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Preliminary experiments of a miniature robotic system for tooth ablation using ultra-short pulsed lasers

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***Abstract*—As a preliminary step to achieve a long-term goal of developing an automatic dental preparation system for clinical operations, we design and build a miniature robotic system which can manipulate a laser beam to move in three dimensional spaces to remove hard tissue from a target tooth. The dental preparation requires the robotic system to own high accuracy, high ablation speed and small size. A 2D galvanometer scanners module is integrated to meet the requirement of a high moving speed of the laser focus. A closed-loop system based on a miniature-sized voice-coil motor and a grating ruler are developed to realize the accurate control of the focus. The overall size of the developed prototype is 108mm×56mm×43mm, which is small enough to be used in close proximity to a patient's mouth. The prototype has been tested by using two different kinds of laser generators, i.e. , a nanosecond laser and a picosecond laser. The experiment results show that the robotic system can provide high moving speed of 1000mm/s with good shape accuracy. From the results, we found that nanosecond laser beam can be controlled to ablate zirconia and aluminum, but not suitable to ablate tooth because of tissue carbonization. By selecting suitable parameters of the picosecond laser generator, a target tooth could be ablated to produce a cylinder shape without carbonization. Limitations of the prototype are identified according to the experiment results.**

I. INTRODUCTION

Dental preparation refers to the process of removing quantitative hard tissue (including enamel, dentin and cementum) of a decayed tooth and forming the expected shape in dental clinical operations. During the preparation, some aspects should be considered: to protect the periodontium, to produce space for the backfill material and the restoration, to ensure the mechanical strength, and some other clinical requirements. There are two typical methods for hard tissue removal in present clinical operations: grinding using turbine-driven drills and ablating using Er:YAG lasers. These two methods generate mechanical and thermal stress, which can create micro cracks of several tens of microns in the enamel. These cracks are starting points for new carious attacks and have to be avoided for long term success of the dental treatment.

In the past decades, the ultra-short pulsed lasers have been widely used in medical areas such as eye surgery, ear surgery, minimally invasive operations etc., and have been introduced into dental surgery to overcome drawbacks of traditional treatment methods. S. Marina et al. evaluated the possibility of using ultra-short pulsed lasers (picosecond and femtosecond lasers) in restorative dentistry and explored the performance of ablation with different laser parameters [1]. Lizarelli et al. carried out ablation experiments using ultra-short pulsed laser on a tooth surface [2]. They demonstrated the possibility of selective control of refractive index change and application in the preferential removal of portions of dental hard tissues. Kraft et al. used ultra-short laser pulses for calculus removal on a root cement surface [3]. Daskalova et al. demonstrated that by selecting suitable parameters one can obtain efficient dentin surface preparation without evidence of thermal damage, i.e., with minimized heat affected zones and reduced collateral damage [4].Niemz MH demonstrated the advantages and limitations using ultra-short pulsed lasers in dentistry [5]. Rode AV et al. demonstrated ablation of dental enamel using a subpicosecond pulsed laser [6]. Krüger et al. pioneered the study on using femtosecond lasers in dental surgery [7].

Most previous dental laser operations have been carried out manually, i.e., the laser beam is manipulated to produce an expected trajectory by human operator's hand. Compared with manual operations, robotic operations will provide potential benefit, including motion planning based on 3D digital model to achieve higher accuracy and stability to avoid trembling of a human hand and efficiency to reduce operation time etc. Furthermore, the ratio between skilled dentists and patients is very low, which is about 1:500~2000 in developed countries, and is about 1:20000 in China. This low ratio produces a great challenge for effective dental treatment. Robotic devices can liberate surgeons from basic tasks and then can have more time to deal with complex treatments.

In this paper, we introduce our preliminary attempt toward a long-term goal of using ultra-short laser for tooth ablation, and thus to realize automatic dental preparation in clinical operations. Based on the actual dental requirements, we have developed a miniature robotic system for manipulation of laser beam, which is the first attempt in literature to combine ultra-short pulsed laser with a small-sized robotic device, and apply them into dental preparation.

The remainder of the paper is organized as follows. In section II, we introduce the constitution of the automatic dental preparation system to provide a background for the robotic system, and describe the performance requirements of the robotic device. In section III, we introduce the optical system of the laser beam transmission, and then the design of the device. In section IV, we describe the physical prototype and provide experiment results on tooth ablation. In section V,

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we conclude the paper and discuss some possible future research directions.

