Specific procedures, such as many ENT procedures, are safer and less invasive, making them a better match for fiber-delivered lasers (Rubinstein and Armstrong 2011). Other procedures require finer precision, no matter how invasive, which align more with free-beam CO2 lasers. While the broad applicability of laser technologies to medical fields and numerous advantages allow their use for many surgical procedures, there are still limitations to physically manipulating lasers directly by hand.

Robot-Assisted Laser Surgery

Robot assistance for laser surgery can increase the accuracy and reliability of medical procedures when compared to traditional operations (Lee et al. 2022). Robot-assisted laser surgery can be divided into two primary strategies: fiber-based steering and free-beam control (Lee et al. 2022). These two approaches offer distinct methods for delivering and manipulating the laser during a procedure, each with its own advantages and limitations.

Fiber-based robotic steering utilizes the flexibility of optical fibers to be routed through narrow, curved paths within the body, providing access to deep or hard-to-reach anatomical areas (Lee et al 2022). This approach is well-suited for minimally invasive surgery that requires navigation through natural orifices, such as endoscopic laryngeal surgery. Robotic steering mechanisms will physically bend the optical fiber tip using mechanisms such as tendon-driven, magnetic, piezoelectric, or fluidic steering to aim the beam. Each mechanism presents distinct advantages in areas such as speed and range, while also having inherent limitations and risks. Despite these advantages, physically bending fiber is inherently slower compared to a free beam using optical mirrors. As a result, fiber-based steering is poorly suited for high-speed laser scanning, where free-beam optical mirrors can be easily achieved.

Free-beam robotic systems manipulate a fixed laser source by steering optical mirrors or lenses via micromanipulators (Lee et al. 2022). Most robotics free-beam systems utilize piezoelectric actuators because of their fast response times and sub-micrometer resolution, making them ideal for laser scanning.

Visualization

The field of robot-assisted laser surgery encompasses a wide range of visualization methods designed to enhance a surgeon's ability to operate effectively. These technologies move beyond limitations of direct line-of-sight surgical control, and offer enhanced detail, improved ergonomics, and integrate critical data into the surgeon's field of view (Qian et al. 2020). These technologies often fall under the broad categories of stereoscopic (3D) vision and two-dimensional vision (Azizian et al. 2018).

3D surgical visualization is the dominant category of visualization in modern robotic surgery. This is mainly because 3D visualization closely mimics standard human vision with natural depth perception (Cepolina and Razzoli 2022). This 3D view is often provided by using a

device with two separate camera lenses to capture an image of the target tissue. Then, these video feeds are separately displayed to each eye. For example, an endoscope equipped with a fiber-delivered laser may also feature two camera lenses at its tip. The surgeon uses a headset during surgery, as shown in Figure 6. Due to the separation of the video feeds, they appear as a single 3D view of the target tissue from within the headset, with proper depth perception (Azizian et al. 2018). Another prominent example of this technology is the Da Vinci surgical system, shown in Figure 4. While depth perception is the primary draw of this technology, it also improves ergonomics compared to traditional surgical methods. Rather than standing over the patient, surgeons are seated at a console, typically with their head resting against the viewing headset, with their arms supported. This reduces physical strain and allows the surgeon to view the target tissue for longer with minimal stress (Cepolina and Razzoli 2022). It also allows for a magnified view of the target tissue, improving visibility past what is possible with the naked eye. These benefits generally improve patient outcomes and reduce procedure lengths (Kang et al. 2021; Velayutham et al. 2016).



Figure 4: Da Vinci Surgical System (Www.Army.Mil 2015)

While 3D visualization is often the predominant technology in modern surgery, 2D surgical visualization remains common and has distinct use cases. 2D visualization often follows a similar approach to 3D visualization, with minor changes. Rather than using two separate video feeds, the 2D approach captures a single video feed, which is projected onto a standard flat-panel screen in the operating room (Fergo et al. 2017). For example, non-robotic laparoscopy often uses 2D rather than 3D visualization (Köckerling 2014). Examples of the surgical operating space are shown in Figure 8, with B displaying a standard 2D monitor view. While 2D

visualization does not provide the depth perception of three dimensions, the operating space can be displayed on simpler equipment and at a much higher resolution (Harada et al. 2018). Alternatively, a 2D system can mimic a more complex 3D system by displaying two video feeds overlaid, as shown in example A in Figure 5. When the surgeon wears proper polarized eyewear, the resulting view provides depth perception similar to that of a full 3D headset (Harada et al. 2018). Both systems provide a magnified view of the target tissue and enable the entire operating room to observe it. Other critical information can also be easily overlaid on the same screen as the surgical view for ease of information access, and with a touchscreen device, the display can be interacted with directly (Fergo et al. 2017).

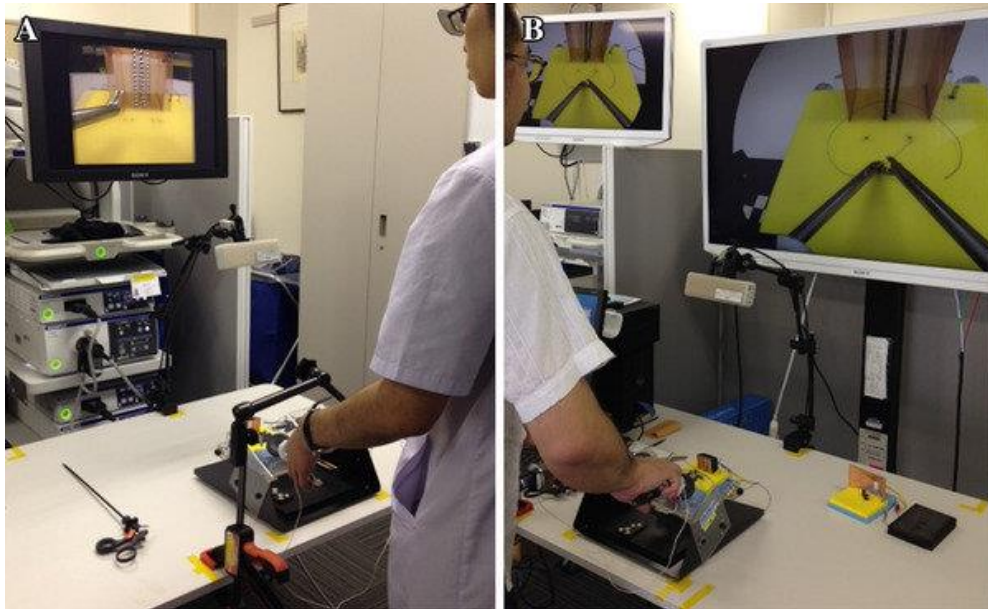


Figure 5: A: 2D/HD and 3D/HD laparoscope system. B: 2D/4K laparoscope system (Harada et al. 2018)

The chosen visualization strategy for a given procedure depends heavily on the specific needs of that operation. A 3D view is highly beneficial for complex, dexterous manipulation that may require long operation times. However, a 2D visualization can present the operating space as a more graphical workspace, while also dramatically simplifying the layout of operating room equipment. When attempting to pre-plan paths, adjust parameters, or target specific coordinates, the direct interaction with the video feed allowed in a 2D interface offers a potentially more direct and less complex alternative to 3D robotic visualization.

