

Force sensing for remote robotic laparoscopic surgery

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Interactive force-sensing feedback system for remote robotic laparoscopic surgery

Ian Mack¹, Stuart Ferguson¹, Karen Rafferty¹, Stephen Potts² and Alistair Dick³

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Abstract

This paper presents the details of a combined hardware/software system, which has been developed to provide haptic feedback for teleoperated laparoscopic surgical robots. Surgical instruments incorporating quantum tunnelling composite (QTC) force measuring sensors have been developed and mounted on a pair of Mitsubishi PA-10 industrial robots. Feedback forces are rendered on pseudo-surgical instruments based on a pair of PHANTOM Omni devices, which are also used to remotely manipulate the robotic arms. Measurements of the behaviour of the QTC sensors during a simulated teleoperated procedure are given. In addition, a method is proposed that can compensate for their non-linear characteristics in order to provide a 'realistic feel' to the surgeon through the haptic feedback channel. The paper concludes by explaining how the force feedback channel is combined with a visual feedback channel to enable a surgeon to perform a two-handed surgical procedure better on a remote patient by more accurately controlling a pair of robot arms via a computer network.

Keywords

Force feedback, force measurement, laparoscopic surgery, quantum tunnelling composite, teleoperation

Introduction

In open surgery, a relatively long incision is made in the patient's body to allow the surgeon to gain sufficient access to perform the desired procedure. The incision is made large enough to allow the use of various surgical instruments and to provide good visual feedback for the surgeon. The surgeon can also feel the tissue by either touching it directly, albeit with a gloved hand, or via the surgical instruments.

In minimally invasive surgery (MIS), small incisions are made either side of the target tissue to allow long slender surgical instruments to be inserted via trocars into a carbon dioxide-filled cavity. A camera and light source, an endoscope, is inserted through another trocar, and the surgeon performs the procedure by watching the tips of the surgical instruments inside the body cavity via a video monitor. This requires excellent hand-eye co-ordination. However, with MIS the surgeon can only feel the patient's tissue by touching it with the long surgical instruments, which also diminish the tactile feedback.

In some spinal procedures, a form of MIS is used where instruments are inserted into tissue through incisions, but no gas cavity is created. Instead, the operation is observed by repeatedly pausing to take, or continuously taking, low power X-ray images of the target area using fluoroscopy. This could result in the surgeon receiving a higher dose of radiation than recommended by safety standards.

In order to remove the surgeon from the hazardous X-ray environment, this research proposes the use of teleoperated surgery. Teleoperated robots allow the surgeon to be remote from the patient during a procedure. The surgeon performs the operation by moving pseudo-surgical instruments, which

send position data over a computer network to remote robots with surgical instruments attached. The remote robots mimic the surgeon's hand movements. Visual feedback is obtained by watching the remote fluoroscopy images via a video link. However, there is a serious limitation to this surgical method in that the surgeon cannot feel the forces exerted by the robots on the patient.

The research reported in this paper demonstrates how a novel design of force-sensing instruments and two small industrial robots can be used to create a more realistic remote immersive experience for the surgeon and reduce the chance of iatrogenic injury to the patient.

The teleoperated surgical system is shown in schematic form in Figure 1. The surgeon observes the remote/patient location by watching video feedback on the monitor of PC #5, which is streamed from the camera connected to PC #4 via a standard computer network. The video feedback data path is shown in blue. The surgeon performs the procedure by moving a pair of surgical instrument handles attached to PHANTOM Omnis, which send position data to PC #1. The position data is sent over a computer network to PC

