LaryngoTORS: A Novel Cable-Driven Parallel Robotic System for Transoral Laser Phonosurgery

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Abstract—Transoral laser phonosurgery is a commonly used surgical procedure in which a laser beam is used to perform incision, ablation or photocoagulation of laryngeal tissues. Two techniques are commonly practiced: free beam and fiber delivery. For free beam delivery, a laser scanner is integrated into a surgical microscope to provide an accurate laser scanning pattern. This approach can only be used under direct line of sight, which may cause increased postoperative pain to the patient and injury, is uncomfortable for the surgeon during prolonged operations, the manipulability is poor and extensive training is required. In contrast, in the fiber delivery technique, a flexible fiber is used to transmit the laser beam and therefore does not require direct line of sight. However, this can only achieve manual level accuracy, repeatability and velocity, and does not allow for pattern scanning. Robotic systems have been developed to overcome the limitations of both techniques. However, these systems offer limited workspace and degrees-of-freedom (DoF), limiting their clinical applicability. This work presents the LaryngoTORS, a robotic system that aims at overcoming the limitations of the two techniques, by using a cable-driven parallel mechanism (CDPM) attached at the end of a curved laryngeal blade for controlling the end tip of the laser fiber. The system allows autonomous generation of scanning patterns or user-driven free-path scanning. Path scan validation demonstrated errors as low as 0.054\(\pm\)0.028 mm and high repeatability of 0.027\(\pm\)0.020 mm (6\(\times\)2 mm arc line). Ex vivo tests on chicken tissue have been carried out. The results show the ability of the system to overcome limitations of current methods with high accuracy and repeatability using the superior fiber delivery approach.

Index Terms—Medical Robots and Systems, Parallel Robots.

I. INTRODUCTION

TRANSPORTAL laser phonosurgery is a common ear, nose and throat (ENT) procedure. Currently, there are two techniques used for laser delivery: free beam delivery and fiber delivery. Both techniques use laser beam to perform incision, excision, ablation, or photocoagulation of laryngeal tissues, such as the epiglottis, glottis and vocal cords. The main differences between the two techniques are the laser delivery method and the laser working distance [1], [2]. In free beam delivery –also known as transoral laser microsurgery (TLM)—a laser micromanipulator scanner is used to deflect the laser beam to the target tissue. The laser scanner can generate patterns such as straight lines, arc lines and circles [3], [4]. An accurate, fast and highly repeatable pre-programmed laser scanning can be achieved, with a typical root-mean-square error (RMSE) of 0.0598 mm [5]. However, the laser beam can only be used under direct line of sight and with a working distance between the laser aperture and the target tissue at about 400 mm. To provide a working channel for the laser beam, a straight rigid suspension laryngoscope is used. This is uncomfortable for the surgeon during prolonged operations, the manipulability is poor and extensive training is required [6]. Furthermore, suspension laryngoscopy may put strain to the patient’s cervical vertebrae and cause dental arch lesions and postoperative pain [7]. In contrast to TLM, fiber delivery transoral laser surgery uses a flexible fiber to transmit the laser beam. Therefore, no direct line of sight is required, and the suspension laryngoscope can be omitted. The laser fiber can be controlled by a curved hand-held surgical instrument or a teleoperated surgical robot arm. However, the accurate pattern
scanning function is lost, and dexterous control of the fiber remains a major challenge.

Robotic systems have been used for transoral laser surgery. The Flex Robotic System (Medrobotics Inc., USA) has been used in vocal cords surgery [8], [9]. However, due to the manual control of the surgical instruments, the levels of accuracy and manipulability are low. The da Vinci SP single access surgery robotic system (Intuitive Surgical Inc., USA) has received FDA approval for radical tonsillectomy and tongue base resection, but not for transoral phonosurgery [10].

