Thermal Analysis of a Magnetically Actuated Fiber-Coupled Laser System for Computer-Assisted Laser Microsurgery

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***Abstract*— Robotized laser endoscopic tools provide surgeons with increased accuracy for ablating tissue. Here, a new continuous laser scanner system was designed and fabricated for conducting experiments into controlled biological tissue ablation. The outcomes of the continuous laser (CW) ablation experiments are compared to a similar set of experiments previously conducted using a pulsed laser system. In ablation experiments on biological tissue, the ablation patterns generated by both systems proved to be consistent, robust, and accurate. When compared to the results obtained from the pulsed laser experiments, the CW laser pattern tracking system produced smaller tracking errors and more accurate ablation patterns.**

I. INTRODUCTION

Laser scanning systems have been used in medicine since 1962, for welding blood vessels, and microsurgery [1], and an early vocal cord operation with a CO_2 laser resulted in blood coagulation and a reduction in bleeding [2]. Later, when a CO_2 laser system was fitted with a microscope, there was: (1) an improvement in the precision of tissue ablation, (2) minimized post-operative pain, (3) a decrease in the operation cost, and (4) reduced morbidity [3], [4]. Still, in long operations, it is physically fatiguing for the surgeon who operates and controls a micromanipulator. This is particularly so when the area of tissue being ablated by the laser is small. Nevertheless, precise tissue ablation remains critical to the quality of the outcome of a procedure [5]. The introduction of robotic systems into laser-assisted surgery, and integrated sensor technology, e.g., cameras, ultrasound sensors, Computer Tomography (CT) and Medical Resonance Imaging (MRI), has greatly improved the outcomes of medical procedures [6]. For laser microsurgery based on raster scanning, i.e., this research, the accuracy of ablated tissue margins is crucial; because it is a move towards partially automating tissue ablation surgery. This is a considerable surgical challenge because of the: (1) small areas of tissue that are commonly ablated, and (2) confined workspace within the human body cavity for raster scanning. Typically, a laser actuator control system is located outside of the patient, but a direct line-of-sight into the surgical workspace is still required [7]. The early research of Giallo and Grant [8] proved that ablation procedures could take place inside the human body, but its performance was never evaluated on actual biological tissue. Minimally invasive surgery technologies that are based on electromagnetic fields are used widely in the designs of biomedical sensors and actuators. This paper is focused on the design, development, and application of a new electromagnetic (EM) fiber-coupled laser scanner system for ablating tissue in the micro-range using real-time closed-loop control [9]. Because of the flexibility characteristics of a fiber optic cable, this new system was designed to: (1) be controlled using an EM field, and (2) show improved tissue ablation qualities by introducing a photo-detector sensor into the design, i.e., to give closed-loop feedback control. Figure 1 shows the design of the new closed-loop magnetically controlled laser scanner system. The detail of the designed current driver board, the fiber optic and the solenoid holder cases has been presented in Figure 2.

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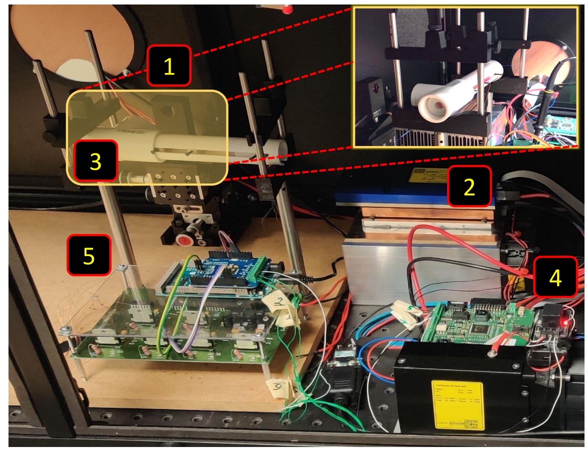

Fig. 1: General view of the designed Laser scanner system. 1) Photo-detector sensor, (2) Lumics Diode Laser system, (3) Designed Laser scanner system, (4) Laser system Driver Board, (5) Custom designed current Driver Board.

