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Implementation of Force Feedback on Surgical Manipulator for Minimally Invasive Surgery

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Abstract: In this paper, a surgical instrument integrated with a piezoelectric force sensor using advanced computational algorithms is proposed. The instrument could measure grasping force directly at the end effector. For this purpose, grasper-integrated piezoelectric force transducers were embedded in the forceps of the instrument. The compact design of the sensor was realized with a long rectangular structure. The instrument was tested focusing on the factors such as resolution and root mean square error by using reference sensors. Through the experiments, it was confirmed that the proposed method worked well. The force feedback at the tip of the forceps is beneficial for avoiding tissue damage caused by the surgeon's grasping and incipient slips. It allows the force feedback control of robotic systems with improved surgeon's operation skill. Furthermore, the sensorized forceps were easily fabricated and are inexpensive.

Keywords: Robotic Surgery, Minimally Invasive Surgery, Force Feedback, Force sensor

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1. Introduction

Over the last decade, robotic technology has been used in education empowerment of health care and virtual reality robots have been training and evaluating surgeons. Techniques such as computed tomography, magnetic resonance imaging, and ultrasound are used in surgical imaging to design software for computer-aided surgery [1-7].

In the early 80's, the great accuracy and untiring nature of industrial robot proves its effectiveness and consider the possibility of using the robot in medicine [8]. By the 1990s robots have been introduced into a variety of areas of medicine including surgery and specifically minimally invasive surgery (MIS) which involves performing surgery through keyholes [9]. MIS has many advantages over certain types of operations performed by open surgery. These advantages included a shorter postoperative hospital stays allowing the patient to resume their daily activities earlier, lower patient stress level, and quick healing. As MIS developed and became more common, robots were introduced into the field [10-12].

MIS places many restrictions and challenges over open surgery [13, 14]. The surgeon performs through a set of holes. Instruments with a long handle cut and grip the tissues within the body, and a camera provides the internal view of the operating field. MIS avoids the long incisions, Patients recover more quickly, reduced hospitalization, and improved healing. The operating area required in MIS is different from open surgery. There are only a few fixed points of entry of instruments. The type of movement is also limited by MIS, lateral movement is impossible. The fulcrum effect is one of the difficult challenges of MIS [15].

The surgical robot has made great progress and is working efficiently in the operating room. The da Vinci tele-operated robotic system is based on a master-slave control concept [16]. It consists of two major units. The surgeon's console unit houses the display system, the surgeon's user interface, and the electronic controller. The second unit consists of four slave manipulators, three for telemanipulation of surgical instruments and one dedicated to the endoscopic camera. By incorporating advances in surgical simulation and robot-assisted surgery, patient-specific surgical plans can be derived with robot manipulation included [17, 18].

The first version of the da Vinci system had no instrument-specific arm. In 2003, Intuitive Surgical introduced a significant upgrade to the system by offering a fourth instrument arm, dedicated to the camera–telescope assembly [19]. Furthermore, the system provides a greater workspace via instrument extension and an increased range of movement. The latest generation, the Da Vinci Si System, was released in April 2009 and has a dual console that allows two surgeons to work collaboratively [20]. This allows more efficient training of residents and surgeons, especially those unfamiliar with robotic-assisted surgery.

While the robotic surgical systems grease complex surgical operations to facilitate complex surgical operations the real-time feedback is a major factor. Surgical manipulators and laparoscopic instruments do not provide tactile sensation hence operator is unable to sense how much force is being applied. Due to loss of information a serious type of trauma or tissue damage could occur, so the operator has to be very careful. This limits the range of surgical techniques and affects the surgeon's dexterity. To address this issue various force sensing techniques are studied for minimally invasive robotic surgery.

Force and tactile sensing instrument development is active research involving several disciplines of science and engineering, among those sensing principles, displacement-based sensing seems to be the simplest way to measure forces. It allows measuring the magnitude of forces over a wide range, but its usefulness is usually limited to the measurement of forces in only one or a few directions. Current-based sensing offers two possibilities to detect forces through the current of the motors and the pneumatic pressure respectively. Elimination of specific force sensors is an advantage of those sensing schemes, but good measurement accuracy is difficult to obtain since the forces are not directly measured.

Friction, backlash, gravity, and inertia of mechanical linkages could greatly degrade the quality of the force measurement. For cases where high accuracy is required, a direct force measurement scheme using strain gauges is preferable. Many research groups have intensively investigated related issues and much research work is currently undertaken [21-23]. However, before a sensing instrument can be practically applied in MIS, major obstacles concerning hardware design, signal processing, surgical systems integration, and human-machine interface must be overcome.