Recently, two fiber-based laser scanning robotic systems have been developed. The µRALP robotic transoral laser surgery system uses a micro-fabricated laser deflecting mechanism on the distal tip of a semi-flexible robotic endoscope [11], [12]. The scanning error of the µRALP system is about 0.070 mm [13]. The working distance of the laser beam is 20 mm and the maximum angle of incidence to target tissue is 15°, while the laser scanning mechanism can only generate 2 DoF motion control via a single reflection scanning mirror [14]. The significant incidence angle will enlarge the size of the laser spot and the spot shape will become an ellipse. Non-targeted healthy tissue will be inadvertently removed due to the resulting tilted cutting. A second system relies on a magnetic fiber-based laser scanner [15], [16]. The workspace is a 5×5 mm square. During an around 2.5mm diameter circular path tracking, a RSME of 0.035±0.018 mm was found [15]. A second study performing 10 repeated patterns of a 2×2 mm ‘8’ shape exhibited a RMSE of 0.021±0.010 mm, demonstrating high repeatability [17]. However, while the accuracy and repeatability were high, the workspace of the scanner are too small for clinical applications. A second limitation is the 2 DoF of the magnetic fiber-based laser, which in combination with the fixed focal length makes difficult to maintain the focal point on the target tissue. In addition, both systems have the fibers integrated and fixed within the device, which poses practical limitations when replacement with a new fiber tip is required due to degradation during the surgery. As presented, there doesn’t seem to be a practical way of replacing fibers. Finally, both systems must also consider sterilization issues and performance degradation due to repeated sterilization and reuse. In summary, both the free beam delivery and fiber delivery techniques, as currently practiced, have significant drawbacks. Current commercial and research robotic systems have not yet addressed a number of significant limitations related to fiber-based laser scanning. A clinical system for transoral laser phonosurgery should fulfill the following fundamental requirements:

- Avoid the use of a suspension laryngoscope by obviating the need for a direct line of sight;
- Provide accurate, repeatable, healthy-tissue sparing, through user-driven and semi-autonomous control of the laser;
- Provide a clinically acceptable and commercially viable proposition.

CDPMs have proven their ability to control surgical instruments through the use of multiple cables working in a parallel and antagonistic fashion [18], [19]. High force transmission, relatively large workspace, rapid deployability and low cost are some of the intrinsic advantages of such mechanisms. The ESD CYCLOPS is a CDPM robotic system currently undergoing pre-clinical validation in advanced GI surgery techniques [20], [21]. Unlike serial mechanisms, parallel approaches do not suffer from errors accumulating through the kinematic chain and thus could provide accurate and repeatable control of an end-effector accommodating a laser fiber. For transoral laser phonosurgery, the CDPM can be attached at the end of a flexible or curved instrument, obviating the need for a suspension laryngoscope. Therefore, this approach has the promise to overcome the limitations related to the line of sight and perform accurate laser scanning. In this paper the LaryngoTORS (Fig. 1), a new transoral robotic surgery (TORS) system is presented. The LaryngoTORS is the first implementation of a CDPM for robotic transoral laser phonosurgery or, to the authors’ knowledge, for laser surgery in general. The paper is focused on the technical development and pre-clinical validation of a CDPM for transoral laser phonosurgery. The accuracy and repeatability of laser path scanning are validated over a range of scanning speeds. Ex vivo chicken tissue tests are performed.

## II. System Design and Prototyping

The LaryngoTORS robot is designed as a bimanual system for transoral laser phonosurgery, based on two CDPM end-effectors.

### A. Robotic System Design

The shape of the LaryngoTORS robot system resembles that of a curved laryngoscope (Fig. 1), and is inspired by the indirect video laryngoscope [22]. A scaffold housing a CDPM pair is attached at the end of the curved laryngeal blade. Cables are transmitted through flexible transmission conduits (Bowden cables), coated with polytetrafluoroethylene (PTFE) tubing to minimize friction. Via small openings positioned around the scaffold, the cables are connected on two instrument-accommodating over-tubes housed within the scaffold. The Bowden cables are fixated to the scaffold to prevent changing of the pathway length during actuation of the robot. Six cables are connected per over-tube. One over-tube is used for controlling the laser fiber tip and the other for a surgical instrument, such as a vocal cord forceps. The