Control Methods

Corresponding to these varied visualization strategies for robotic surgery are several robotic control systems. These control systems typically aim to allow for complex movements that would be difficult or impossible to perform without robotic assistance, each with its own specific benefits. Typically, robotic systems for laser surgery are controlled using telemanipulators, sometimes combined with concepts of shared or supervisory control.

Telemanipulators are one of the most common surgical systems used for current robotic surgery practices (Nguyen et al. 2023). There are a variety of different telemanipulator systems used for robotic laser surgery (Dagnino et al. 2011). Examples include master-slave systems, such as the Da Vinci surgical system, flight-simulator-style joysticks, standard controller joysticks, and stylus-tablet systems. These systems typically involve a surgeon-operated controller and either a single or multiple robotic arms that execute movements based on the controller's instructions. Telemanipulator systems typically do not involve any direct computer assistance, as surgeons themselves directly control all movement. Instead, the input is typically translated, scaled, and tremor-filtered before the surgical apparatus carries out the provided movements, allowing the systems to increase precision significantly (Low and Phee 2006). These systems also allow for significant ergonomic improvements, as the controllers can be more ergonomic than a more traditional surgical apparatus due to the separation of the controller and surgical element (Low and Phee 2006).

While many different types of telemanipulators are used, certain ones provide far more precision and reliability than others (Dagnino et al. 2011). The Da Vinci surgical system is often an example of a precise and effective telemanipulator for controlling surgical robotics (Low and Phee 2006). In some cases, systems like the Da Vinci robot are used to grasp laser fibers to perform a surgical operation (Dagnino et al. 2011). However, for laser surgeries, different telemanipulator technologies are more common, where the control method is more directly suited to the task (Dagnino et al. 2011). Some of the predominant methods include controller thumbsticks, stylus-tablet interfaces, haptic styluses, and flight sticks. While each of these is capable of reasonably precise surgical maneuvers, they are not all created equal. As shown in Figure 6, stylus-based control methods are frequently more precise and effective for laser surgery in comparison to joystick-based methods, as they have the least error.

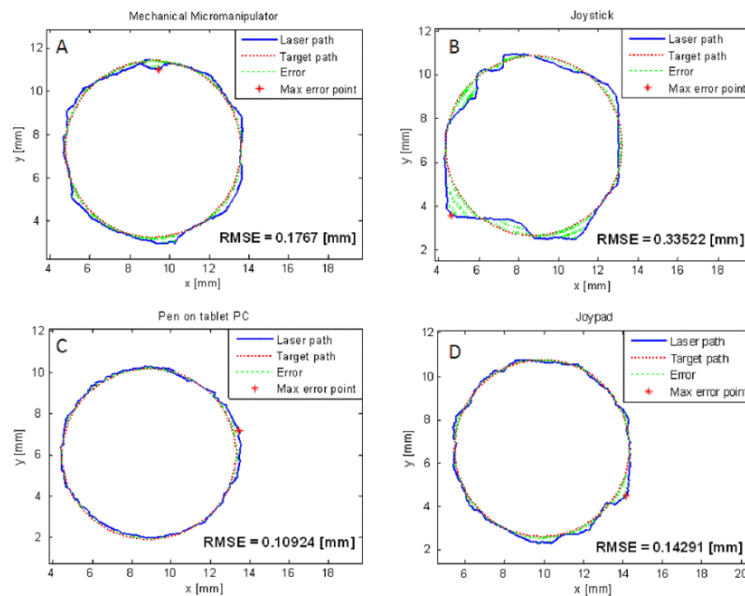


Figure 6: Laser path over target path for different control devices (Dagnino et al. 2011)

Stylus-based devices generally fall into two main categories. They are typically touchscreen styluses, commonly used on tablets and similar devices, or haptic styluses. Haptic styluses are free-floating devices connected to a robotic arm. When you move the stylus, the position information is sent to the surgical robot. The robot arm provides resistance and force-feedback, while also providing the same smoothing and position processing as a Da Vinci robot (Olivieri et al. 2018). This allows for precise 3D movement. An example of one of these devices is shown in Figure 7. Both standard and haptic stylus devices offer a familiar interface that significantly improves dexterity and precision. Stylus-tablet systems specifically were found to be the preferred control method for surgery like phonomicrosurgery due to their ergonomics, ease of use, and the overall safety and surgeon comfort during the operation (Dagnino et al. 2011). This makes the stylus-tablet interface an ideal choice for controlling laser positioning during a surgical procedure, at least for free-beam lasers.

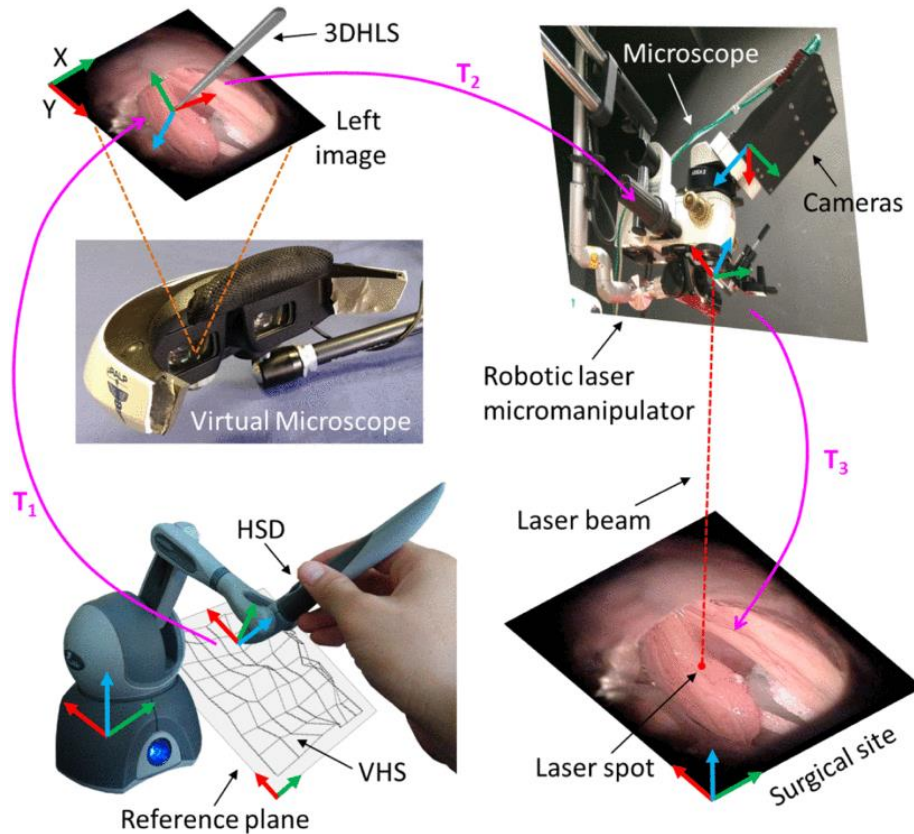


Figure 7: MicroRALP Haptic Control and Stereoscopic View (Olivieri et al. 2018)