II. THEORETICAL MODELING OF AN AUTOMATED LASER SCANNER SYSTEM

A review of the new fiber optic control system design revealed a major design constraint, i.e., the strength of the electromagnetic field needed to generate the system's controlling torque. The deflection of the fiber optic cable is

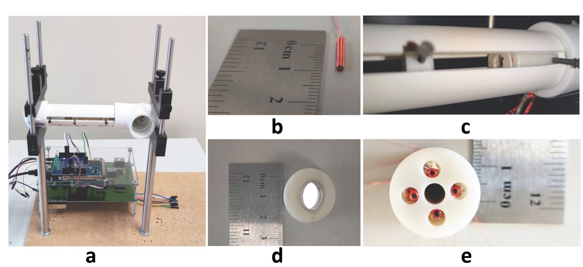

Fig. 2: a) The designed current driver board, fiber optic, solenoid coil holder cases. b) The designed solenoid coil used to control the movement of the optical fiber. c) The holder case for the lenses, fiber and the solenoid coils. d) The beam splitter used for the feedback control. e) The holder case for the solenoid coils.

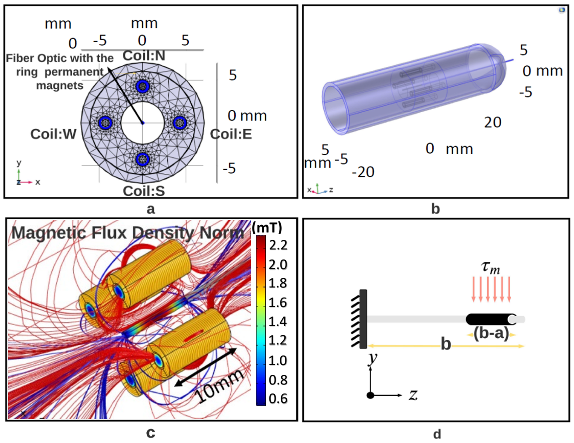

Fig. 3: Optical fiber deflection: a) Front view , b) side view c) Simulated electromagnetic Flux density norm by COMSOL, d) Simplified model of fiber optic deflection.

controlled by the application of a torque generated through an interaction between magnetic flux generated by the solenoid coils and a ring of permanent magnets surrounding the fiber optic cable (Figure 3). The fiber optic cable was considered to be a cantilever, fixed at one end and free at the other. By assuming small deflections at the free end, the Euler-Bernoulli Theory was applied to the cantilever, and the differential equation of motion derived [10].

$$EIy''''(z,t)+\tau_m y''(z,t)+\rho A\ddot{y}(z,t)=0 \qquad (1)$$

where, in Figure 3, the fiber optic cantilever: b is the fiber optic cable length, τ_m is the generated torque applied at the free end of the cantilever, I is the moment of inertia, E is the Young's Modulus, A is the cross-sectional area, ρ is the radius of curvature, $\dot{y}$ and y' are the partial derivatives of $y(z,t)$ with respect to time (t) and position (z).

A. Simulation of the fiber optic deflection and thermal analysis of the biological tissue interacted with laser beam

Maxwell's equations were used to model the electromagnetic (EM) fields and to determine the torque generated by the EM fields. A 3D model COMSOL model was constructed to show the interaction between the solenoid coils and the ring of permanent magnets surrounding the fiber optic cable. As can be seen, in Figure 3, by applying currents to the coils EM fields are generated around the fiber optic cable (red lines). When the EM fields generated in the coils interact with the magnetic fields of the permanent magnets (blue lines), the generated torque controls the displacement at the free end of the fiber optic cable. The heat generated by the laser beam is transferred into biological tissue through thermal conductivity. A COMSOL model finite element analysis determined that the time-dependent heat propagation into biological tissue depends on how laser energy is applied. The simulated results from the COMSOL model for a continuous wave laser with a 1470nm wavelength and 15 Watts power are shown in Figure 4. A generated COMSOL model of biological muscle tissue used the following properties: thermal conductivity $k=0.49W/m\cdot K$, density $\rho=1090kg/m^3$ and specific heat capacity $c_p=3421J/(kg\cdot K)$. As can be

