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The implementation of an intuitive man-machine interface in robot-aided endoscopic laser surgery

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Abstract

The precision of laser endoscopic surgery mainly depends upon the skill of the surgeon i.e. the accuracy of movement and the coordination between firing and speed of movement, which determines the depth of vaporisation. We implemented an intuitive drawing interface to control a robot in order to facilitate manual skills and enhance precision. The accuracy of the robot system was evaluated by assessing its performance with sinusoid test signals; the enhanced precision in comparison with classic surgery was demonstrated by cutting characters on an apple. In addition, we monitored the speed of the laser movement and the focal distance of the laser by tracking the laser spot on the screen. This is used to generate continuously a high quality cut of constant depth.

Keywords: Intuitive interface, Minimal invasive surgery, Endoscopic robot, CO_2 laser

1. Introduction

Minimal invasive surgery (MIS) has become increasingly popular on recent years [1]. In MIS procedures surgeons acquire visual information of the operative site by an endoscope and manipulate instruments through small apertures to perform surgery. Endoscopic surgery has the advantages of less pain and morbidity for the patient while possibly enhancing precision through the enlarged view [2]. Endoscopic surgery on the contrary, requires additional skills and training of the surgeon, in order to prevent complications. The main difficulties are the hand-eye coordination, the lack of depth of vision and the instruments used. Lasers are widely applied in MIS procedures, especially in gynecology [3]. It is an ideal cutting instrument because of its precision having coagulating properties for vessels up to 1mm. During CO_2 endoscopic surgery a red He-Ne laser spot indicates the impact point of the invisible CO_2 laser on the TV screen. Since the laser is coupled to the endoscope, the laser spot is moving simultaneously with the endoscope. Thus, surgeons perceive the visual information from the TV screen and steer the endoscope with one hand to cut with the laser. It is as drawing on the screen by the laser. The focal distance of the laser, speed of movement and the accuracy of the movement are essential for the cutting performance since power density is highest at the focal distance and since depth of cutting depends on the speed of movement. In comparison with open surgery CO_2 laser surgery required from the surgeons a new style of control. The motion command is opposite to the desired motion as perceived, and the scale is arbitrary and unknown. Indeed, there are no direct indications for the focal distance. Surgeons only approximately estimate the distance to the tissues by referencing the size of the organs or the spot position on the screen [4]. In addition, the foot pedal used to activate the laser can distract the surgeon. Accidents were reported by accidentally activating the laser. It is physical demanding to manipulate the endoscope with camera and laser for a long time, maintaining precision and safety. Thus, taking all difficulties into account, it is not easy to achieve high quality performance during long periods. Therefore, specific training and improved man-machine interface by the aids of robotics and advanced technology, such as stereovision or voice command were introduced [5].

We improved an existing endoscopic robot to manipulate the endoscope and laser. An intuitive and ergonomic wireless pen and drawing interface are introduced to control the laser tip. The pen button replaces the foot pedal. A real-time DSP controller represents the commands from the surgeon to robot. The spot moving speed is monitored and the distance to the tissues is estimated by image processing techniques.

2. Methods

The modified endoscopic robot is the FIPS system from KARL STORZ GmbH & Co (Tüttlingen). This robot has only 4 degrees of freedom (DOF), 3 revolute and 1 prismatic joints, (Figure 1). Its fixed rotational point that coincide with the trocar insertion through the abdominal wall made it possible to limit the robot to 4 DOFs. The original 8 buttons control commanding the 4 DOFs is sufficient to position the endoscope. The robot was developed to hold the camera, not to perform surgery. The scale between the drawing movement input to the laser spot output is adjustable to switch between fine or fast cutting situations.

