Closed-Loop Control of a Magnetically Actuated Fiber-Coupled Laser for Computer-Assisted Laser Microsurgery

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Abstract—Patient outcomes in the medical field are improving through the use and incorporation of robotics technology and laser physics, e.g., the use of optical fibers and lasers in micro-surgery. This paper describes the design and implementation of a new optical fiber laser micro-surgery system, one that is the first to use closed-loop feedback control. In this computer-assisted laser scanning tool the laser beam is controlled by four magnetic actuators. After attaching permanent magnets to the free end of the optical fiber, it is the control of these four magnets that produces an accurate laser scanning system, one suited to micro-surgery applications. The interaction between the electromagnetic fields generated by the external magnetic coils and the flux of the internal permanent magnets, produces the control torques required to produce the desired movement of the optic fiber. The tracking error of the optic fiber is compensated for by using a photo-detector sensor as the feedback transducer in the control system. The magnetic torque bends the optical fiber and the feedback from the photo-detector gives automated control and high-speed laser scanning of the fiber tip. The simulation and the experimental results are accurate and are co-related.

I. INTRODUCTION

Minimally invasive medical surgery has improved through the integration of technologies from robotics and physics, e.g., by developing master-slave optical fiber endoscopic tools and incorporating lasers. Nowadays, these combined technologies are applied in micro-surgery, and in particular in endoscopic tool applications such as tissue laser ablation. But, actuator control that allows for accurate laser microsurgery through raster scanning is uncommon because of their size in comparison to the confined workspace in which they operate. Typically, laser control actuators are located outside the patient and necessitate a direct line-of-sight into the surgical workspace. Today, for reasons described, lasers are commonly used for surgical procedures that are being carried out on delicate organs, i.e., organs that require accurate and precise laser beam localization. Eye, throat, and urology surgeries are typical. The properties of lasers that make them suited to such surgical procedures are their monochromaticity and collimation. These laser properties produce the high intensity energy, i.e., high power in a narrow beam, that can ablate tissue and organs precisely [1]. The first application of a laser system in medicine was in 1963, when a laser was used for a retinal tears surgery [2]. In the early 1980s a laser system was applied in an orthopedic procedure. In these early medical procedures both continuous and long pulse laser were used for ablation surgeries. But, they caused both tissue carbonization and fracturing around the tissue margins. [3], [4]. [5] showed that the level of laser irradiance had a significant impact on the outcomes of laser ablation procedures, i.e., good laser ablation was achieved using low average energy focused on a small area. The laser system introduced by Terry Myers [6] had the ability to cut bone precisely with little carbonization or mechanical stress. [7] introduced CO$_2$ lasers into medical procedures. Here, the light energy levels of CO$_2$ lasers was magnified by introducing carbon dioxide molecules into the device. Experiments showed that by utilizing a scanning laser, the quality of the outcomes of laser microsurgery improved. Laser scanning enabled fast and efficient laser ablation along with an associated reduction in the levels of thermal damage to healthy tissue. The benefits obtained through using lasers in soft tissue surgeries include: (1) improved post-operative functionality, (2) decreased morbidity (disease), (3) better homeostasis (coagulation, changing blood from a liquid to a gel), and (4) minimal peripheral tissue injury [8], [9]. The technology used for laser microsurgery is classified into two types, i.e., free-beam systems and fiber-coupled systems. Free-beam laser systems are used to ablate tissue from relatively long distances; typically hundreds of millimeters. Free beam systems come equipped with scanning capabilities that includes: (1) minimizing tissue carbonization, and (2) reduced thermal damage to surrounding tissue.

Ultimately, free-beam systems have led to clean laser cuts in tissue and improved surgical outcomes [10]. In contrast, a fiber-coupled surgical laser has shown that it is more flexible; and more capable, of delivering the laser energy required to perform tissue ablation when the endoscopic tool is in

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close proximity to the surgical site. This makes fiber-coupled laser systems the ideal choice for both minimally invasive surgeries and endoscopic tool surgeries. With fiber-coupled laser systems scanning capabilities are not currently offered, meaning that the quality of laser-tissue ablations is limited. In addition, the type of laser and the specific wavelength utilized by it, for minimally invasive surgeries, is dependent upon the surgery being performed as well as the tissue being ablated.

More recently, medical devices have been used in association with robotic systems, because of the accuracy of robot system positioning and of their potential for future development. Integrating laser endoscopic scanning tools with robotics has improved the accuracy of surgeons, particularly for ablating tumors. Endoscopic tools are the most common devices that use lasers and optic fibers, because they are small in size and have a proven track record of accuracy.