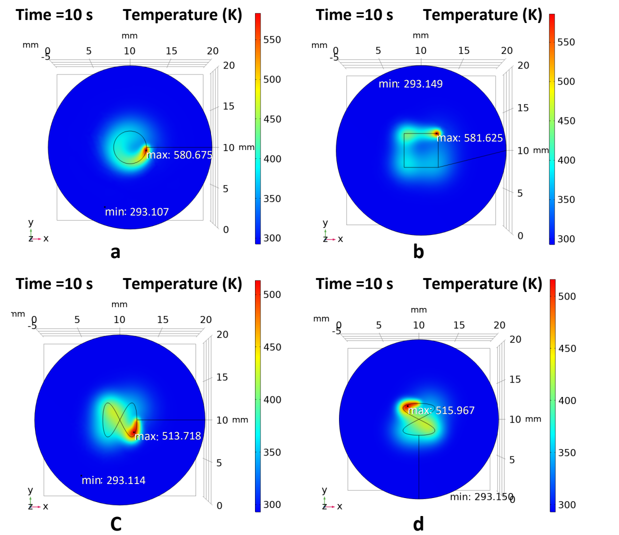

Fig. 4: COMSOL heat propagation results on biological muscle tissue using four scanning patterns: a) Circle Pattern, b) Square Pattern, c) Infinity Pattern, d) Eight Pattern.

seen from Figure 4, and similar to the physical experimental results, the heat transfers into the biological tissue to a depth of more than 1mm when a beam diameter of 250μm is used. At the temperatures produced the biological tissue either coagulates or carbonizes, and unfortunately, destroys the desired pattern. Figure 5 shows the temperature distribution on the surface of the biological tissue for both the CW laser and the pulsed laser, respectively. The study concluded that more accurate and precise ablation results were obtained if high-powered, ultra-fast, pulsed laser systems were used in an ablation procedure.

B. Test and evaluation of the designed system

In this section the design of a scaled-down CW laser scanning system (Figures 1 and 2) was tested and evaluated under controlled conditions. The results obtained with this

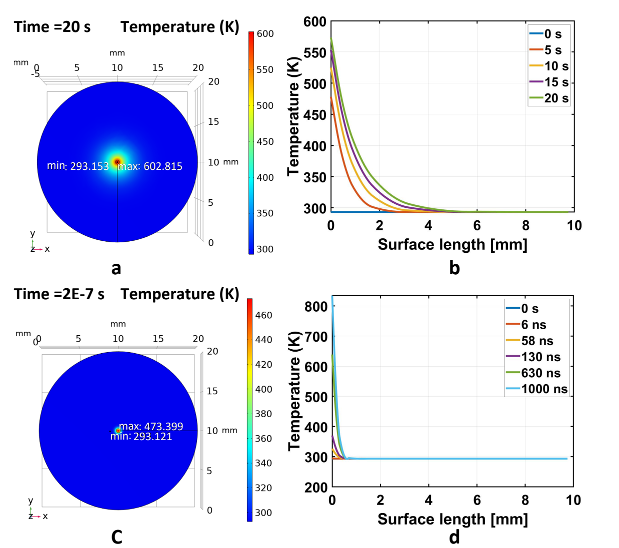

Fig. 5: COMSOL heat propagation into biological muscle tissue: a) 3D model of CW laser system, b) The temperature of Biological tissue vs. surface width for CW laser system, c) 3D model of Pulsed laser system, b) The temperature of Biological tissue vs. surface width for Pulsed Laser system.