Even with an intuitive, accurate user interface for the control system, there must be a corresponding system that accurately translates the operator's inputs into the precise movements required for a surgical operation. Multiple technologies can be used for this purpose, examples of which are shown in Figure 8. Standard motors are a common

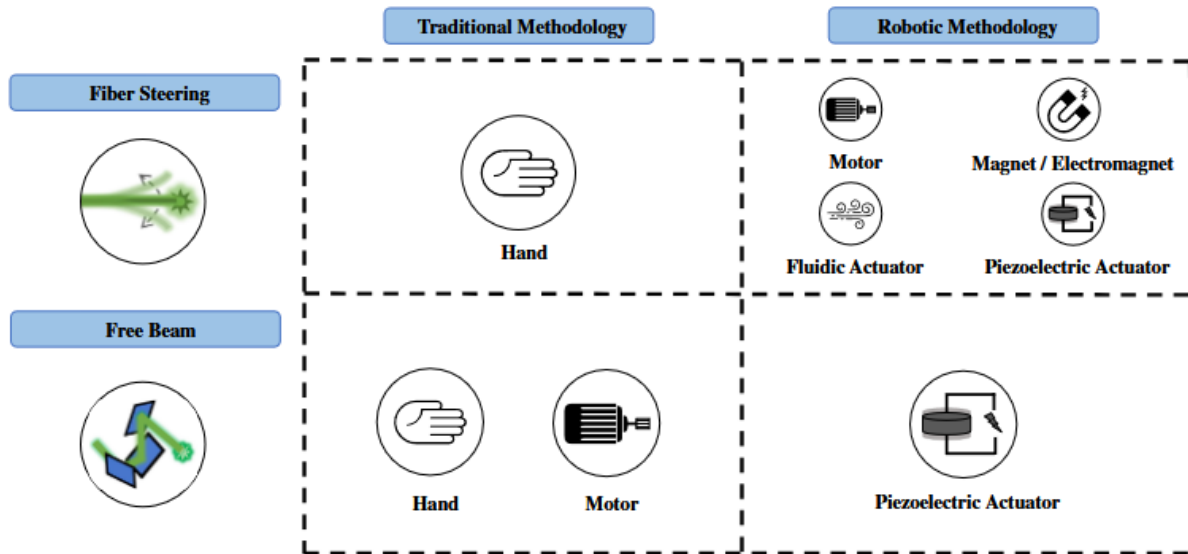


Figure 8: Actuation technologies for laser steering (Lee et al. 2022)

approach to steering the robot-controller laser. Motors will aim the end-effector (in this case the laser) in the location described by the input from the surgeon (Lee et al. 2022). While this can be quite accurate, the speed of laser steering is often low when motors are involved (Lee et al. 2022). The main alternative approach for free-beam laser control is using piezoelectric actuators, which are actuators that react to electric voltages and physically move and change shape, allowing for extremely fine and controllable movements on a nanometer level (Lee et al. 2022). Improved control systems, such as motors or piezoelectric actuators, significantly improve the accuracy of laser operations, but they do not eliminate all difficulties.

Challenges in Laser Surgery

The complex nature of controlling lasers, combined with their inherent dangers, presents several potential challenges and complications. Lasers can cause potential scarring, pigmentation changes, thermal damage, and more. In a study analyzing complications of laser dermatologic surgery, one patient undergoing treatment for a port wine stain developed tissue graying in the treatment area (Willey et al., 2006). This was caused by thermal injury from the high fluence required for photocoagulation (cauterization of blood vessels). Similarly, another patient got blisters and crusting complications that healed with hypopigmentation (lighter patches of skin) that were caused by deep thermal injury from high fluence. A different patient suffered from scarring because of aggressive ablation. This was caused by a lack of attention to any non-healing areas. Of the nineteen cases of skin injury, twelve were caused by multiple passes of the laser, excessive fluence, or inadequate attention to detail. These causes would have been preventable if the laser had been operated more carefully.

The technical demands of operating a laser contribute to high learning curves and operator fatigue. For example, in Small Incision Lenticule Extraction (SMILE), there is a steep

learning curve for inexperienced surgeons. In their first 100 surgeries, they had lower efficacy and safety indices and longer suction engagement duration than in their subsequent 100 surgeries (Zhang et al., 2023). A separate study analyzed the time it takes physicians to learn to perform laser coagulation and found a correlation between increasing operator experience and improved survival rates. It was also found that operators required between 26 and 35 procedures to reach an adequate level of performance; however, there was variance in the time each operator took to learn and their level of expertise (Suzanne et al., 2014). Laser surgery requires working in static positions with repetitive motions, which can increase the risk of musculoskeletal injury. This can lead to operator fatigue, making it more challenging for surgeons to successfully treat patients (Yale et al., 2024). Robot-assisted laser surgery has been proposed as a solution to overcome these limitations, offering enhanced dexterity, stable beam delivery, and reduced operator fatigue.

Scenario

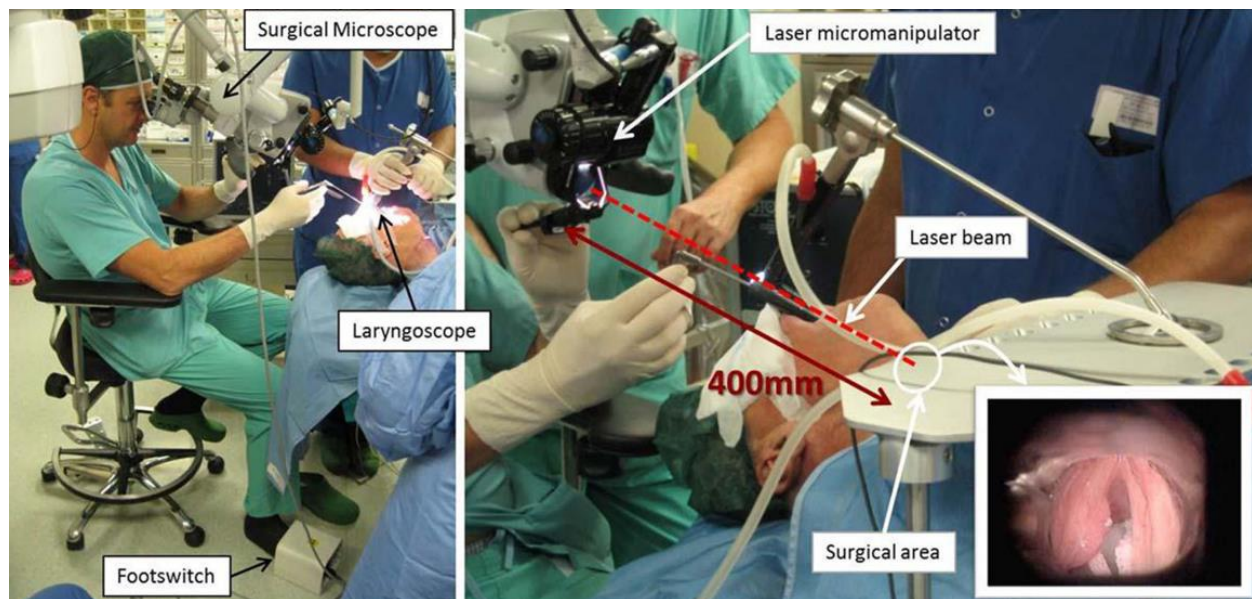


Figure 9: Transoral laser microsurgery surgical setup(Lee et al. 2022)