The actuation and control of laser-based endoscopic tools is commonly through a master-slave human-computer interface, i.e., the surgeon’s control interface. This human-computer interface is commonly located outside of the human body, because the interface is large. Limitations, and in particular the poor quality of an available control interface, see Giallo and Grant [11], led to early research into the design and control of miniature laser ablation devices which were located inside the human body. Giallo and Grant [11] determined that the precise control of such devices would not only increase the quality of microsurgery, but that the control of miniature laser devices would bring new technical challenges. In separate research a magnetic guidance system was designed to navigate a catheter inside a human body, this was used for cardiac electrophysiological ablation [12]. A coupled mechanical and magnetic actuation and control system was developed for surgical catheters, i.e., closed-loop control for magnetic catheters [13]. The computerized closed-loop position control of a catheter for heart surgery was achieved by designing a catheter that used permanent magnets embedded inside the heart. These catheters were guided inside the human body using an external magnetostatic field, one that controlled both the direction of the magnetic field and the field magnitude [14]. In [15]–[17] an open-loop contact-less, magnetically actuated, optical fiber was presented to control a laser beam. This system used electromagnetic forces. However, this system used open-loop control, so the system needed to be calibrated and tuned for every new reference signal. In order to control a system of an uncertain order, it is necessary to design and develop controllers, i.e., PID controllers, adaptive controllers, etc., that are designed specifically for the system they are being applied to. That is, a controller that helps the system to track the desired reference signal as accurately as possible [18]–[24].

The research here is focused on automating a fiber-coupled magnetic laser scanning system, one to be used in endoscopic laser scanning microsurgery. A general representation of the closed-loop magnetically actuated control system is shown in Fig.1. As can be seen, the solenoid coils are located around the optical fiber in a N-S-E-W arrangement and the permanent magnets are attached to the free end of the optical fiber. An electronic interface board was designed to control the current being supplied to the coils. By supplying current to the coils an electromagnetic fields was generated around the optical fiber. The interaction between the permanent magnets and the solenoid coils produces the desired torque and force needed to control the position of the optical fiber in 2D space. The main goal of the research was to build and test a closed-loop laser ablation system via computer-controlled miniature solenoid coils, i.e., controlling the electromagnetic fields, and introducing feedback. In experiments this test-bed controlled an optical fiber and proved that the laser beam could draw any desired geometric patterns that was asked for, both accurately and precisely. The advantages derived by implementing this actuation approach included: (1) non-contact actuation, (2) high-speed scanning, and (3) high resolution.

The paper is organized as follows, Section II describes the mathematical analysis and the simulation of the designed system, Section III presents the physical experimental test-bed that was designed and assembled to test and verify the performance of the system for accurate laser control and to generate the desired output geometric patterns, and Section IV draws conclusions on the research conducted to date.

II. THEORETICAL MODELING AND SIMULATION OF FLEXIBLE FIBER-COUPLED LASER

This section describes the mathematical modeling and analysis of a fiber-coupled laser system under externally induced torques. The external torques were generated by the interaction between the magnetic flux generated by solenoid coils positioned around an optical fiber and the permanent magnets which are attached at the free end of optical fiber. By controlling the current in the coils, the required movement of the optical fiber, and hence the laser beam, results in the ability to generate complex geometric output patterns in 2D space.

A. Mathematical analysis of flexible optical fiber

A schematic diagram of an optical fiber, considered to be a cantilever beam, is shown in Fig.2. The optical fiber is considered fixed at one end and free at the other end. The optical fiber bends under the action of externally applied torques and forces. In this study five small permanent magnets were

![Fig. 2: Optical fiber deflection with the external force or torque. (a): Side view. (b): Front view](image-url)
located at the free end of the optical fiber. The optical fiber bends due to the application of the external torque created by the interaction between the magnetic materials and the magnetic flux generated by the solenoid coils. Given the end conditions the deflected shape of the fiber optic is considered as either a parabola, or a cosine wave. Consider an optical fiber of length \( L \) shown in Fig.2. Let \( \tau_m \) be the applied torque at the free end of the optical fiber. By using the Euler-Bernoulli theory and assuming small deflections of optical fiber, the motion of the optical fiber can be expressed as the differential equation (1) [25].

\[
EIy''' + \tau_m y'' + \rho Ay = 0
\]  

(1)

Where \( I \) and \( E \) are the moment of inertia and the Youngs modulus respectively, \( A \) is the cross-sectional area of the optical fiber, \( \tau_m \) is the applied external torque, \( \dot{y} \) and \( y' \) are the partial derivative of \( y(t) \) with respect to time \( t \) and position \( x \) respectively. By applying the external electromagnetic field, the induced torque \( \tau_m \) to the end of optical fiber can be written as (2) [26]

\[
\tau_m = V_m M \times B
\]

