Control of automatic laser surgical system

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Abstract—**This paper discusses the testing of a prototype of a laser surgical system controlled by two motors. The paper introduces the experimental setup for building the system, the problems encountered, the algorithm for controlling the motor, and the fields to be further studied in the future.**

Keywords—laser cutting , surgery, motor control, mirror reflection system

I. INTRODUCTION

Laser cutting is an important approach in surgery to accurately cut, coagulate, or remove the designated tissues with minimal damage to the surrounding areas. It is widely used in surgical applications such as oncology, neurological surgery and cardiovascular surgery[1]. In current practice, laser cutting is mainly manually operated by experienced surgeons. However, operating the laser cutting machine is a very sophisticated work that needs a great amount of persistent attention, and the cutting speed is also restricted by the limitations of humans. So it would be helpful if we can develop a laser surgical system that can automatically cut the tissues following the designated setup. Currently our team is working on a surgical system that can be used to accurately and efficiently remove the tumors during a surgery using a laser system that uses the laser beam to cover the designated area and remove the tumor using the heat from the laser.

To be specific, the objective of this project is to develop a dual-motor reflection system that works in a small-sized automatic surgical machine, which leads the laser to the designated position and cut the tissue according to its shape. The system is designed to be applied in surgeries to assist the surgeon to remove the focus accurately and efficiently. With the edge of the cutting area as an input, the system will control the motors to change the orientation of the mirrors in the system, so that the laser beam is reflected under control and follows a designated pathway through calculation. With the configuration of the system fixed and the distance to the target as well as the radius of the laser beam determined during setup, the system will be able to enable the laser beam to cover all the area of the focus. The tests will be carried out on a prototype using 3D printed components to hold the motors and fix the mirrors, and a laser pointer will be used as a laser source for testing.

II. METHODS

In this project, there are two motors positioned perpendicularly with a mirror attached to their axles, as shown in Figure 1. The model of the motors is RMD-L-4010, which is a motor with built-in encoder with high control accuracy. The motors are fixed on a motor holder shown in Figure 2 and attached to a 3D-pinted fixture. The motors are connected to a PCB module that supports power as well as sends control signals to the motor, as shown in Figure 3. The PCB module is powered by a 24V 6P lithium battery as the power input. The control is carried out by a Teensy module connected to the PCB board, which is a development platform based on Arduino.
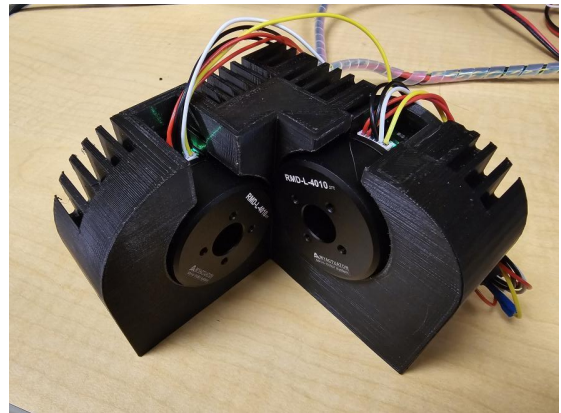

Figure 1. Configuration of the motors
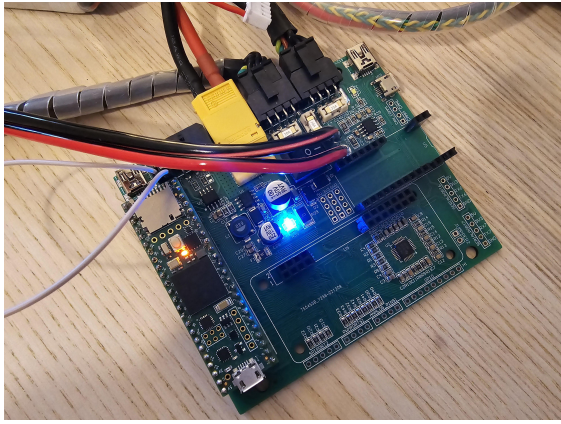

Figure 2. The motor with the holder

Figure 3. The PCB board with Teensy

The laser pointer is held by a 3D-printed holder, as shown in Figure 4. The holder consists of two parts: the fixture and the base. The fixture holds the laser pointer and is attached to the base through a track. The fixture can move along the track and adjusts to the height that best aligns with the first mirror. After adjustment, two screws are inserted into the track to fix the position of the fixture.