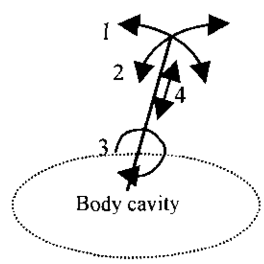

Figure 1. The 4 DOFs of FIPS system: 1,2,3 are revolute joints; 4 is prismatic joint

A digitizer tablet and a wireless pen that are commonly used in Computer Aided Design (CAD) were implemented to replace the button control interface in order to take advantage of humans' drawing skill. The tablet is known to be a better interface for continuous tracking and drawing [6]. The relative position on the 2D tablet is translated to the endoscope's orientation by the two rotation axes. A low pass filter is installed to eliminate the tremor of the surgeon to improve the stabilisation of the robot.

The laser trigger is put on the pen instead of the commonly used foot pedal. By pressing the button on the pen when drawing on the tablet, surgeons can easily control laser firing without affecting the stability. It is simple, intuitive and ergonomic for both novice or experienced surgeons. They can look on the screen and draw/cut/ablate tissues by the intuitive drawing interface as if drawing on the screen. In figure 2, the set up of the whole system is shown. With this system, surgeons can operate, using the intelligent robot and intuitive interface.

3. Results

The system was made operational successfully. The accuracy was tested by applying sinusoid input signals to the two revolute axes. They were used to handle the orientation of the endoscope and laser to cut on the tissues. Two sinusoid signals with 90-degree phase lag were applied from the DSP itself to both axes simultaneously. Then, the robot will draw a circle on a surface. Afterward, we use the tablet to measure the output of the tip of the endoscope where we coupled the wireless pen as the extension of the endoscope. It is put perpendicular to and contacts the tablet at the center of the circle. The amplitude of the sinusoid signal is 5° in each direction and the frequency is 0.25 Hz. The distance from the rotation point (trocar) of the robot to the tablet is set fixed at 21cm for easy calculation. As shown in figure 4, the output of the x-y plot on the tablet does not fit perfectly to the input circular trajectory but the repeatability of the robot is quite good. In figure 5, from the separate results of both axes in time series, we can see the maximum error of both axes is around 0.7°, occurring at maximum speed. The backlash-induced error is relatively small.

The intuitive interface robot is mainly designed as an instrument to be manipulated by surgeons. To demonstrate the feasibility, we applied a second test, which used the interface to write some characters on the surface of an apple. This illustrates the idea and achievement of this development. The test is performed in a simulated operating situation. The user looked at screen and wrote the characters by hand. The result can be seen in figure 6. The reference scale indicates that each character is about 3 mm high × 3 mm wide.

A simple linear model was built to estimate distance to tissues. We acquire the images of the endoscope sequentially from a frame grabber. The image-processing algorithm for laser spot tracking is implemented in