(2)

Where \( M \) is magnetization, \( V_m \) is the volume and \( B \) is the magnetic field. By applying the parameters from Fig.2, for a distributed torque an approximation of the deflection on the optical fiber which satisfies (1), and can be expressed as (3) [27],

\[
\Delta = \frac{V_m BM}{6EI} \left[ \frac{(b-z)^3}{b-a} - 3(b+a)(b-z) + 2b(b+a) - a^2 \right]
\]

(3)

Where \( b-a \) is the length of magnetic material. By considering the optical fiber with length \( b \) at the point \( z = b \), the deflection will be calculated as (4)

\[
\Delta = \frac{V_m BM}{6EI} \left[ 2b(b+a) - a^2 \right]
\]

(4)

The parameters which were used in this paper are as follows: \((b-a) = 6\, \text{mm}\) is the length of optical fiber coated by five ring permanent magnets, and \( 200\, \mu\text{m} \) is the length of multi-mode optical fiber and, \( b = 7\, \text{cm} \) is the length of fixed end optical fiber.

**B. Simulation analysis of the laser scanning system**

In this section the design and simulation of a optical fiber surrounded by five ring permanent magnets, acted on by an external torque, was carried out. COMSOL software was used to conduct a finite element analysis. In order to mathematically model the electromagnetic field and hence the desired torque, Maxwell’s equations were used, (5)

\[
\int_S \nabla \times b \, da = \oint_C \mathbf{b} \cdot d\mathbf{l} = \mu_0 I_{\text{enc}} + \varepsilon_0 \frac{d}{dt} \int_S \mathbf{e} \cdot \hat{n} \, da
\]

(5)

Where \( b \) is the magnetic flux, \( e \) is the electric field, \( I_{\text{enc}} \) is the enclosed current, \( \varepsilon_0 \) is the electric permittivity of free space, and \( \mu_0 \) is the magnetic permeability of the free space. Also, Maxwell’s equations can be expressed in frequency domain, see [28],

\[
\nabla \times H = J
\]

(6)

\[
B = \nabla \times A, \quad \text{and} \quad B = \mu_0 \mu H
\]

(7)

\[
E = -j\omega A
\]

(8)

\[
J = \sigma E + j\omega D
\]

(9)
TABLE I: Specification of the components for magnetically actuated Fiber-coupled Laser system

| Component                  | Specification                                                                 |
|----------------------------|-----------------------------------------------------------------------------|
| Solenoid Coils             | 35 AWG, 150 turns with 1.42 mm inner diameter, 2.88 mm outer diameter and the length of 6 mm |
| Ferromagnetic cores        | Ferrite 77 Material with 1.5 mm diameter                                      |
| Ring Permanent Magnets     | Axially Magnetized Permanent magnets with 260 um inner diameter and 2 mm outer diameter |
| Optical Fiber              | Multimode optical fiber with 200 um core diameter                            |
| Lenses                     | 6 mm in diameter, one with a focal length of 10 mm and the other with 30 mm focal length |
| Photo-Detector Sensor      | PDP90A Lateral Effect Sensor                                                 |

Where $H$ and $E$ are magnetic fields electrical fields respectively, $B$ is magnetic flux density, $D$ is displacement current density. $\sigma$ is electrical conductivity, $\mu_0$ is magnetic permeability in free space, and $\mu_r$ is the permeability of the material, $\varepsilon$ is dielectric permittivity and $\omega$ is the operation frequency. This boundary problem was solved using both analytical and numerical approaches to find the electromagnetic fields, and to find the required torque. The module Magnetic Field was used to simulate the four miniature solenoid coils, the ring permanent magnets attached to the optical fiber, and the induced electromagnetic field around the optical fiber.

The 3D model of the designed solenoid coils and the optical fiber surrounded by ring permanent magnets is shown in Fig.3. As can be seen from the results, by driving the current in the coils, electromagnetic fields were generated around the optical fiber (Red lines) that interact with the electromagnetic fields generated by the permanent magnets (Blue lines). By controlling the current in the coils torques were generated in the desired directions. Two coils were used to control the movement of the optical fiber in one Cartesian quadrant at a time. The result for the induced electromagnetic field and the generated torque for the circle reference pattern are shown in Figs. 4-5. As can be seen from the results, by controlling the current of two coils at a time, the movement of the fiber optic at one Cartesian quadrant can be controlled. Fig.5 shows the movement of the optical fiber in $x-$ and $y-$ axis.