II. DESIGN REQUIREMENTS OF THE ROBOTIC END-EFFECTOR

A. Architecture of the automatic dental preparation system

We first introduce the constitution of the automatic dental preparation system. As shown in Fig. 1, the system includes the following components: a miniature robotic end-effector, a tooth fixture, a laser generator, a laser transmission arm, a laser scanner and a computer console. As shown in Fig. 2, the shape of the target tooth (in blue color) is changed before and after dental preparation. The original shape is acquired by the laser scanner before the operation. The expected shape is designed using Mimics. These two shapes will be sent to the controller of the robotic device, and plan a suitable trajectory for the robotic end-effector. Then the robotic end-effector manipulates the laser transmitted by the laser transmission arm to ablate the target tooth until the expected shape is achieved. The motion planning and control software are running on the computer console.

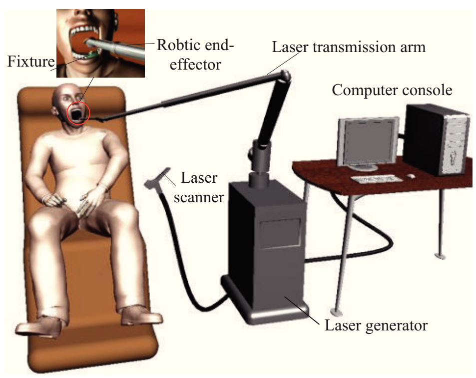

Fig. 1 Conceptual illustration of the automatic dental preparation system

Fig. 2 Shape of the target tooth (in blue) before and after preparation

In this paper, we focus on the design and experiments of the robotic end-effector. All the other components of the system (including laser scanner, laser transmission arm and laser generator etc.) are available and provided by our collaborators. This miniature robotic end-effector will be installed on the transmission arm, and then connected and fixed on the tooth fixture so as to maintain no relative motion between the end-effector and the target tooth during dental burring operation.

B. Performance requirements of the robotic end-effector

The goal of dental preparation is to remove decayed tissues from a target tooth. Manual operation is difficult to maintain high accuracy because of the narrow space within patients' oral cavity, unexpected movement of patient's head and tongue, visual judgment error of the dentist and location error of the dentist's hand.

Based on the goal of dental preparation, the performance requirements of the robotic end-effector can be summarized as following five aspects:

(1). High accuracy. The shape accuracy and the smoothness of the final surface are two main performance metrics for evaluating the quality of the preparation procedure. The shape accuracy of the final prepared tooth includes two requirements: the linear error is required to be less than 0.2mm, and the angular error is required to be less than 2^o. From literatures, current manual accuracy is about 10^o for the average angular error. Thus requires the robotic system can control the motion of the laser focus at a high accuracy.

(2). High speed ablation. Based on the results of the previous laser experiments we carried out using several teeth, the moving speed of the laser focus should be higher than a certain threshold to prevent the tooth from carbonizing because too much energy of laser accumulates on one specific point of the tooth surface. Previous research [1] showed that fast scanning speeds resulted in better interaction and reduced temperature increase. Furthermore, high speed ablation is also required in order to ensure the efficiency of preparation. In this paper, our design goals are that the speed of our device is supposed to be at least 1000mm/s, and the preparation time is no more than one hour.

(3). Small and light. The robotic end-effector is inserted into a patient's oral cavity. Therefore, the size of the end-effector needs to be small enough (the diameter of the tip of the end-effector should be less than 25mm) and flexible enough to access all the teeth within the mouth cavity. Besides, the end-effector should be light in weight in order to reduce the load exerted on the patient's tooth.

(4). Safety. The end-effector should be easy for sterilization. And real-time monitoring is also needed to make it convenient for the dentist to check the outcome of the preparation and stop the robotic system in case of emergencies at any time. In addition, tooth powder and plasma will be produced during the operation, thus requires the system be able to discharge these substances. Finally, the adjacent teeth and the periodontium should be protected from ablation.

(5). Convenience. The end-effector will be connected with the tooth fixture and the laser transmission arm, so we should ensure the connections are accurate, reliable and convenient.