Figure 4. The holder of the laser pointer

Two mirrors of different sizes are attached to two mirror fixtures of different lengths, as shown in figure 5. The bottom of the mirrors are clamped by a small plate attached to the fixture through two screws. The mirror fixtures are then attached to the motor and further calibrations of its orientation will be carried out. The base size of the fixtures are adjusted during testing to eliminate the interaction of two fixtures. As the mirror holder of the fixture is also breaking easily during testing, the back of the fixture is reinforced. A small amount of adhesive is applied at the bottom of the mirror to avoid it from loosing during the tests.

The reflected laser will be directed to the receiving plate, which has an area of 10cm × 10cm. The receiving plate is made of three parts: the front frame, the back frame and the curtain screen. Both frames have a thickness of 1cm and are 3D-printed. The front frame has a base that makes the whole plate stand on the platform and keeps it vertical. The back frame is attached to the front frame through four screws in the corner. The curtain screen is made of paper and placed in the

middle of the two frames and it is also fixed by the screws as the screws penetrate the four corners of the paper. The center of the paper is set as the origin during the calculation, and the positions of the two motors are calibrated so that the laser is directed to the center of the receiving plate during the initial setup, as shown in Figure 6.
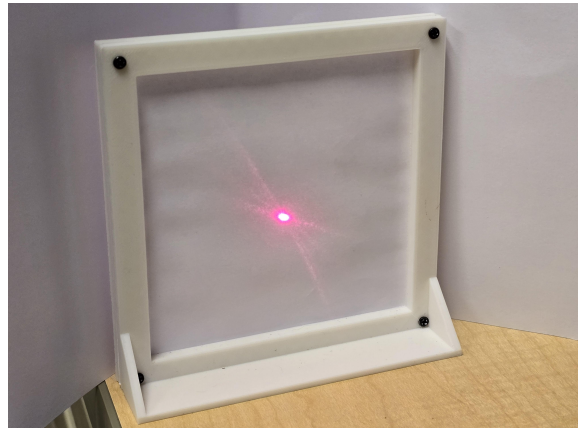

Figure 5. The fixture of the mirrors

Figure 6. The receiving plate with motor orientation calibrated

So overall speaking, the beam will come in from a fixed orientation, and be reflected by the two mirrors before reaching its final destination on the receiving plate. The whole prototype configuration is shown in Figure 7.
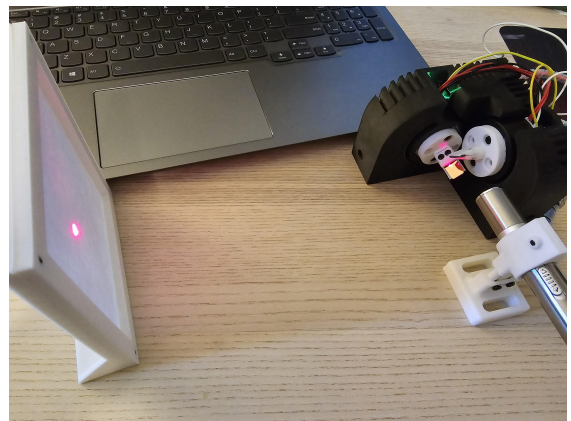

Figure 7. Configuration of the prototype

The system takes a 2D shape as an input, which is denoted as a set of points in the 2D coordinate. The motor then controls the motor to direct the laser beam to follow a track that covers all the area inside the shape, which is similar to a 3D printer filling a layer with melted filament, but in a different routing sequence.

The motors are identified through their motor IDs. The motor with the longer mirror has a motor ID of 1 and the motor with shorter mirror has a motor ID of 2. The light is first reflected by the smaller mirror on motor 2 and then reflected by the longer mirror on motor 1. Motor 2 controls the movement of the final point along the x-axis, while motor 1 controls the movement of the point along the y-axis. For the motor control, the rotation in the counterclockwise direction is positive. So if we set the angular change of the motors to be θ_1 and θ_2, respectively, and we set the distance of the mirror set to the receiving plate to be d, then we have

$$x = d \cdot tan(-\theta_2)$$
$$y = d \cdot tan(-\theta_1)$$

So given the coordinate of the target point, the angular change of the two motors can be expressed as