An example of a challenging laser procedure is transoral laser microsurgery (TLM). TLM is a procedure that removes vocal-fold lesions (Figure 10) requiring a surgeon, scrub tech, assistant, and anesthesiologist. After anesthesia and intubation, a rigid Zeitel's laryngoscope (Figure 11) is secured to the patient's bed to maintain exposure and free the surgeon's hands. The laryngoscope is fixed to the bed, freeing an additional hand for the team. The CO₂ Micromanipulator includes a microscope for viewing the larynx (which requires a direct line of sight) and a joystick to control the laser position. The surgeon steers the laser with their left hand and physically manipulates the tissue with a suction tube using their right hand. The scrub tech

then sets the necessary laser parameters (e.g., power, scan pattern, offset). The surgeon controls laser activation and beam focus via a foot pedal and a knob, respectively.

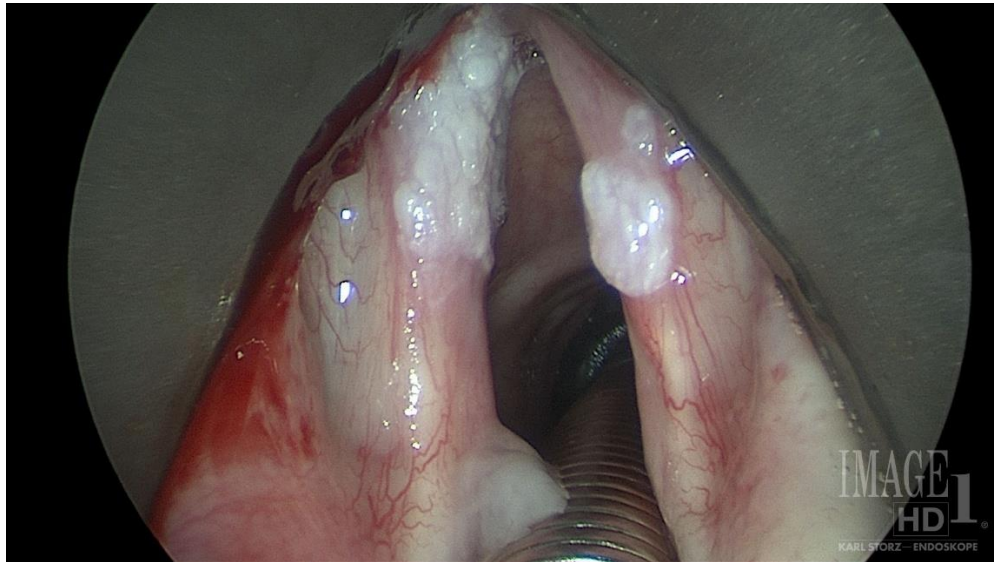


Figure 10: Endoscopic view of the larynx with multiple white lesions (Dr. Carroll, 2025)

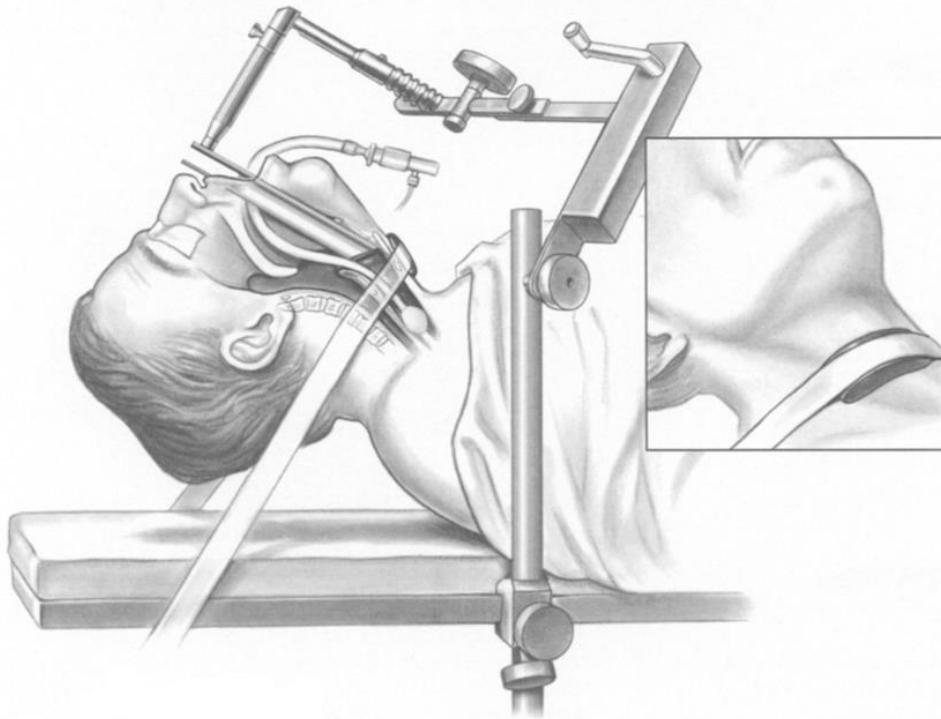


Figure 11: Zeitel's laryngoscope to create a direct path to the larynx (Hochman et al. 1998)

Compared with conventional surgical methods, the laser method yielded clean, flat vocal cord edges due to its precise cutting (Zhang et al. 2015). There was no measured bleeding at the surgical site, and the wound edges were more precise. In contrast, the conventional method

resulted in slight bleeding and less precise results, and posed spatial challenges when attempting to guide the equipment to the target tissue.

However, TLM requires a direct line-of-sight to the tissue. The anatomy of the larynx can vary significantly depending on age, sex, lifestyle habits, and other factors (Riede et al. 2023). In patients with a large tongue and/or a small jaw with teeth, achieving direct line-of-sight to the lesion can be extremely difficult. The surgeon may reposition the laryngoscope to apply greater tongue to view the lesion, which can increase postoperative discomfort.

Even with visualization of the lesion, in TLM (11), the surgeon operates under significant ergonomic and perception constraints (Lee et al. 2022). Visualization of the surgical site is via a surgical microscope, with the operator 400 mm away. The laryngoscope or suction tube is held in the right hand to maintain access to or manipulate the tissue, while the left hand (often the non-dominant hand) is used to manipulate a joystick to control the laser position and a pedal for activation (Lee et al. 2022; Rubinstein and Armstrong 2011). Although the system can perform laser scanning, it still requires the surgeon to manually place the pattern using a joystick. In a comparative study evaluating different input modalities (e.g., joysticks, gamepad controllers, mechanical micromanipulators, or a stylus), the joystick control with a microscope resulted in an average max RMSE of 0.8322 ± 0.3374 mm (Dagnino et al. 2011).