III. DESIGN OF THE ROBOTIC END-EFFECTOR

A. Overview of the optical system

The optical system is designed as shown in fig. 3. In the system, a two-DOF scanning system consists of a vibrating mirror X and a vibrating mirror Y. When the parallel laser beam is emitted from the laser generator, and transferred to the scanning system through the transmission arm, the vibrating mirrors X, Y will change the beam's direction in sequence and then sends it into the protruding optical lens. Passed through the lens, the beam becomes a focused cone shape. By selecting the appropriate distance between the tooth and the lens, the focused laser reflected by the static mirror will be exactly a circle area with a certain radius at the surface of the tooth. This focused laser can produce high energy and can remove stiff materials such as enamel and dentin. By using appropriate lasers (like femtosecond laser), it will produce a little quantity of heat. Therefore, it is almost no damage to surrounding tissues around the laser focus. Parameters in the optical system are summarized in TABLE I.

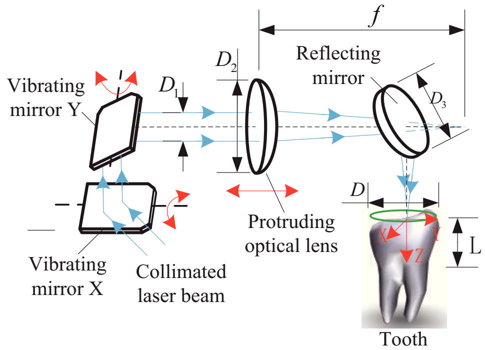

Fig. 3 Optical components and transmission path of the laser beam

TABLE I. MAIN PARAMETERS IN THE OPTICALSYSTEM

Parameter	Meaning
D	diameter of the target tooth [0~11.7mm]
D_1	diameter of the incoming laser beam
D_2	diameter of the protruding optical lens
D_3	diameter of the static reflection mirror
L	the range of dental drilling along the z-axis [0~6mm]
f	the focal length of the protruding optical lens

B. Design solution for 3D motion control of the laser focus

Based on the optical system, we can decompose the laser focus' 3D motion into a 2D planar motion and a straight line motion along the tooth's depth (z-axis). The 2D planar motion can be realized by changing the direction of the laser beam through the pendular movement of the two vibrating mirrors. And the straight line motion can be realized by the back and forth translation of the protruding optical lens.

Considering the principle of ultra-short pulsed lasers and the ablation rates [1], it is necessary to control the laser focus to move at a high speed in a plane. Therefore, the challenge for the 2D planar motion control is to maintain a high scanning speed of the laser focus.

A conventional driving method has been attempted by adopting linear motors with a transmission mechanism (e.g. slider-rocker mechanism) to realize the two vibrating mirrors' pendular movement and thus realized the laser focus' 2D planar motion. The disadvantage of this method is that the size of the whole optical system will be very big because of the transmission mechanism. Furthermore, the incorporation of the transmission mechanism may increase the inertia of the mechanical system and thus reduce the system's response speed [8]. Besides, the errors of the transmission mechanism (including machining errors, assembly errors, etc.) may greatly decrease the system's positioning accuracy.

Therefore, we decided to adopt a direct-driven method, i.e., we used pendular motors to directly drive the vibrating mirrors without any transmission mechanisms. As the mirrors are quite light and without transmission errors, the 2D high speed scanning can be realized with an adequate type of pendular motor of small size, high movement speed and high accuracy. To ensure the accuracy of 2D scanning, closed-loop control should be adopted with high-resolution position sensors, e.g., angle sensors and photoelectric coders.

For the straight line motion, high resolution is required to meet the requirement of accurate ablation, whereas a high velocity is not necessarily required. We adopted a linear motor to drive the protruding optical lens moving along a linear guide. Furthermore, we adopted closed-loop control by using a high resolution grating ruler to get real-time feedback of the lens' position. This solution can maintain the motion of the lens with high resolution, good stability and response rate.

C. Selection of motors and optical components

To meet the requirements of robotic system's size and weight, all the components of the system should be as small and light as possible.

Considering the tooth's size range, we finally select the diameter of the protruding optical lens to be 25.4mm. Furthermore, the end-effector will be used in the patient's mouth, and the distance between the farthest tooth and the entrance mouth cavity is about 60mm, so we select the focal length to be 150mm considering the movement range of lens and the height between the center of the reflection mirror and the tooth surface. These parameters also depend on the specifications of available protruding optical lens in the market.

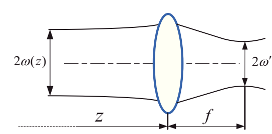

Fig. 4 A Gaussian laser beam focused by a protruding optical lens

As shown in Fig. 4, a laser beam is focused into a high energy laser focus after transmission through a protruding optical lens. From the focus law of the Gaussian beam [9], we can derive the following equation

$$\omega_0' = \frac{\lambda}{\pi\omega(z)} f \tag{1}$$

where $\omega(z)$ denotes the radius of the incoming Gaussian beam (which depends on the transmission distance of the beam). λ denotes the wavelength of the laser beam. f denotes the focal length of the protruding optical lens. ω_0' is the radius of the focused laser focus/region.