Fig. 8: Experimental result of Magnetically actuated system for Optical Fiber deflection in circle pattern case

III. EXPERIMENTAL RESULTS

This section presents the experimental results and the validation of the designed model described in Section II. Also, the closed-loop control strategy that was used to improve the tracking position error, and characterize the accuracy of the system, is described here. A photo-detector sensor was used to measure the reflected beam light and to act as a feedback sensor. This feedback data was used to reduce the error between the desired input and the measured variable output to zero.

A. Experimental Test-bed

Fig.6 shows the experimental test-bed for a closed-loop magnetically actuated fiber-coupled laser system. The sensor coils were mounted around the optical fiber, and the wires leading from the coils were soldered to PCB traces and connected to the current driver board. The current driver board was attached to an Arduino Duo micro-controller, this sub-system calculated the amount of current to be sent to each coil using Serial Peripheral Interface (SPI) communication. A closed-loop controller system was designed to control the optical fiber along a reference trajectory defined by the user. The laser beam light was reflected to a photo-detector sensor via a glass beam splitter. The actual output position was measured in each axis every $\text{1\,ms}$ using the micro-controller

B. Closed-loop control using photo-detector sensor

In this section the designed system was tested and analyzed by generating different geometric reference patterns. The solenoid coils have the same dimension and number of turns and control the deflection of the optical fiber on
the \( xy \) plane. Four magnetic fields were induced in the five ring permanent magnets and the interaction between the magnetic fluxes generated the required torques to deflect the optical fiber. A closed-loop control system with a feedforward command is shown in Fig.7.

A proportional-integral (PI) controller was used to compensate for the positioning error in the system. As can be seen, the actual position of the laser light beam was measured by the photo-detector feedback sensor and compared with the reference signal to produce the error signal. The generated error was then fed to the PI controller and added to the feedforward command to increase the performance and accuracy of the system. The experiment results for different reference pattern signals such as a square, infinity, circle, and Figure-Eight, are shown in Figs. 8-12. As can be seen from the results, the system was capable of generating any desired pattern with high resolution and accuracy. Also, the system was tested to create the pattern signals repeatedly to analyze the repeatability of the laser scanner. The Mean Square Error (MSE) of the results for different patterns have been shown in Table.II. The results show that the designed approach could be applied to any pattern signal and the system does not need to be re-tuned because a different pattern signal is asked for. In order to increase the accuracy of the system and improve the mean square error, more precise photo-detector sensor can be considered. Fig.8 shows a good match between the experimental and simulation results mentioned in section II.

The designed closed-loop laser system is capable of tracking the reference pattern with high accuracy and speed.

| Pattern   | MSE [\( \mu m \)] |
|-----------|-------------------|
| Circle    | 164               |
| Square    | 155               |
| Infinity  | 187               |
| Eight     | 198               |

**TABLE II: Mean Square Error of the designed system for different reference patterns**
IV. CONCLUSIONS

In summary, this paper presents the design, modeling, and physical testing of a new magnetically actuated system to deflect and control an optical fiber. By considering the optical fiber to be a cantilever, fixed at one-end and free at the other, the amount of the deflection and the angle of the free-end, can be modeled and calculated using the Euler-Bernoulli theory. In order to apply the desired properties for electromagnetic field control, a series of ring permanent magnets was attached at the free end of the optical fiber. Four solenoid coils were installed around the optical fiber to produce movement in the $xy$ plane. The coil currents were derived using the custom designed current driver board, one which was controlled by an Arduino Duo micro-controller and transmitted through an SPI communication. By driving the current in the coils, external electromagnetic fields were generated around the permanent magnets. The interaction between the generated electromagnetic fields, by the coils and the ring permanent magnets, generated the desired torques to control the optical fiber in the $x$– and $y$-axis. In order to increase the accuracy of the system, closed-loop PI controller was used. The beam of light generated by the fiber-coupled laser device was deflected by a glass splitter to a photo-detector sensor. The actual position of the light was measured by the sensor and was used as feedback to the controller. The control command generated by the tracking error and PI controller was added to the feed-forward command and applied to the coils through the current driver board to control the current in the coils. The simulation and experimental results showed that an optical fiber can be accurately controlled by applying an external torque and by applying magnetic actuators. The main features of the newly designed system are: (1) high resolution at the micron scale level, i.e less than 200$\mu$m, (2) the ability to generate different geometric patterns with high accuracy and precision, (3) Low-cost system as a solution for automated minimally invasive surgery, and (4) non-contact actuation system with high scanning speed rate.

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