During TLM, the surgeon may need to trace a linear path along the vocal folds. Due to the complex geometry of the larynx, the working distance between the micromanipulator and the tissue can vary, thereby shifting the laser spot size. The laser will lose focus, resulting in decreased cutting efficiency and increased thermal spread. The physician must periodically refocus the laser to maintain a narrow spot size to ablate tissue along the line. These demands accumulate for less experienced surgeons, increasing the risk of error. Inappropriate laser power can increase the danger of endotracheal tube ignition. Poor ergonomics can further exacerbate fatigue and increase the likelihood of errors. Additionally, the surgeon must maintain a constant focus to avoid contact burns to the lip and nose, which adds an extra cognitive load throughout the procedure.

Existing Systems

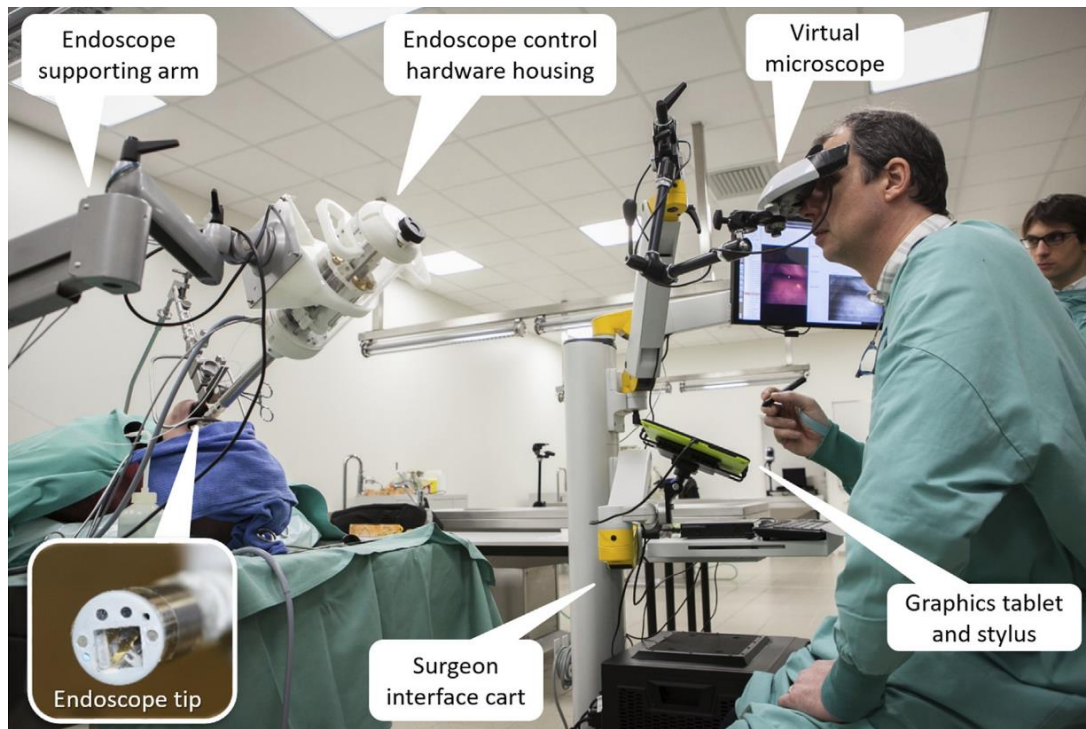


Figure 12: MicroRALP Surgical Setup (Mattos et al. 2021)

Given gaps in perception, control, and ergonomics in TLM, systems have been developed to improve ease of use for physicians. For example, the μ RALP (Mattos et al. 2021) was developed in response as a free-beam robotics system for TLM. Unlike traditional free-beam operations, the laser was delivered through an optical fiber and redirected and manipulated through a lens and mirror, respectively, at the tip of the endoscope (Rabenorosa et al. 2015). Additionally, their robotic endoscope featured dual high-speed cameras, providing a stereoscopic view of the surgical site (Mattos et al. 2021). Lastly, rather than relying on a joystick to position the laser, the system utilizes a tablet pen interface, allowing surgeons to draw directly on the surgical sight. This reduced the technical skill required for the operation and significantly improved visualization.

Another surgical system, the Computer-Assisted Laser Microsurgery (CALM), was developed to address control and ergonomic issues in TLM (Lee et al. 2020). This system addressed those issues by utilizing a stylus-based user interface for laser control and a real-time intraoperative planning tool to enhance performance. This reduced the impact tremors had on tool handling and simplified the user interface. When creating circular cutting patterns, this form of control had a root-mean-squared error that was 55-62% less than GSTA (generalized super-twisting algorithm) control and 27-40% less than TDC (Time Delay Control). CALM also had a

substantial decrease in peak errors compared to GSTA and TDC. However, CALM still had errors, primarily due to discontinuous friction effects, such as sliding and stiction.

Since the shape and small size of the larynx provide a significant obstacle to physicians during TLM, robotic microsurgical forceps were developed (Chauhan et al. 2019). This is a robotic system featuring motorized forceps integrated into a robotic manipulator. It also features a force sensor to measure the tissue gripping force. When surgeons used this device, they reported improved access to the larynx and found the gripping force feedback useful. The tracking motion error was less than 400 μm . This device improved the ergonomics of TLM surgeries while enhancing the procedure's reachability and accuracy.

Stakeholder Analysis

A literature review and interviews with [surgeons] revealed a few key improvements that stakeholders find valuable. Some of the areas our lab has identified as reasonable to explore are leveraging computer control of robotic systems to optimize performance and providing supplemental visualizations to improve the physician's situational awareness.

While surgeons already use microsurgery systems, their robotic nature is not fully utilized. Many systems mimic the surgeon's movements. This is useful in transferring surgical skills; however, it leaves powerful performance improvements unused. These performance improvements can be categorized into two areas: reducing human error and leveraging capabilities beyond human limits.

Human error in surgery can lead to adverse patient outcomes. While operations inherently carry risk, reducing this risk as much as possible is desirable for all parties. Human error during these operations can result from hand tremors, difficulties in learning control interfaces, human inaccuracies, reactions to unexpected events, and an inability to precisely understand current system dynamics.

Hand tremors during surgery are straightforward to understand and a common issue for microsurgery control systems to address. This is typically achieved through motion scaling or smoothing and is often one of the first issues addressed by more advanced systems, such as those beyond endoscopes. Some inaccuracy may not come from an unintended movement of the hand, but instead from an accident or inexperience. Bumping or moving the laser to an unintended region can be an issue regardless of the cause.