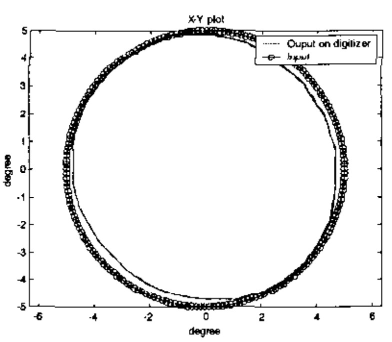

Figure 4. The results of sinusoid testing on the tablet

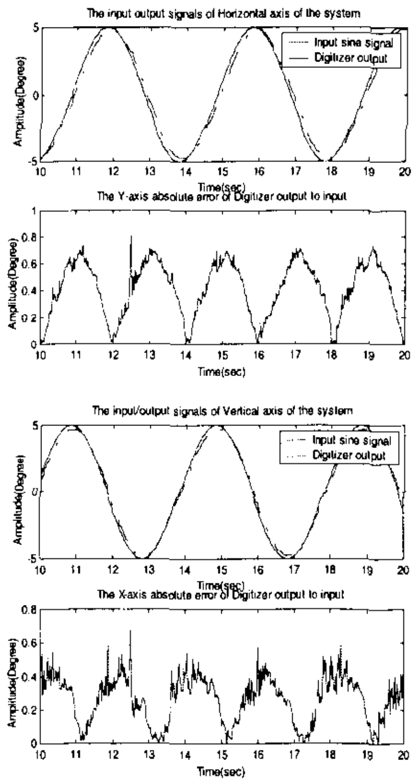

Figure 5. The input/output signals and errors of both axis

the program. It can calculate the distance between laser spot and center of the lens on the image and evaluate the distance to tissues. The frequency of the measurement is about 5 Hz. The estimated distance is shown on the screen and feedback to the controller to calculate the speed of movement. The image processing is not very fast and robust due to the time needed by the frame grabber card and the image-processing algorithms.

Figure 6. The PMA apple

4. Discussion

A medical robot for endoscopic surgery should have the following characteristics: accuracy, stability, mobility, lightweight, easy sterilizing, back-drivability, small, high safety, simple manipulation and easy installation. Initially, the data from the first test suggested that the accuracy of our robot was not very good. The errors came from many sources such as the time delay between the input and output signal, the vibration of the structure that supports the robot, the deviation when installing the tablet, the dynamic friction in each axis and so on. In the second writing test shown in figure 6, however, the user could write characters smoothly and easily due to the adaptation of the hand-eye coordination. In conventional manual endoscopic laser surgery, the outcome varies depending on the dexterity and skill of the surgeon. It is obvious that it is almost impossible to achieve the same results as using the robot. The 4 DOFs simplified the control of the robot and furthermore the implementation of the drawing interface resulted in ergonomic and intuitive accurate manipulation of the cutting using a laser.

In hand held procedures, the cutting characteristics of the laser are only roughly controlled due to a lack of information. Indeed the focal distance determines the power density, which together with the speed of the movement of laser determines the energy per area. We extract information of distance from the video stream by tracking the laser spot, providing the auto focus function. We also estimated the movement speed of the laser contact point. This can provide surgeons with a sense of the desired movement. Moreover it becomes possible to automatically smoothen laser speed in order to maintain a constant depth of cutting. The writing test in figure 6, where the absorption rate is represented by the depth and width of the cutting line shows that the absorption rate is almost uniform by the intuitive writing interface manipulation. This illustrates that our interface simplified the control and enables surgeons to perform a high quality cutting. Our application takes advantage of human skill, which as well plays an important role in the procedures. With our drawing interface to manipulate the robot, surgeons are able to improve the cutting performance significantly.

The auto focus of the laser is not yet completely installed due to the robustness of image processing. Like most algorithms, the illumination and the calculation time rule the performance of the tracking program. Improvement is possible by upgrading the frame grabber card, applying advanced image processing technique and optimising the program. In addition the distortion should be taken into account to have a more accurate model. Clinically, however, the actual method probably is sufficient in most circumstances.