We can derive that

$$D_1 = \frac{4\lambda}{\pi d} f \tag{2}$$

where λ denotes the wavelength of the femotosecond laser beam ($\lambda = 1064nm$). d is the required diameter of the laser focus($d = 30\mu m$).

A type of 2D galvanometer scanners (type S-8107M) is selected based on the diameter of the incoming laser beam.

The mirrors are driven by pendular motors. Its small size, high speed, high positioning accuracy, high anti-interference with almost no vibration provide a good solution to satisfy the basic requirements for the dental preparation. Specification for the motors is shown in TABLE II.

TABLE II. SPECIFICATION FOR THE PENDULAR MOTORS

Size & weight	Φ22mm×38mm, 50g
Optical aperture (mm)	7
Maximum scan angle	±12.5°
Marking speed (mm/s)	4000
Repeatability (μRad.)	<8

We assume the total mass of the lens and the slider of the linear guide is M , and the dynamic friction coefficient of the linear guide is μ , and the force that the motor needs to drive the slider and the lens is F . Then we can build a mathematical model to compute F , i.e.

$$F > \mu Mg \tag{3}$$

Based on the model and the survey result of the market, we selected the linear guide (type SEB8-40, moving range is 20mm, dynamic friction coefficient μ is 0.004, and sliding parallelism is less than 3um) and the grating sensor, and then compute parameters of the linear motor, including required resolution and movement range. Specifications for the motor and sensor are shown in TABLE III.

TABLE III. SPECIFICATIONS FOR THE SELECTED MOTOR AND SENSOR

Type	size and weight	Performance
voice coil motor AVM 12-6.4	$\varphi 12.7mm \times 20.4mm$ 12.9g	Max load 3.5N Moving range 6.4mm
distance-coded reference MercuryTM 2000	20.57mm×12.7mm× 8.38mm	Resolution 1um repeatability precision ±3um to ±5um

IV. PROTOTYPE AND EXPERIMENTS

A compact virtual prototype is built as shown in Fig. 6 based on the selected components. The accuracy of manufacture and assembly should be ensured to maintain the correctness of the laser path and not to introduce mechanical errors. The physical prototype is shown in Fig. 7. The overall size of the prototype is 108mm×56mm×43mm. Screws were adopted to adjust the mechanical tolerance during manufacture and assembly.

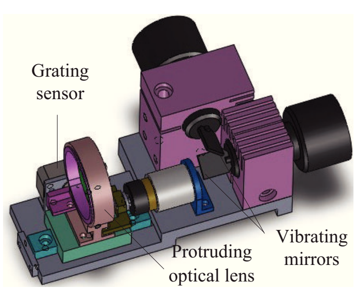

Fig. 6 The virtual prototype

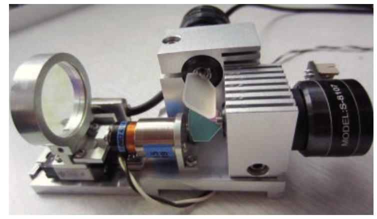

Fig. 7 The physical prototype

A. Nanosecond laser experiments

With the physical prototype, a controller card, motor drivers, a digital analog converter (DAC) and a power are added to build the robotic system for laser experiments. Fig. 8 shows the components of the system.

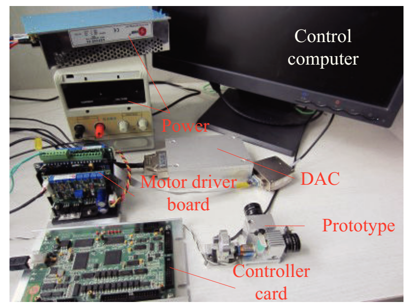

Fig. 8 The components of the robotic system

It's necessary to test the performance of the system's accuracy first. Thus, experiments were carried out with a nanosecond laser generator (fiber laser, maximum output power 30w, maximum repetition frequency 50 kHz, pulse width 100ns, wavelength 1064ns) to test the movement control accuracy, which was validated by controlling the laser focus to follow a given shape such as a ring. It should be noted that the laser beam needs to be adjusted to pass through the center of the vibrating mirrors and the lens before ablation experiments.