Events that occur during laring may also lead to human error, even if unintentional. Stakeholder interviews revealed that patients may move slightly during procedures, which can be problematic if the vocal folds twitch while a laser is firing. Another common situation is particulate matter obscuring vision during a procedure, necessitating a wait until the obstruction clears. Human reaction time may not be fast enough to catch these events in time to respond

safely. However, a computer may be able to intervene fast enough to prevent unintentional damage in the case of patient or workspace movement.

Lastly, there are some physical properties of laser dynamics that physicians traditionally must learn rather than perceive. These can relate to cutting depth, focal distance relative to the target, and tissue surface temperatures. Physicians must learn, through training and experience, how their tools and work surface interact, which is less than ideal. They must pause as needed during surgery to ensure the tissue is cut to the correct depth, maintain a temperature below an acceptable threshold, and adjust the laser focal length to keep the tool effective. All issues can be avoided by providing the operating physician with more information about their workspace or by improving the automation of their equipment.

Scope of Work

How can combinations of visual feedback (e.g., thermal overlays, 3D views) and control paradigms (manual tablet input vs. pre-planned trajectories) be designed to optimize performance while minimizing procedural complexity in robot-assisted transoral microsurgery?

We propose creating a tablet-stylus interface for robotic TLM to enhance situational awareness, improve control, enhance safety, and reduce the surgeon's cognitive load. The interface will display and be organized around the 2D and 3D visualization of the tissue surface, serving as the primary stylus workspace. The stylus will be used to create real-time and pre-planned paths, automating laser focus. It can be projected across all views and function as a complementary frame of reference: the 3D model provides geometric reasoning for path design. At the same time, the 2D stream preserves tissue appearance and camera view. The interface will feature toggleable overlays, including beam position and size, planned paths in both 2D and 3D views, virtual fixture boundaries, tissue temperature, and a topographic view. By combining various visual feedback and stylus controls, the system aims to enhance situational awareness while reducing the cognitive burden on the surgeon.

Assumptions

Surgical robots such as the MicroRALP or laser endoscopes can maneuver or operate inside the body cavity, which is not possible with the size of Franka Panda arm and cameras. Since our goal is to improve the surgeon user interface using existing systems, we will make generalizations about the size and nature of the working environment. Specifically, we assume the robot and camera can fit into any workspace that uses the user interface.

Functional Requirements

Visualization of the Surgical Sight

The user interface centers on continuous visual feedback from an RGB-D camera, allowing surgeons to switch seamlessly between two complementary representations of the surgical site: a registered 3D surface render that shows depth and curvature, and a 2D view of the camera's native perspective. The two representations will be synchronized so that changes to the environment are reflected in both views.

The 3D view option will have fluid viewpoint manipulation to aid in creating laser trajectories and understanding the geometry of the target anatomy. Rotation, translation, and zoom are exposed through touch gestures on the tablet. Single-finger drags manipulate the view in the currently selected manipulation mode (rotation or translation), while two-finger pinching and spreading adjust the zoom. Mode switching between rotation and translation is used to avoid unexpected camera motion during planning. It is triggered either by a dedicated on-screen button or a double-tap gesture that alternates between rotation and translation. For users who prefer discrete controls, button-based inputs for rotation, translation, and zooming are available on either edge of the tablet screen. These controls include a "home" action at the center that restores to the default viewpoint. The 2D view option displays the live camera feed. It offers the same viewpoint controls (rotation, translation, and zoom) as the 3D view option—the consistency of controls between 2D and 3D aims to minimize the learning curve and reduce control errors.

To provide further visualization of the environment, additional overlays will be augmented with 2D and 3D views. An overlay of the predicted laser position and beam size will be displayed as a high-contrast marker and a circular halo around the marker. As the laser moves, the changes will be reflected continuously on both views. The physician may also change the marker and halo colors. The surgeon may also enable thermal surface information overlays on both views within virtual fixtures to reduce clutter and avoid obscuring anatomical details. Alternatively, the surgeon can place draggable "heat probe" nodes that reveal the local temperature at a point without changing the surface views. Lastly, depth mapping can be enabled and displayed as a colored topographic layer for both views. All overlays are independently toggleable from a control panel, with customizable opacity and colors per overlay.

Control Methods

The control design below enables surgeons to accurately mirror their intent through precise input devices (a stylus) and reviewable plans, thereby effectively predicting robot behavior. A stylus-first interaction model distinguishes deliberate actions from incidental touch.

To enforce spatial constraints on both the robot and the laser, the surgeon will create a virtual fixture before executing a trajectory, thereby reducing the risk of misfires. Virtual fixtures can be created directly in either the 2D or 3D view using predefined shapes (circles, rectangles,

and ovals) and freehand shapes. Each virtual fixture is projected across views and rendered with a high contrast dashed boundary and soft exterior masking to reduce clutter. Additionally, each virtual fixture can be selected from a control panel, independently toggled on or off, and assigned a distinct boundary color. For volumetric virtual fixtures, a plane-cut tool is used to define areas above or below the plane where the laser can operate, which is positioned using control arrows for both position and orientation. During laser execution, virtual fixtures are enforced to prevent laser firing and path generation outside them, minimizing misfires.

Procedural intent is captured as pre-planned trajectories from curves and shapes (lines, arcs, rectangles, and ovals) that can be edited through control handles (curvature, scale, and rotation). In addition, surgeons may sketch freehand trajectories. Then each trajectory is projected onto the 2D and 3D views. A control panel will list all trajectories, including their execution order, color assignments, and speed, allowing for reordering, visibility toggling, and color adjustment. Trajectories can be removed by either enabling the eraser tool and stroking across the path or by selecting the trajectory in the control panel and pressing the Delete button. The dual projection in both 2D and 3D views reduces ambiguity about the path's location in 3D space. For tasks requiring full surface coverage of an area, the control system generates raster-fill patterns confined by a virtual fixture. The surgeon can specify the number of sweeps (pattern repeats) and line density (lines per unit distance), and the system will generate a trajectory based on the specified raster pattern. Similarly, each trajectory can be projected across all views and edited or deleted through the control panel. Before executing a set of trajectories, users can view a live preview of the intended toolpath, laser spot size, trajectory sequencing, and speed. The preview runs in both 2D and 3D, allowing rapid detection of unintended behaviors before they occur.

In addition to the pre-planned trajectory, the surgeon can directly manipulate the laser position in real time using a drawing mode. The stylus motion is captured as a “tailing brush”, where the laser moves to the point at a fixed velocity without a trajectory. The position and spot size of the laser are projected as the surgeon moves the stylus. The tailing brush promotes uniform ablation at a constant velocity and attenuates hand tremor. The virtual fixture will remain active in real-time control of the laser.

When the surgeon needs to refocus the laser to reduce bleeding, a “beam profile” widget in the settings panel will visually encode the spot size across the available focal settings. The surgeon can adjust the beam size using a draggable slider or direct numeric entry, both of which are bound to the system limits. The surgeon can turn the laser on and off at any time using a toggle button, but the laser can only be fired after receiving dual acknowledgment. The safety clinician will continuously monitor the robot's physical configuration and deactivate the laser if any deviation or uncertainty occurs. Additionally, if the environment within the surgical sight changes abruptly or smoke obscures vision, the interface will stop any robot movement and lasing. This provides an additional safety factor when the system is uncertain about its environment.