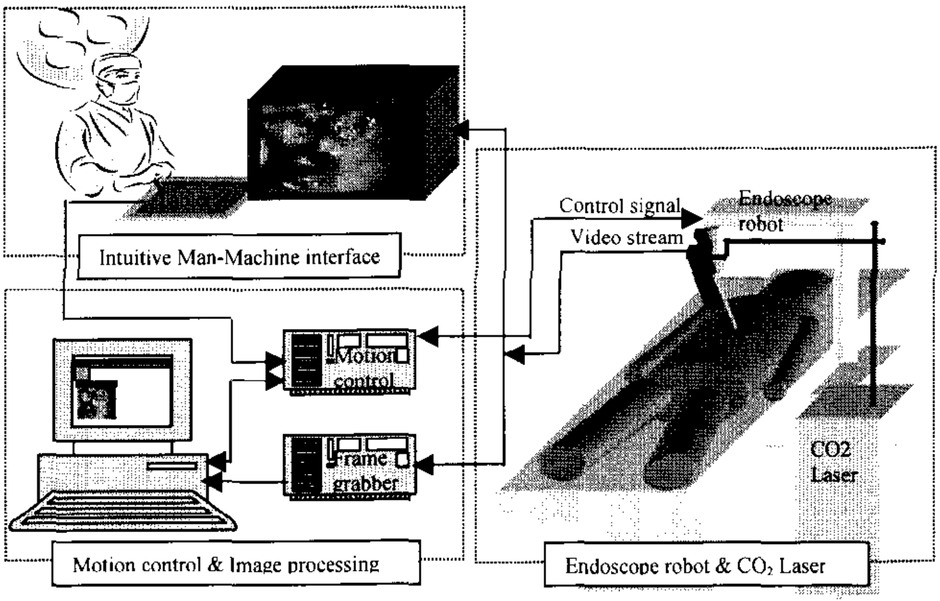

Figure 2. The intuitive operating robot system

Distance to tissues is very important in laser cutting since the laser should always be focused. In order to implement an auto focus function on the system, we must have a sensor to measure the distance to the tissues. As illustrated in figure 3, vision and laser cutting use different channels. We can adjust the center of lens and the laser beam to be parallel. Therefore, δ remains constant. By using simple optics theory, we assume that s is proportional to d without considering the distortion of lens. However, the size of images shows on the screen s_s is constant. Thus, we can get the relation between d and δ_s is inverse proportional. We use this algorithm to obtain the approximate d to use in our auto focus function. Since δ_s can be measured manually or by image processing techniques. At first, we acquired the reference δ_s from the image when the laser is focus on the tissues. Then, image-processing techniques are implemented to track the laser spot on the screen continuously where the distance d can be evaluated. By this information, we can control the prismatic joint to focus the laser automatically. Moreover, by accessing the information of distance and of orientation of the laser beam, the movement speed of the laser contact point can be estimated and shown. It could be further extended to display the profile of the surface inside human body.

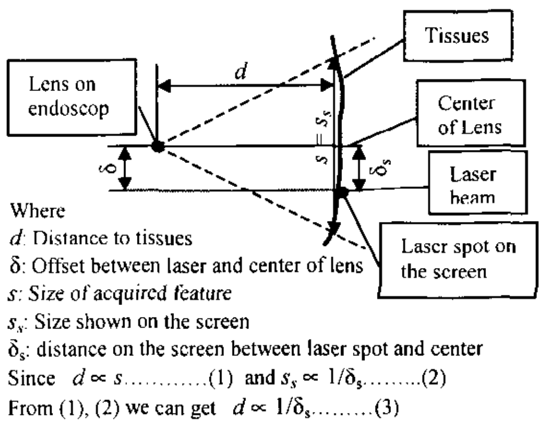

Figure 3. The relation between distance to tissues and laser spot on the screen

Because the FIPS system is originally designed for holding the camera, not for precise cutting, it still requires further enhancement or redesign to improve repeatability, accuracy, stability and back-drivability. Since this system only acts as one hand of the surgeon, a second robot could be developed to enhance the other hand's ability. Finally, the most important issues in medical robotic application are the safety requirements, which includes: hardware, software and redundant sensors. The robot system must perform fail-safe operation and should have the ability to predict errors not only to perform safely but also to prevent human mistakes. Therefore, the development of specific intelligent monitoring system is crucial in the future. Firing accidents could be prevented by linking firing to movement.

5. Conclusions

This paper describes the ideas and realization of converting the navigation endoscope robot into an advanced intuitive operating instrument. By implementing the acquainted intuitive man-machine interface and replacing the foot pedal with a pen button, surgeons can achieve comfortably more accurate operation with less training. The relationship between the spot and the screen is used to obtain the distance from the laparoscope point to the tissues and the speed of movement. This is used to automatically focus the laser by fixing the distance to the surface and to monitor the speed of movement in order to obtain a constant high quality char-free cut of the spectacular CO_2 laser.

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