$$\theta_1 = -atan(\frac{y}{d})$$
$$\theta_2 = -atan(\frac{x}{d})$$

In order to move from one point to another point in a smooth way, we can move the motor in small steps and set a short delay after each step. Given the coordinate of two points A and B, in order to move from A to B, we may divide the segment AB into many small segments with length Δl. The length of Δl as well as the delay can be determined by the actual need for the cutting speed. In order to know the displacement of x and y for each step, we need to first obtain the information of the orientation of the segment AB. Assuming that B is on the right ride of A and B is below A, we have

$$l_{AB} = \sqrt{(x_A - x_B)^2 + (y_A - y_B)^2}$$

Let the angle between segment AB and the x-axis be α, we have

$$cos\alpha = \frac{x_B - x_A}{l_{AB}}$$
$$sin\alpha = \frac{y_A - y_B}{l_{AB}}$$

So the displacement in the x and y direction can be calculated by

$$\Delta x = x_A + \Delta l \cdot cos\theta$$
$$\Delta y = y_A - \Delta l \cdot cos\theta$$

The laser beam first follows the track of the given contour. After that, it decreases the size of the track for scanning with a fixed portion amount of displacement for the next sets of points, as shown in Figure 8. That is to say,

$$\frac{AA_1}{AO} = \frac{BB_1}{BO} = \frac{CC_1}{CO} = \frac{DD_1}{DO} = \frac{EE_1}{EO} = p$$

The amount of decrease is based on the diameter of the laser beam. The larger the diameter, the smaller the next track. The requirement is to at least cover all the areas included in the original shape. In order to carry out a relatively uniform scan, we need to make the origin close to the center of the tumor. As most tumors have some irregular polygonal or oval shape, we may denote it as a random polygon with obtuse angles in the corners. In order to make sure to cover all the area, we need to find the next set of points based on the minimum value of maximum decreased portion p among needed displacements. If we exceed that value, there will be uncovered area, which is not the expected result.
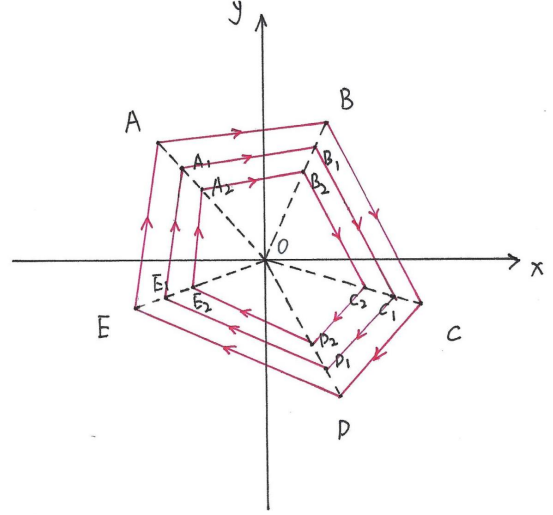

Figure 8. The configuration of the track

In order to calculate the portion of size decreasing, we need to calculate the distance of the origin to the segments. We first need to calculate the slope of the segment, take segment AB as an example, we have

$$m = \frac{y_B - y_A}{x_B - x_A}$$

From the equation of line AB

$$y - y_A = m(x - x_A)$$

We have the equation of line AB in the general form

$$(y_B - y_A)x - (x_B - x_A)y + (x_B y_A - x_A y_B) = 0$$

Based on the equation of a point to a straight line we have

$$h = \frac{|Ax_0 + By_0 + C|}{\sqrt{A^2 + B^2}}$$

In which $x_0 = y_0 = 0$ for the origin. So plugging in A, B and C into the equation, we have

$$h = \frac{|x_B y_A - x_A y_B|}{\sqrt{(y_B - y_A)^2 + (x_B - x_A)^2}}$$

So the maximum portion p of size decreasing can then be expressed as

$$p = \frac{r}{h}$$

In which r is the radius of the laser beam. So the minimum value of p is

$$p_{min} = min\{p_A, p_B, p_C, p_D, p_E\}$$

The next set of points, take A_1 as an example, can be denoted as

$$x_{A_1} = x_A \cdot (1 - p)$$

$$y_{A_1} = y_A \cdot (1 - p)$$

And then the laser follows the trace of the decreased contour until $1 - np < 0$, in which n is the number of contours scanned.