Performance Requirements & Constraints

Since our project focuses on TLM interfaces, the performance requirements of our system should be tied to the system-agnostic interface rather than the physical constraints of our specific system setup. Issues such as camera resolution or robot speed not meeting industry standards are expected and can be addressed by using more precise or powerful equipment. This project's requirements will be outlined by delays not exceeding traditional human response time and by providing surgeons with capabilities that existing equipment does not already offer.

Delays may arise from the systematic processing and transfer of data from the physical world to the operator and back. The data processing pipeline (World -> sensors -> hardware -> network -> server -> pre-processing -> network -> on-device processing -> operator) and back again introduces compounding delays at every point. Anything after the robotic control interface on the server is our responsibility, so the total RTT—from receiving information from the software robot control interface to responding to that stimulus—should be fast enough for an operator to work safely and comfortably. A “safe” response time is defined as <300ms. Including a buffer for robotic systems taking up to 200ms, our interface should aim to add <100ms of latency (Xu et al. 2014).

While any system introduces inherent noise/inaccuracies when measuring, our system should not exceed an acceptable level. TLM must operate with sub-millimeter accuracy within a 10 mm x 20 mm workspace (nominal vocal fold size), so any conversions to visual pixels or operator instructions must not increase the sub-millimeter maximum error capability of TLM robots. Additionally, any overlays must be displayed to the operator with sub-millimeter accuracy and converted to the display's pixel resolution (Greer et al. 2008). This means that any virtual representation of the interaction between the robot and the estimated workspace, or any transformed camera view, must maintain the same sub-millimeter deviation from the physical ground truth. This includes 2D and 3D representations of the work surface, the robot's position relative to it, and laser dynamics, including beam profile, cut depth, and working distance.

Standards

The development of this system can be dangerous; however, standards can be employed to reduce the risk of laser misfiring. For safety, the laser can only turn on when **both** the user **and** the investigator press **their respective activation switches simultaneously**. The user's activation switch can be a toggle on and off button on the iPad, while the investigator presses on a foot pedal Figure 13.



Figure 13: An example of a foot pedal that both users may have.

Resources

Given our resources, it is paramount to account for each device's intrinsic limitations. Below are the specifications of each resource we will be using:

CO2 Laser

1. Lumenis AcuPulse
 - a. Class 4 Laser
 - b. Wavelength: 10.6 μm
 - c. Power Range: 1-20 W
 - d. Aiming Beam: Red 635 nm

CO2 Laser Manipulator

1. Franka Emika Panda Arm (7-DOF)
 - a. Max EE speed: 2 m/s
 - b. Repeatability Pose Accuracy: 0.1 mm

Cameras

1. The Intel® RealSense™ Depth Camera D405 (RGB-D)
 - a. Main Physician View
 - b. Resolution: 1280×720
 - c. Frame rate: 30 fps
 - d. Depth accuracy (7–50 cm): $\pm 1.4\%$ at 20 cm
 - e. Ideal working distance: 7–50 cm
2. FLIR A655sc Thermal Camera

- a. Tissue Temperature Tracking
- b. Resolution: 640 x 480
- c. Full Window 50 Hz
- d. Min Window (640 x 120) 200 Hz

User Interface

1. Tablet
 - a. 120Hz refresh rate
 - b. Version newer than 8th gen iPad or Pro7 or S7
 - c. Able to browse the web
 - d. Any OS
2. Stylus for iPad: Apple Pencil Pro
 - a. Haptic feedback
 - b. Squeeze and barrel roll
 - c. Pixel-precision
3. Stylus for Android tablet: Microsoft Surface Slim Pen 2
 - a. Haptic feedback
 - b. Zero-force inking
 - c. 4096 points of pressure sensitivity

Software

1. For deployment: Docker
 - e. 64-bit CPU
 - a. 4GB of RAM
 - b. Windows 10 or later
2. For version control: GitHub

Demonstration of Performance

System Accuracy

The accuracy of the robot–camera registration will determine how well the robot maps from the robot end-effector pose to RGB-D image coordinates. Where given a pixel point \hat{u} , the correct robot position can be calculated through the transformation matrix from the camera to the robot in Equation 1.

$$p_{robot} = T_{Camera}^{Robot} \hat{u}$$

Equation 1: Transformation between pixel and robot

Finding the transformation matrix will require a calibration step. The initial setup will require the robot to aim at a specified location to determine a home position (ideally, the center of the camera image). The robot will move in a grid pattern, stopping at each point to shoot the laser and record the hotspot pixel and the aiming beam pixel. Once a grid with known physical dimensions is made, a direct conversion to pixels can be made by counting the number of pixels per unit distance on an image. Now, a homography matrix can be made to map from pixels to physical distance and vice versa.

With this mapping and finding the actual pixel location the robot is pointing to, we can find the registration error. Where u' is the truth value and u are the transformed pixel point. Additionally, Equation 2 below can be used to calculate RMSE from a set of input pixels and their corresponding actual outputs for both real-time control and planned trajectories.

$$e_{RMSE} = \sum_i \sqrt{\frac{1}{N} (\hat{u}_i' - \hat{u}_i)^2}$$

Equation 2: RMSE of registration error and implementation

User Accuracy

Evaluating the user accuracy of the system can be done by measuring quantitative performance improvement over traditional systems or by gathering qualitative feedback from participants in a user study. Again, since only the interface is being developed, quantitative performance measures should compare against other robotic systems, not against the interfaces they use. This can be done through a comparative user study between having and not having features.

The comparative user study will consist of one or more predefined procedures per feature for trained TLM surgeons to complete, each procedure performed first without the interface feature (control) and then with it (experimental). These trials can be used to quantitatively measure performance differences in two main ways: speed and error. The control trial can be used to set a speed benchmark, and time improvement can be measured with the experimental trial. Error can be measured in each trial by deviation from the predefined procedure, and improvement by comparing trials.

Alongside quantitative improvements to the interface, surgeons' feedback on procedure complexity is equally important. New interface features need to be considered applicable to surgeons. Additionally, areas for further exploration or improvement can be noted at the conclusion of the study. Survey and interview questions are available in the Appendix: Interview Questions.