<table>
<thead>
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<th>Item</th>
<th>Specifications</th>
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<tbody>
<tr>
<td>Size of scaffold</td>
<td>22×20×22mm (W×H×L)</td>
</tr>
<tr>
<td>Size of over-tube</td>
<td>ø1.5 mm diameter, 10–20 mm length</td>
</tr>
<tr>
<td>Cable location [x, y, z]</td>
<td>Scaffold [mm]</td>
</tr>
<tr>
<td>Laser arm cable 1</td>
<td>[-1.25, 8, 11]</td>
</tr>
<tr>
<td>Laser arm cable 2</td>
<td>[-1.25, 8, -11]</td>
</tr>
<tr>
<td>Laser arm cable 3</td>
<td>[-8.25, 0, 11]</td>
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<td>[-8.25, 0, -11]</td>
</tr>
<tr>
<td>Laser arm cable 5</td>
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<tr>
<td>Laser arm cable 6</td>
<td>[-1.25, -8, -11]</td>
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Fig. 2. Design of the LaryngoTORS robotic system. a) Side view showing the main parts: motor unit, handle, Bowden cables for cable transmission and the curved laryngeal blade with the scaffold. b) Inner view showing the cable transmission. A force sensor is used to achieve tension control. c) Top view of the robot body.

shape of the scaffold is based on the distal tip of conventional laryngoscopes [23], [24], which is a hollow elliptical cylinder (Fig. 4). The dimensions of the scaffold and the cable location of the laser arm are shown in Table I. The origins ([0,0,0]) of the robotic coordinate system is located at the center of the 12 cables entry points on the scaffold. The Z-axis is the longitudinal axis of the cylindrical scaffold and points to the end of the scaffold (Fig. 3a). The cable configuration of the both end-effectors are symmetrical along the Y-Z plane. The dimensions and cable locations can be adjusted based on patient-specific data and operational needs.

The six cables connected to the fiber-controlling over-tube allow 5 DoF motion; three translations, pitch and yaw. The three translational DoF are required to move the fiber tip to the desired position and control its distance from the target tissue. Approximately a 1 mm distance is required for laser incision or dissection, and 2–5 mm for ablation or hemostasis. The two rotational DoF are used to improve manipulability and enlarge the controllable workspace. The 5 DoF motion can ensure that the laser fiber tip stays at the desired distance and the fiber axis at a proper direction, so the laser spot projection is circular. A roll DoF is not required for the laser fiber. Servo motors are used to control the six cables. The over-tube used to control the auxiliary surgical instrument is also controlled in the same fashion, with the addition of a stepper motor placed external to the surgical system units to rotate torsionally stiff flexible instruments whenever a roll DoF is required. Since the shapes of over-tube, fiber and forceps can be closely approximated by cylinders, collision detection can be easily detected and prevented by measuring distances between section lines within the control routine.

Fig. 2 shows the designed robotic system. For a bimanual robotic system, 12 motor units are required (Fig. 2c). The CDPM is designed to attach on a curved laryngeal blade to overcome the limitations of the direct line of sight. The angle θ is 20° (Fig. 2a), while it can be adjusted between 0°–70° according to patient requirements [25].

B. Simulation

Simulation of the workspace is performed for the laser instrument and compared with actual clinical workspace requirements of laser phonosurgery. The length of an adult’s vocal cord is between 11–21 mm, and the width approximately half of it [5]. Based on these, the desired workspace for one side vocal cord and glottis should be roughly a 25 mm diameter half-cylinder. To achieve the desired workspace, the scaffold parameters of the CDPM are defined as shown in Fig. 3a. The diameter of the over-tube is 1.5 mm. The distance between the end tip of the simulated instrument and the front set of cables is 20 mm.

The controllable workspace of the CDPM should satisfy two conditions:

\[ A\vec{t} + \vec{f} = 0 \]  
\[ t_i \in [t_{min}, t_{max}], i = 1, 2, ..., 6 \]

For the two conditions to be fulfilled, the tensions vector \( \vec{f} \) need to meet the so-called force-closure condition.
the external wrench and A is the structure matrix, described in [26], [27]. The tension of all cables needs to keep the instrument in equilibrium. Each cable tension force \( t \) must be positive and above a small pretension (0.3 N), which needs to be maintained in the mechanical system and needs to be below a maximum force (30 N) that can be generated by the motors and endured by the cables. The configuration and the controllable workspace of the laser fiber arm and the forceps arm is symmetrical. The workspace is numerically calculated using the force-closure and wrench-feasible workspace on a grid search over all five dimensions. The workspace (without external wrench) of the laser fiber arm is shown in Fig. 3b and Fig. 3c. Without rotation, the controllable workspace is close to a 5.5 × 12 mm triangle with a 10 mm depth. When rotations are included in the simulation, the controllable workspace expands to a 28 mm diameter half cylinder with 11 mm depth. As the laser fiber can be placed into either over-tubes, the entire workspace of the laser arm is roughly that of a full cylinder with a 28 mm diameter. This is more than adequate, as the maximum size of the distal tip of conventional laryngoscopes is only 22 mm in diameter [23], [24].