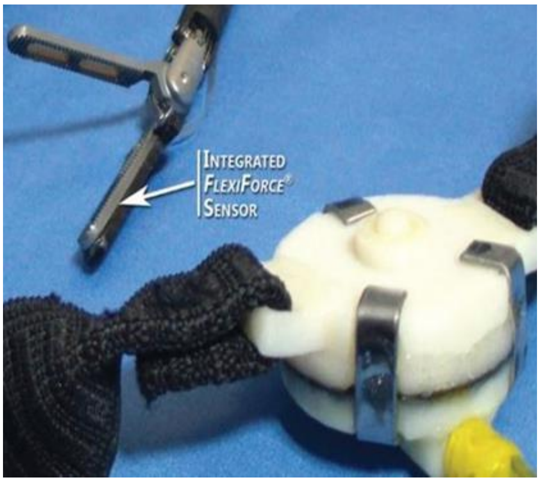

Figure 1. Integration of Force Sensing Resistor on End Effector.

Tactile sensing also depends upon the type of operating tissue which varies greatly from organ to organ. The modeling of needle insertion helps in accurate surgical simulation and robotics technologies applied to percutaneous therapy. Search models have been the topic of many studies. Knowledge of forces during needle insertion can help to identify models and different tissue types. Human biological tissues are known to exhibit in nonlinear properties and consist of inhomogeneous the Hunt-Crossley model has been confirmed as being suitable for describing the properties of viscoelastic tissues especially when small deformations are involved. One of the key issues is that the insertion force varies from one patient to another for the same tissue, the insertion force can be different depending on the age, gender, or body mass of the patient. Even for one patient, the insertion force needed for one tissue can vary, for example, if the tissue is diseased. Moreover, requiring data from biological tissues and developing an appropriate model for application and simulation or robot-assisted surgery is difficult due to tissue deformation, inhomogeneity, and nonlinearity. As a result, it is necessary to design to needle insertion force so that it accounts for the uncertainty in the tissue decomposition.

This study aims to propose a system that can provide force feedback to the operator during surgery. Different types of force sensors are tested and their accuracy is studied. The maximum stress applied to tissues such as the liver was measured as about 200 kPa before damaging [24]. The stress can be calculated as 5 N, assuming that the grasper's surface is 25 mm2. The assessment of the prototype indicates the potential of the feedback system which can be used for further development in this domain in the future.

For papers that report original research, you should use the titles "Materials and Methods", "Results", "Discussion" and "Conclusions" (optional).

2. Materials and Methods

The laparoscopic arm is modified and mounted on a manipulator. The manipulator is controlled through a console that incorporates encoders. The position of encoders gives the coordinates for inverse kinematics function which then translated into motors movements while the End Effector is controlled separately. A camera is mounted on the manipulator for vision purposes and a force sensor is used on the end effector for the force feedback system.

Figure 1 shows the block diagram of the manipulator. Operator control is the input that feeds the microcontroller which in response precisely controls the rotation of each joint to reach a specific point in space. The feedback from encoders of the stepper motor is read by the microcontroller to measure any error in the rotation of the motor. The feedback from the force-sensing resistor (FSR) is also fed into the microcontroller which measures the physical pressure it is facing by holding the object.

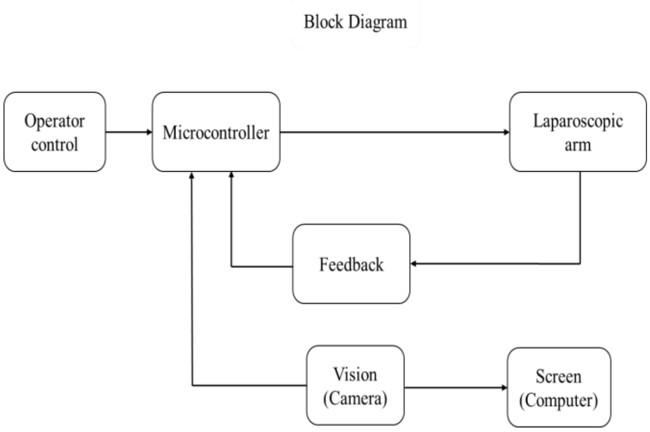

Figure 2. Block Diagram of proposed Surgical Manipulator

The robotic arm is designed on SolidWorks and 3D printed. 3D printed the arm provides the required strength flexibility of design. 3D printing the robotic arm allows to test of the various design with the least cost and in a shorter time.

Figure 4 shows the printing process. The SolidWorks designed parts are imported to the printer's specific slicing software Cura and printed by using PLA filament. PLA is non-toxic and provides excellent strength to weight ratio of 3.29 which allows the design to be lightweight but strong enough for the required operation.

Figure 3. 3D printing of Robotic arm.