We first attempted to use teeth as experimental material. After a number of trials, we found that no matter how we changed the laser generator parameters and the vibrating mirrors' velocity, the teeth were either unresectable or carbonized even crumbled with high temperature rising after a period time of ablation (shown in Fig. 9 (a)). These results indicate the nanosecond laser may not be able to ablate teeth. So we selected two typical kinds of dental materials-aluminum and zirconia-to continue the experiments as the first step to test the accuracy of the device.

The computer program was preset to control the laser focus to ablate a ring (the outside diameter 10mm, and the inside 4mm) on an aluminum block (the vibrating mirrors' speed 1000mm/s, the protruding optical lens kept still). As shown in Fig. 9 (b), the inside and outside diameters of the ring are consistent with the theoretical values. Six aluminum blocks were ablated. The average value and the standard deviation of the inside diameter are 4.11mm and 0.07 mm^2 , and the average value and the standard deviation of the outside is 10.02mm and 0.13 mm^2 .

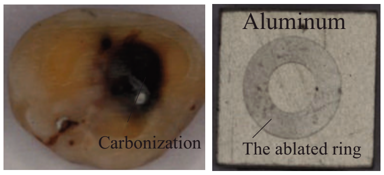

Fig. 9 a) The carbonized tooth b) a ring ablated on a block of aluminum

Then we continued to test the three-dimensional ablation accuracy of the system. We still preset the program to control the laser focus to ablate a ring (the outside diameter 10mm, and the inside 4mm) on a zirconia square, and the linear motor drove the lens to move 10μm per 25 seconds. This means the ideal ablating result should be a cylinder. After one hour, we find that outside face is a cylinder, while the inside face is a cone (shown in Fig. 10 (a)). Both faces are relatively smooth, and the ablate depth is 2.54mm rather than the theoretical value 1.5mm. In order to observe the ablating effect of the bottom, we replaced the zirconia with an aluminum cylinder, and repeated the experiment while the parameters remained the same. The result shown in Fig. 10 (b) displays the bottom is relatively smooth but not very flat. And the ablate depth is 3.16mm, which is still greater than the theoretical value 1.5mm. We will discuss the possible reason in next section.

Fig. 10 a) A block of zirconia before and after ablation and

b) an aluminum cylinder after ablation

To explain the cone, as shown in Fig. 11, the shape of the typical Guass laser beam is an inverted cone, and the cone angle is θ. The focal depth refers to the effective ablation height. When the ablated shape is a cylinder, parts of the material cannot be accessed by the laser beam because of occlusion when the ablation depth increased along z-axis. This issue can be solved by changing the inclination angle of the laser beam.

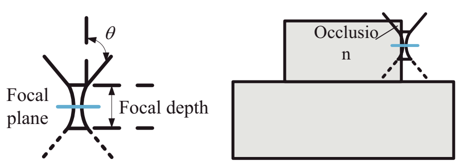

Fig. 11 A cone shape of the typical Guass laser beam and the occlusion effect

B. *Picosecond laser experiments*

The essential goal of the system is to apply the robotic system in dental preparation, so experiments were carried out on tooth with picosecond laser to explore the laser ablation effect on tooth. The feasibility of using picosecond laser to ablate teeth has been tested [10]. But we still have to find appropriate parameters to ensure two aspects: (1). the picosecond laser can ablate the teeth without carbonization, cracks or high temperature rise. (2). the time that costs to ablate to a given depth will not be too long, i.e., to consider the ablation efficiency at the same time.

A series of experiments were carried out on tooth slices (every slice's thickness 1.5mm) with a picosecond laser generator (maximum output power 10w, maximum repetition frequency 10 kHz, pulse width 15ps, wavelength 1064ns), in order to explore suitable parameters for tooth ablation. Fig. 12 shows the whole picosecond laser experiment system. Fig .13 shows the ablation result on a tooth slice.