C. Prototype

A prototype of the LaryngoTORS has been developed (Fig. 1). The robot body is mounted on an adjustable surgical table support arm, which can be locked after the robot is placed into the desired position. A single end-effector was used in the first prototype, but as the two CDPMs are symmetrical the addition of the second over-tube does not affect the design.

For cable actuation 6 brushless DC motors (1226S012B with a 64:1 gear head, Faulhaber, Germany) and EtherCAT controllers (MC 5004 P, Faulhaber, Germany) are used. The tension on each cable is measured by a load cell (LCL-005, OMEGA Engineering, Inc., USA). A 6 mm pulley is built onto the load cell. A DAQ interface (Instrument i100, GW Instruments, Inc., USA) is used to acquire the tensions from the loadcells. 6 mm cable spools are mounted on each motor. Motor control in teleoperation mode is achieved using a master manipulator (Geomagic Touch, 3D Systems, USA), or programatically from the computer.

The part of the robot that attaches to the motor unit and is introduced transorally, is envisaged as a patient-specific and disposable part. For validation, the single-use prototype shown in Fig. 4 includes a handle for the operator to place the robot, a curved laryngeal blade with the CDPM, Bowden cables (1.4 mm Round Wire Coil, Asahi Intec, Japan) with inner PTFE tubing (Adtech Polymer Engineering Ltd., Germany), spectra cables (0.19 mm diameter, 13kgf, PowerPro, Shimano, Inc., Japan), a brass over-tube, a fiber sheath (Laser Fiber Sheath, Lumenis Ltd., Israel) and a 5mm diameter USB camera with 6 LEDs. The spectra cables are made of ultra-high-molecular-weight polyethylene (UHMW-PE). The UHMW-PE cables are extremely stiff for their cross-sectional area. These are not prone to fatigue and are rated for breaking at approximately 130N (13kgf). The cables from the motor unit are routed through the handle to the scaffold, via PTFE tubing within Bowden cables. The Bowden cables are fixed at the end of the handle onto the scaffold. PTFE is used to minimize friction between the cables and the Bowden transmission conduits. The cables are attached to the over-tube by creating a loop which is accurately adhered with glue.

III. System Validation

In TLM, the size and shape of the scan pattern are pre-programmed, and a joystick on the micromanipulator is used to set the center of the scanning pattern and change its direction. Currently, an arbitrary free scan path is not allowed and therefore many small-scaled scan patterns are required to dissect irregular pathological margins. This leads to increased procedural time and some loss of accuracy, thereby compromising the advantages of the free beam delivery technique. We follow an improved approach for describing and executing a free scan path: the implementation is a master-slave controller in which by using control points, an autonomous path can be determined. The master manipulator is used to determine desired control points in the workspace, which are then used to generate the final path and perform the path scan automatically. The ideal pose of the fiber tip is normal to the target tissue, which results to a circular spot shape of the aiming beam. The operator can choose the proper pose based on the apparent spot shape of the aiming beam. The control points include a starting point, an endpoint, and roughly equidistant via points to sparsely describe the desired trajectory.

The pose of the end-effector is recorded for all control points, and the sequentially saved points serve as the input data to generate the entire scan path (x, y, z, yaw, pitch) using the Catmull-Rom spline interpolation. The motor controller then executes the continuous generated path. An inverse dynamics PD control algorithm with tension optimization is performed [28], [29]. The control is based on a PD tension control routine, described in [30]. Inverse Kinematics is used to transform the desired position in the end-effector space to a desired rotation in the motor joint space. The Jacobian which describes this transformation can be used in combination with the static equilibrium equations of all the cable force-vectors to numerically calculate the optimal tension distribution. By only allowing solutions which are within bounds — i.e. a positive tension to prevent cable slackness and within a maximum limit to prevent cable failure — the CDPM remains controllable.
within its workspace. The friction is minimized by reducing cable tensions by the control routine. The above method calculates the desired cable tension, which is compared to the measured cable tension. The error between the desired and measured cable tension is multiplied by a proportional gain to control the rotation of each motor. The parameters of the PD controller and the tension gain were determined heuristically. A bench test was performed to evaluate the accuracy and repeatability of the generated scan paths. Ex vivo tests on the chicken tissue were also performed for further validation.