For the application of surgical manipulator, a highly precise control and real-time feedback system is required. Stepper motors are widely used in robotics due to their precise control. The standard PBX Series 2-phase stepping motor offers balanced performance enhanced by high torque, low vibration, and low noise.

PXB43H-O1B, 2-phase (1.8 deg/step) with encoder offers high torque and precise feedback capability. It incorporates incremental encoder feedback and two feedback resolutions i.e., 200 and 400 pulses/rev, hence provides closed-loop system capability.

A rotary encoder is used inside the console assembly to control the position of stepper motors. It converts rotary position to an analog or digital (e.g., digital quadrature, 32-bit parallel) electronic signal.

Such encoder can be either absolute or incremental. The signal from an absolute encoder gives an unambiguous position within the travel range without requiring knowledge of any previous position. The signal from an incremental encoder is cyclical, thus ambiguous, and requires counting of cycles to maintain absolute position within the travel range. Both can provide the same accuracy; the absolute encoder is more robust to interruptions in transducer signal, whereas the incremental encoder reports position changes in real-time.

The control signal from an encoder is feed in the EasyDriver which controls the rotation of the stepper motor. It provides lower latency as compared to other motor controllers thus reduces the propagational delays between encoder input and motor rotation output. So, the input and motor rotation are exactly synchronized. It can drive up to about 750 mA per phase of a bipolar stepper motor.

The control of the end effector is achieved by the servo motor. It provides high holding torque in a small footprint with the help of a gear set. As for the end effector it only needs to be open and close so 180o servo motor achieves this task efficiently.

A piezoelectric sensor converts the mechanical stress into electric charge and gives AC at the output. The piezoelectric effect is a reversible effect that means as mechanical stress is applied it gives voltage as output and when voltage is given to the sensor it gets stretch or compresses. These sensors are made up of Quartz crystal, a naturally occurring piezoelectric material. It provides impedance < 500 Ω and voltage < 30Vp-p. The strain sensitivity is about 5V/µƐ. The piezoelectric force sensor is repurposed for the required application and its accuracy is tested.

Figure 4. Piezoelectric force sensor.

FSR measures physical pressure, squeezing, and weight applied across it. The FSR is made of 2 layers separated by a spacer. The more one presses, the more of those Active Element dots touch the semiconductor and that makes the resistance go down. FSRs are a resistor that changes its resistive value in ohms (Ω) depending on how much it is pressed. These sensors can also be used for force sensing.

3. Results and Discussion

Figure 5 shows the complete assembly of the manipulator with a modified laparoscopic arm as an end effector. The manipulator takes input from the encoders, and the values of the encoders are taken for applying the inverse kinematics. The solution of inverse kinematics only gives angles or rotations for three joints but the rest are controlled by encoders embedded in the console. Which are directly controlling the motors of the end effector (servo motors). The goal of this study is to implement force feedback on surgical manipulators.

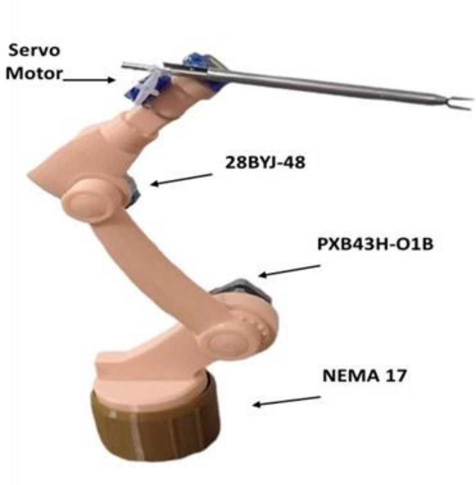

Figure 5. Final Assembly of Surgical Manipulator.

Table 1 shows the DH parameter of the robotic arm. These parameters are computed and fed to the microcontroller. When the end effector is required to reach any pre-defined coordinates, these specific values are used.

Table 1. DH TABLE OF 3 DOF ROBOTIC ARM

Joint i	a_{i-1}	α_{i-1}	d_i	θ_i
1	0	0	0	θ_1
2	L_1 = 100 mm	0	0	θ_2
3	L_2 = 125 mm	0	0	θ_3
4	L_3 = 110 mm	0	0	0

Because many medical devices and surgical tools, such as grippers and laparoscopic instruments, do not provide tactile sensation, there is no way for a surgeon to sense how much force is being applied when using the instrument during robotic surgery. The loss of tactile feedback limits the range of surgical techniques and affects the surgeon's dexterity. Often vibration is used to mimic sensation but it is not feasible to introduce vibration into a delicate procedure so for tactile force feedback various force sensors are introduced into minimally invasive robotic surgery. The placement of the sensing elements is also an important matter that could greatly influence the quality of force measurement.