III. RESULTS

There are many problems found during the testing process. It was found that in order to control the motor effectively using Teensy Arduino, the position plan max acceleration/ deceleration/ speed, as well as the speed plan max acceleration needs to be set to a small value. The motor position zero needs to be set to a value that is generally lower than 10000 pulses. It is also found that although applying the same version of Teensy 4.1, the current setup is not compatible with Arduino 2.x version, and lower Arduino version such as Arduino 1.8.16 needs to be applied in order to enable the motor run normally according to the parameters of the functions as well as to read the correct data back about the current position. One of the greatest difficulties is that the software for tuning the motors does net work with most of the computers in use. For the computers compatible with the software, it may become not compatible after a system update, or in random cases. Another major issue is that the motors have different kinds of errors themselves, such as not being able to connect to the software, does not move, or does not respond to the control of Teensy. Among the seven motors by hand only two turned out to be working in the end. And one of the two motors also encounters an expected resonance with the fame that makes the motor vibrate fiercely once turned on. It will stop vibrating upon a touch, and start vibrating again after running for some time. The tricky thing is that those motors are actually adjusted to the same settings in the software. A possible approach might be resetting the motor configuration to the factory default settings, which includes rewriting the setting up file provided by the manufacturer.

Finally the motor is able to follow a designated track during the test, and there are some small vibrations as the laser point follows the track. It might be hard to observe from the motor, but as the vibration is amplified by the distance of the beam to the receiving plate, further tuning of the motor might be needed to provide a smoother tracking.

IV. CONCLUSIONS & DISCUSSIONS

Automatic laser cutting is a very promising field in future surgery. In this project, a prototype is built for testing the dual-motor reflection system which is designed to be working in a small-sized automatic surgical machine. Currently the motor is able to follow a designated track, while additional tuning of the motor needs to be carried out for optimization. There are actually several methods of establishing the track at the beginning, such as scanning the area continuously from one side to another. This approach was not applied in the end

because it is likely that this will have the risk of causing the laser to cover the undesired adjacent areas. When a tissue is heated by a strong laser beam, the collagen will breakdown, causing the tissue to shrink[2]. So the undesired tissue will be dragged to the designated cutting area due to non-uniform shrinking. But if we first cut along the contour and then move to a smaller contour, although shrinking still occurs, it will be uniform towards the center of the tissue, and the tissue, if dragged in, will be the area previously cut, which is still the focus that needs to be cut, thus causing less threat to the surrounding healthy tissues.

And also, one of the assumption made here is that the tumor is generally having obtuse angles along its edge and the origin is generally selected to be at the center of the tumor, that is to say, the distance between the origin and the edge of the tumor generally does not vary a lot from each other. If the tumor is having some uncommon irregular shape, the tracking method may cause some of the tissues to be receiving much more heat than others due to overlapped coverage. For example, as shown in Figure 9, the ratio is much smaller than . As we need to ensure to cover all the area, we need to use the lowest ratio for each step towards the center, which is . This will cause the tissue along to be covered by laser for about 4 times, which is 2 times more than needed as it only needs about 2 steps. One of the solutions is to apply an adaptive cutting speed based on the ratio between local step ratio needed and global step ratio applied. If there is a lot of overlap, then we increase our speed after the first step, as the tissues at the edge will only be covered once so that it needs to be scanned at the original speed. Further modifications might include separating the tumor areas into different sub-areas where we are able to locate an origin that has similar distances to the edge points.
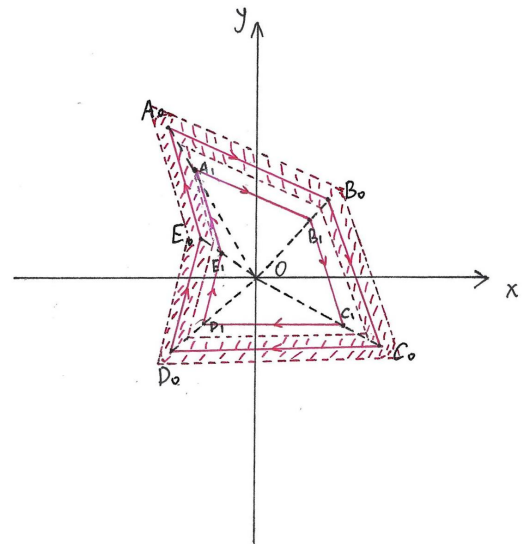

Figure 9. A special configuration to be further studied

Additional work in the future includes adjusting the laser strength by changing the tracking speed on different parts of the tissue, if we are able to have a 3D shape as an input. The cutting speed will be adjusted according to the depth on each part of the tissue.

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