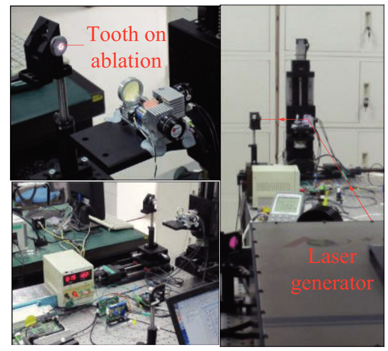

Fig. 12 The picosecond laser experiment system

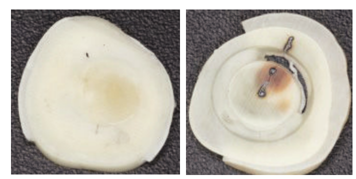

Fig. 13 A tooth slice before and after ablation

We preliminary decided the parameters for the laser generator (output power 3.5w, repetition frequency 10 kHz), the vibrating mirrors speed (500mm/s), and the linear motor's feed speed (10μm per 25 seconds). Then we used these parameters to ablate a cylinder on a tooth (the outside diameter 12mm, and the inside 4.8mm, which ensures a complete coverage of a common tooth, and the cylinder is regarded as a rough approximation of the preparation tooth.). The upper and lower surfaces of the tooth were grinded flat beforehand in order to easily fix the tooth on the experiment table. After one hour, the ablation result is shown in Fig. 14. We got a relatively good cylinder while the bottom is still not flat especially at the boundaries of the enamel and dentin. The diameter of the top surface is 4.94mm. The ablation depth is 2.96mm more than the theoretical value 1.5mm. Besides, the temperature increased about 10℃ measured by a temperature sensor stuck on the back of the tooth.

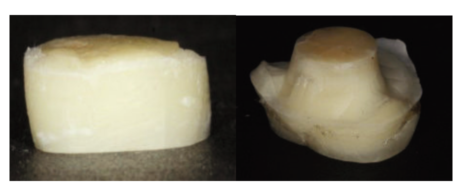

Fig. 14 A tooth before and after ablation

We can note that in both nanosecond and picosecond laser ablation experiments, the bottoms are not flat and the ablate depths are inconsistent with the theoretical value. There are two possible reasons for these errors. First, the materials used in the experiments, especially the tooth, are heterogeneous.

The laser will ablate more material at one place while less at another. Second, it is difficult to maintain exact alignment of the laser focus and the surface of the material along axis Z, and thus the removed volume of the material is inconsistent during the feed movement of the lens. In next step, we will propose a new device to overcome these drawbacks.

D. Discussions

From the results of nanosecond and picosecond laser experiments, we can summarize the limitations that exist in the developed robotic system. First, accuracy of the ablation depth as well as that of the bottom surface needs to be improved. Second, the ablation time needs to be reduced.

In the next step, we will use femtosecond laser to ablate teeth. We can increase the output power of laser and the speed of the pendular motors to improve the ablation efficiency without carbonization or cracks. For the same material, femtosecond laser ablation shows smoother surface with less heat than picosecond laser and nanosecond laser [11]. That means the femtosecond laser will also help solve the temperature rising issue. Furthermore, a motion planning and control algorithm needs to be designed to control the laser focus to achieve the complex 3D shape of the target tooth.

In order to put this robotic device into clinical studies, the size of the developed end-effector should be small enough to be used in a mouth cavity. As shown in Fig. 15, we have built the 3D virtual prototype of the integrated end-effector based on the developed device. From the virtual model, we can see that the end-effector is small enough. In next step, we will develop a physical prototype and test it in a phantom head model.

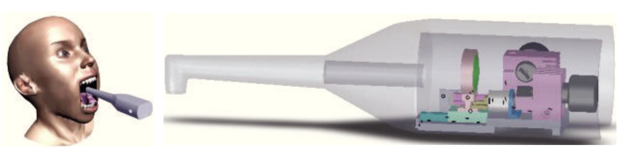

Fig. 15 The integrated end-effector and a Phantom head model

V. CONCLUSIONS AND FUTURE WORKS

In this paper, we have introduced a miniature robotic device to provide an automatic treatment solution for clinical dental operations. A compact design to achieve 3D motion control of a laser focus is proposed. By controlling the pendular motion of two vibrating mirrors, and the back and forth translation of a lens, we can control the laser focus to provide coverage of a 3D volume of the target tooth. Closed-loop control is provided for voice-coil motor with a high-resolution optical grating ruler.

Experiment results show that the movement range, the motion velocity and resolution of the laser focus can meet the requirements of typical dental operations. From the results, we find that by selecting suitable parameters of the picosecond laser generator, a target tooth can be ablated to produce a satisfied cylinder shape without carbonization. Limitations of the prototype are identified according to the experiment results.

In the future, we plan to integrate the system with other components, i.e., a ventilation/suction system and a cooling system, connectors of the laser transmission arm and the fixture in order to comprehensively evaluate the robotic system's performance. Moreover, we will study how to further reduce the size of the device and carry out ablation experiments on teeth within a phantom head model or in an animal's mouth cavity.

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