In this design, the end effector of the manipulator is equipped with the Piezoelectric force sensor which gives the voltage spikes as the grasper grips a tissue. The value of output voltage implies that how much force is being applied to the tissue. The voltage value of the Piezoelectric force sensor is read by the microcontroller and plot GUI interface in real-time. The output waveform of the sensor. Figure. 6, shows the sensorized forceps with sensor wires running through the instrumental shaft.

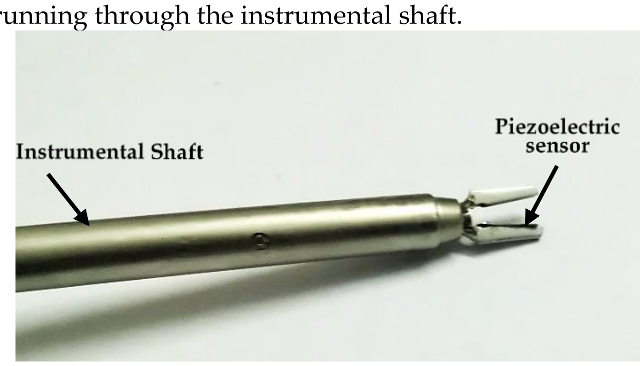

Figure 6. Developed sensorized surgical instrument.

Figure 7 shows the output waveform of the piezoelectric sensor. At the start when the end effector is in rest position the sensor value is way below the set threshold value. Then grasper is close to holding the test object, the output of the sensor instantly rises above the threshold and reaches its maximum value, and drops as it is released. It is done continuously to test the robustness and accuracy of the sensor.

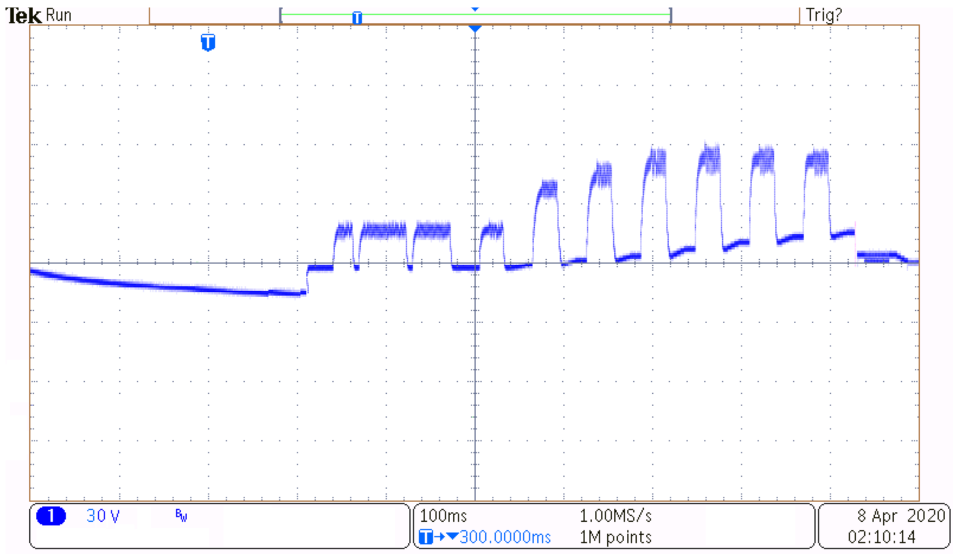

Figure 7. Piezoelectric Force Sensor output waveform

By the implementation of a force sensor on the grasper of the modified laparoscopic arm, it is observed that it provides a sense of applied force with great accuracy. The diagnosis articulates the force reflected at 34s when the gripper hit the base was 390 mN of flexure stress as shown in the Fig. 7. The maximum force the force sensor could pick up was 900 mN. Results show that this sensor provides the necessary feedback which is required and can be developed further for higher accuracy to implement on the actual surgical manipulator arm.

4. Conclusions

A surgical robot with cognitive engine is designed to augment and enhance the hand-eye coordination capability of the surgeon during operation to achieve the desired outcome and reduce invasiveness. The compact design of the sensor was realized with a long rectangular structure. The instrument was tested focusing on the factors such as resolution and RMS error by using reference sensors. Through the experiments, it was confirmed that the proposed method worked well. The force feedback at the tip of the forceps is beneficial for avoiding tissue damage caused by the surgeon's grasping and incipient slips. It allows the force feedback control of robotic systems with improved surgeon's operation skill. Furthermore, the sensorized forceps is easily fabricated, inexpensive. In this study, the proposed design is emphasized handling the tissue with the measurement of applied force only at the front portion of the inner surface. However, during operations, palpation the force sensing at the end of the grasper's tip is necessary because pushing or dragging on the tissues is also needed. This can be done in future studies.

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