A. Bench Test

As shown in Fig. 5a, a paper screen was attached at the front of the robot’s scaffold. A laser fiber (FiberLase CO2 fiber, Lumenis Ltd., Israel) was inserted in the over-tube through the fiber sheath until the end tip was extended by 5mm in front of the over-tube. The distance between the end tip of the fiber and the front set of cables is 20 mm, which is in accordance with the simulated configuration in section IIB. A red aiming beam is used during the bench test. Fig. 5b shows a 6×2 mm ground-truth arc line (green), generated by 5 control points (blue) and Catmull-Rom spline interpolation. Fig. 5c shows the executed scan path (green). Using MATLAB software, the path of the aiming spot centroid was visually tracked by the CMOS camera based on color and shape features and compared with the ground-truth scan path. The experimental results are shown in Fig. 5d-e and the RMSE and maximum absolute error (MAE) are shown in Table II. The RMSE between the tracked and generated path was 0.054±0.028 mm at a velocity of 0.5 mm/s. During 6 repetitions, the repeatability was 0.027±0.020 mm RMSE. The measured cable tension forces and respective motor positions for 3 of the arc scans (in Fig. 5) are shown in Fig. 7. Further, two straight line scans in the horizontal and vertical directions were performed. The experimental results are shown in Fig. 6 and Table II. As shown in Table II, the repeatability of the motion is high. By enabling the users to manually set the control points, any effects of friction, cable winding and cable elongation are intrinsically taken into consideration. Subsequent repetition of the motion through the same points is executed in high precision.

The accuracy of scan path over a range of end-effector velocities was assessed. Since the frame rate of the used USB cameras is low (30 FPS), the image of the aiming spot becomes blurry when the motion speed is high. Therefore, an optical tracking rig (120 FPS, Optitrack Prime 13 Cameras, Natural-Point, Inc., USA) was used to measure the same scan path executed at increasing velocities of 1.0, 1.5, 2.0, 2.5 and 3.0 mm/s (Fig. 8). The control points were manually defined. The RMSE for each velocity respectively was calculated and shown in Table III. Scan path execution accuracy wasn’t significantly affected by increasing velocities, with the RMSE remaining below 0.1 mm. The RMSE is larger than the experimental results performed on the paper screen, which may be due to the precision of the OptiTrack Prime 13 Cameras (calibration residual mean error: 0.014 mm) and the fact that motions were tracked in 3D compared to 2D when measurement on the paper target.

B. Ex vivo Test

Ex vivo tissue tests on manual laser ablation were performed. Chicken tissue was held at the front of the robot.
Fig. 7. The measured tension forces (top) and respective measured motors position (bottom) for three consecutive arc scans.

Fig. 8. The bench test of path scan at different velocities. a) A marker was attached at the end of over-tube for optical tracking, b) Two calibrated OptiTrack Prime 13 Cameras, c) The measured results of path scan with different velocity via optical tracking.

Fig. 9a shows a $7 \times 4$ mm tissue being excised using a $2 \, \mu m$ wavelength medical laser (RevoLix jr, LISA Laser Products GmbH, Germany). The incision path is approximately a $10 \times 5$ mm arc line. *Ex vivo* testing has also been carried out to demonstrate the performance of the generated path on the tissue. All the scan paths were performed at a velocity of 2.0 mm/s. Fig. 9b shows the task performed along the margins of a target. A 6 mm diameter semi-circular target was placed on a piece of chicken tissue. A straight path and a curved line path were defined by user-defined control points along the straight and arc margins respectively. The defined scan paths were successfully executed. Fig. 9c shows the results of arbitrary scan paths, shaped as number “3” (8 control points) and letter “D” (9 control points). All the *ex vivo* tests were performed with a 272 $\mu m$ laser fiber (FlexiFib-SU fiber, LISA Laser Products GmbH, Germany) and the laser power was set to 3 W at continuing wave mode.