TABLE I: Root Mean Square Error (RMSE) and Standard Deviation (SD) of the output error signals for the scaled down system and the original designed system.

	Scaled down system		Original designed System [9]	
Pattern Type	**RMSE**	**SD**	**RMSE**	**SD**
Circle Pattern (f = 1Hz)	40.0μm	33.9μm	194μm	192μm
Circle Pattern (f = 3Hz)	37.8μm	31.5μm	150μm	148μm
Circle Pattern (f = 5Hz)	38.7μm	38.0μm	139μm	132μm
Circle Pattern (f = 1Hz)				
Amplitude: 2.0mm	40.0μm	33.9μm	193μm	192μm
Amplitude: 1.5mm	25.6μm	21.0μm	121μm	109μm
Amplitude: 0.5mm	20.2μm	15.4μm	67.2μm	55μm
Square (f = 1Hz)	124.7μm	72.6μm	178μm	112μm
Infinity (f = 1Hz)	107.5 μm	101.7μm	183μm	184μm

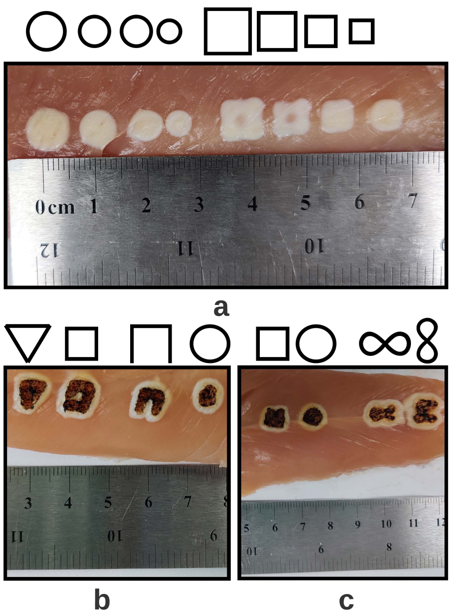

Fig. 6: a) Experimental result of the laser scanner system for circles and square patterns with 1 Watt intensity power. b) and c) Experimental results of the laser scanner system for different patterns on chicken biological tissue.

new CW laser scanner system showed that it was capable of generating highly accurate geometric patterns over a range of frequencies. The Root Mean Square Error (RMSE) and Standard Deviation (SD) results obtained from the original pulsed wave laser system [9] were compared to the results obtained from the new CW laser system, these are summarized in Table I. The table shows that more accurate positional control was obtained with the new modular CW system. Examination of the results obtained from actual ablation experiments with biological tissue, see Figure 6, show that the heat propagation throughout the biological tissue impacts the quality of the results; in fact, the CW laser system creates imprecise patterns on the biological tissue. By comparing the results of the geometric patterns obtained from the two laser ablation systems it was concluded that the ultra-fast pulsed laser system produces finer ablation paths, and that it causes less damage to biological tissue.

III. CONCLUSIONS

In summary, this paper presents a laser ablation comparative study, pulsed laser ablation compared to continuous wave (CW) laser ablation. A new CW laser ablation system was designed, modelled, built and physically tested on biological tissue. The geometric patterns etched into the biological tissue were generated by deflecting the optical fiber tip under electromagnet control. The simulation and physical experimental results once again demonstrated that the position and speed of an optical fiber laser tip can be accurately controlled by an electromagnetically generated torque. The new system design demonstrates that: (1) high-resolution position control results were obtained at the micron scale level, i.e., less than 200μm, (2) a variety of geometric patterns can be produced with high accuracy and precision, (3) a low-cost laser ablation system is possible for automating minimally invasive surgery, and (4) a non-contact actuation system, one with a high speed scanning, is possible for tissue ablation. Based on the results obtained in the comparative study it is concluded that future research into biological tissue ablation should focus on the use of high-frequency pulsed laser systems and on the design of micro-miniature electromagnetic actuation systems for position and speed control.

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