~~“It was concluded that the ability to resolve 0.05 mm sutures for anastomosis () of 1 mm vessels was the limit of fine resolution for surgeons, and was therefore considered a minimum requirement.”~~ (<https://ieeexplore.ieee.org/document/4542805>)

Possible tech stack

Front-end:

- **TypeScript**
- **Vite** (dev tooling, HMR, bundling)
- **Canvas API** (2D view, overlays, stylus drawing)
- **WebGL/Three.js** (3D surface rendering from RGB-D camera)
- **Pointer Events API** (Apple Pencil/stylus input)

Communication:

- **FFserver** for RGB-D camera feed (30-50ms latency)
- **WebSocket** for control commands and status replies (laser position, virtual fixture, trajectories)

Back-end:

- **FastAPI** for API calls
- **FFMPeg** for WebRTC server
- **Python wrapped C** to control the robot arm and laser (Franka Panda library)
- **Docker** containers to host services (HTTP server & web socket connections, video stream connections, robot controller)

Appendix

Table 1.1: Examples of surgical applications of lasers in various medical fields
(Lee et al. 2022; Shokrollahi et al. 2004; Belykh et al. 2017; Mathis et al. 2015; Yan et al. 2010; Maloney 1992; Niemz 2019)

Medical Field	Laser Source	Steering Method	Examples of Procedures/ Applications
General Surgery (Basic techniques used across fields)	CO2 Nd: YAG Ho: YAG	Fiber Free-Beam	Cutting Lymphatic sealing
Urology (Urinary tract and male reproductive system)	CO2 KTP Ho: YAG Tm: YAG Pulsed dye Diode Thulium Fiber	Fiber Free-Beam	Bladder/kidney stones Bladder tumors Prostate coagulation Prostate resection
Gynecology (Female reproductive system)	Nd: YAG CO2 Diode	Fiber Free-Beam	Laparoscopic treatment Hysteroscopic treatment Foetoscopic treatment Colposcopic treatment External condylomas
Gastroenterology (Digestive system disorders)	Nd: YAG Diode	Fiber	Recanalisation of the esophagus Gastric tumors Bleeding ulcers Liver disease
Orthopedic Surgery (Musculoskeletal system, bones, joints, muscles)	Nd: YAG Ho: YAG	Fiber	Cutting and ablating tissue Smoothing cartilage Knee surgery Lumbar disc decompression
Oral/Maxillofacial Surgery (Mouth, jaw, face, and neck disorders)	CO2 Nd: YAG	Fiber Free-Beam	Tumor excision/biopsy Papilloma vaporization
Thoracics (Chest cavity and organs)	CO2 Nd: YAG	Fiber Free-Beam	Trachea recanalization Upper airway recanalization
Ophthalmology (Eye and vision disorders)	OPSL	Fiber Free-Beam	Diabetic retinopathy Macular degeneration Retinal vein occlusion Iridectomy Corneal ablation
Dermatology & Plastic Surgery (Skin medicine, cosmetic/reconstructive surgery)	CO2 KTP Nd: YAG Pulsed dye Diode Ruby	Fiber Free-Beam	Vascular lesions Laser ablation and resurfacing Hair removal Tattoo removal Burn excision Photo-rejuvenation
Pain Therapy (Managing acute and chronic pain conditions)	Diode	Fiber	Acute pain therapy Chronic pain Wound healing
Oncology (Cancer diagnosis, treatment, and prevention)	CO2 KTP Nd: YAG	Fiber Free-Beam	Tumor excision/biopsy Photodynamic therapy Palliative tumor ablation

	KTP Gold vapor		
Neurology (Brain, spinal cord, and nervous system disorders)	CO2 Nd: YAG	Fiber Free-Beam	Open/endoscopic cranial surgery Ablation of brain tissue Photodynamic therapy Intervertebral disk degeneration
Fetal Surgery (Fetal operations)	Nd: YAG Diode	Fiber	Urinary tract obstructions Chest masses Amniotic bands
ENT (Ear, nose, and throat disorders)	CO2 KTP Nd: YAG Diode	Fiber Free-Beam	Vocal cord polyps Obstructing carcinoma Nasal airway obstruction Microsurgery
Otology (Specialty of ENT, ear disorders, and hearing problems)	CO2 KTP Er: YAG	Fiber Free-Beam	Middle ear surgery Stapedotomy
Laryngology (Specialty of ENT, voice box (larynx) and vocal cord disorders)	CO2 KTP	Fiber Free-Beam	Laryngeal cancer Laryngomalacia Vocal fold lesions Microsurgery

Interview Questions

Instructions: Please rate your level of agreement with each statement using the following scale:

- 1 = Strongly Disagree
- 2 = Disagree
- 3 = Neutral
- 4 = Agree
- 5 = Strongly Agree

General Usability:

1. The tablet-stylus interface was intuitive and easy to learn.
2. I could accurately control the laser path using the stylus to a degree that would be adequate for surgical procedures.
3. The interface had the necessary tools to complete the tasks properly.
4. The interface could easily reflect intended actions that would be done in a procedure.
5. The interface has responded quickly to my actions.

Region of interest (virtual fixture) feature:

1. Creating and customizing the region of interest (virtual fixture) on the interface was easy and helpful.
2. The region of interest (virtual fixture) helped reduce the chances of error.

Pre-Planned Trajectory feature:

1. It was easy to create different trajectories.
2. It was easy to edit each trajectory.
3. It was easy to change the order of each trajectory.
4. It was easy to create trajectories that reflected intended paths.
5. It was easy to view the trajectory in the 2D view.
6. It was easy to view the trajectory in the 3D view.
7. The simulation playback of the pre-planned path helped in visualizing the trajectory.
8. It was easy to create laser scanning patterns.

Real-Time Laser Control feature:

1. The Real-Time laser control reflected on my intended paths.
2. It was easy to use.
3. I would use the Real-Time Laser Control feature.
4. I prefer using Real-Time Laser Control over creating pre-planned trajectories.

Laser Setting Feature:

1. The laser focus stayed consistent throughout the procedure.
2. It was easy to track the position of the laser.
3. It was easy to track the beam size of the laser on the tissue.
4. It was easy to change the focus of the laser.
5. Seeing the laser position and size overlay was helpful.

General Visualization:

1. Overlays aided in creating informed actions.
2. Having the thermal overlay helped in understanding the thermal spread of the surgical site.

3D View:

1. The interface accurately represented the surgical site in the 3D view.
2. It was easy to change the viewpoint in the 3D view.
3. The 3D view helped in visualizing the surgical site.

2D View:

1. The interface accurately represented the surgical site in the 2D view.
2. It was easy to change the viewpoint in the 2D view.
3. The 2D view helped in visualizing the surgical site.

Ergonomics:

1. The tablet-stylus interface was more ergonomically comfortable than the traditional laser control methods I use.
2. I could use this system for extended procedures without fatigue.
3. The UI layout was comfortable and convenient to use.

Clinical Utility:

1. The system would help me better identify key information needed during surgery.
2. The visualization and video stream provided by the interface were sufficient for effective laser control.

Overall Assessment:

1. I would feel confident using this system in a real surgical setting.
2. This system has the potential to decrease the learning curve of surgical procedures without negatively impacting patient outcomes.

Open-Ended Questions:

1. What specific features of the interface did you find most useful?
2. What aspects of the system would need improvement before clinical implementation?
3. Were there any tasks that felt particularly difficult or uncomfortable to perform?
4. How does this system compare to your current laser control setup in terms of ease of use, precision, and ergonomics?
5. What additional features or capabilities would make this system more useful for your clinical practice?
6. Do you have any other comments or suggestions?

Thank you for your participation and valuable feedback!

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