### Table III

<table>
<thead>
<tr>
<th>Speeds</th>
<th>RMSE (mm)</th>
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<tr>
<td>1.0 mm/s</td>
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<tr>
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<tr>
<td>3.0 mm/s</td>
<td>0.086±0.045</td>
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Fig. 9b shows the task performed along the margins of a target. A 6 mm diameter semi-circular target was placed on a piece of chicken tissue. A straight path and a curved line path were defined by user-defined control points along the straight and arc margins respectively. The defined scan paths were successfully executed. Fig. 9c shows the results of arbitrary scan paths, shaped as number “3” (8 control points) and letter “D” (9 control points). All the *ex vivo* tests were performed with a 272 $\mu m$ laser fiber (FlexiFib-SU fiber, LISA Laser Products GmbH, Germany) and the laser power was set to 3 W at continuing wave mode.

### IV. Clinical Feasibility Analysis

As discussed in [31], many emerging surgical robotic systems suffer from clinical applicability limitations, such as the problem of limited workspace or sterilization. The clinical applicability of the LaryngoTORS robot are discussed next.
Fig. 9. Ex vivo test. a) Ex vivo laser ablation on a piece of chicken tissue, b) the ex vivo laser path scan along with an attached target, c) ex vivo laser arbitrary path scan.

A. Detachable Part

As shown in Fig. 10, after disconnecting the cable connectors, the robotic body can be divided into two parts. The transoral introducer can be detached from the robot body and, due to its simplicity, it can be provided as a single-use part. Thus, sterilization costs, time and patient cross-contamination risks can be reduced, while ensuring reliability by avoiding wear and tear due to repeated sterilization. More expensive parts such as the motor units and the controllers can be draped to prevent contamination, and do not require to undergo sterilization. The exact mechanism for coupling and uncoupling the two parts will be investigated in future work, but the solution is expected to be in line with a simple wire rope fitting (e.g., shank ball). The specifications of the transoral introducer can be chosen and customized based on procedure-specific needs. For instance, the configuration of cable distribution can be modified based on the position of the target tissue. The design of the detachable part can be adjusted to different clinical requirements and accommodate for patient anatomy variations. Although the specifications of the LaryngoTORS can be fully customizable based on patient specific data, it still may not be suitable for a small number of patients with a difficult airway, but this would also the case for conventional TLM operations [32].

B. Compatibility

As mentioned in the bench and ex vivo validation, the LaryngoTORS is directly compatible with commercial laser fibers and not limited to specific products. With the fiber introducer sheath, any optic fiber up to a maximum outer diameter of 1.2 mm can be accommodated. Such laser fibers are not limited to therapy and can also be used for diagnosis, such as endomicroscopy, multispectral imaging and intraoperative optical coherence tomography (OCT). A major benefit is that no modification of the fiber or the system is required.

C. Device ergonomics

The shape and size of the applied part of the LaryngoTORS has been based on existing clinical instrumentation, which also require a clamp to keep in a steady position. In that respect, the device adheres to the current workflow. The ergonomics of using the device are different, as surgeons will tele-operate the device and therefore can adjust their screen, chair and manipulators to suit their needs and preferences.

V. Conclusion

The LaryngoTORS is the first CDPM system that has been developed for transoral laser phonosurgery. The experimental results have demonstrated the high accuracy and repeatability achieved. By obviating the need for a rigid and straight laryngoscope, the approach is less traumatic to the patient and as it is not dependent on a suspended microscope, it can easily be configured more ergonomically for the surgeon. Therefore, the system provides the accuracy of TLM, less patient pain and without surgeon discomfort. Additionally, the LaryngoTORS overcomes limitations seen in other robotic systems for fiber delivery transoral laser surgery, such as a small workspace and limited DoF, while not compromising in terms of accuracy and repeatability. A bimanual system with stereo vision, visual servoing control and autonomous task performance are currently under development. Additionally, a cadaver trial has been scheduled for further validation. This work showed that CDPMs have sufficiently high accuracy and repeatability for control of lasers for surgical tasks. When compared to other systems for transoral laser phonosurgery,
the LaryngeTORS provides unique advantages in terms of a large workspace and a high accuracy through a flexible pathway. It is therefore a promising direction to continue to pursue in future developments.

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