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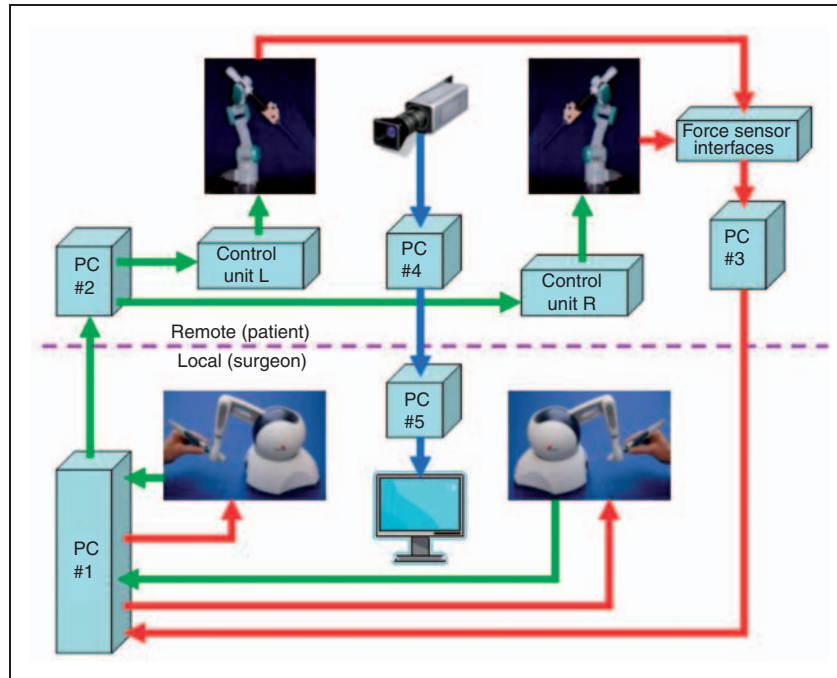


Figure 1. The teleoperated surgical system. The robot positioning data paths are shown in green, the force feedback data paths in red and the video feedback path in blue. Data paths that cross the purple dashed line are via standard computer networks.

#2. This computer calculates the required position and orientation for each Mitsubishi PA-10 robot with its attached surgical instruments. The computer then outputs data to the control units, which move the robotic arms, and hence the surgical instruments, to positions that mimic those of the surgical instruments held by the surgeon. The position data paths are shown in green. Forces applied to the surgical instruments attached to the robotic arms are measured by the force sensor interfaces and sent to PC #3. The force feedback data is transmitted via a computer network to PC #1. This PC calculates the data to be sent to the PHANTOM Omnis to render the feedback forces for the surgeon to feel. The force feedback data paths are coloured red.

The paper is divided into three main sections. The first section describes the force-sensing and rendering system, and explains the criteria that have to be met to accomplish the required sensitivity and analyses the behaviour of the sensor devices. The middle section sets out the details of the force-sensing instrument design. The final section covers kinematic control of the robots, the positioning algorithm, the overall control system for remote operation, and reports on initial user studies. The paper ends with some conclusions.

Sensing and feedback

The human body has five major senses, namely sight, touch, hearing, taste and smell. The senses take information from the surrounding environment and the interpretation of this information by the brain is known as human perception.

In an ideal telerobotic surgery, the surgeon would be unaware of the fact that there was any physical separation between himself and the patient. Therefore, in order to

create the perception of performing surgery directly on a patient, the surgeon's senses have to be encouraged into believing there is no patient/surgeon separation.

The important senses for perception of the surrounding environment during a surgical procedure are vision, touch, smell and hearing. Feedback paths, or channels, for two of these senses, namely vision and touch, are implemented in this research.

Visual feedback

During an operation, visual feedback provides data pertaining not only to the colour and shape of the tissue, but also to the velocities of objects with respect to the surgeon and to other objects. When performing surgery, visual feedback provides the most complete set of tissue quality information, compared with tactile and force feedback, which only provide information about tissue features local to the surgical instruments (Reiner, 2008).

Visual feedback for the surgeon is provided by inputting the fluoroscopy video to a computer, PC #4 in Figure 1. The resulting video is streamed back over a computer network to a PC local to the surgeon, PC #5 in Figure 1. The surgeon can view his actions, as performed by the teleoperated robots, on the computer monitor.

Haptic feedback

In this section we review the state of the art in terms of force feedback for remote surgical procedures. Haptic feedback relates to touch, and comprises both tactile feedback and force feedback information. Tactile feedback is perceived by

cutaneous receptors in the skin, which can sense, for example, texture or temperature. Force feedback is perceived by receptors in muscles, tendons, joints and skin through direct contact with an object (Craig and Rollman, 1999). It provides force, position and velocity information about objects.

There is some crossover, however, as vibration and stretching, for example, are a combined perception between force feedback and tactile feedback (Csillag, 2005). Haptic feedback is obtained from the skin, which is the sensory organ for touch, and the limbs, which have the sensors for force detection. Tactile and force feedback, being so closely linked, make efficient use of the human body's automated motor responses. This reduces hand-eye co-ordination errors by speeding up reaction times (Hale and Stanney, 2004).

After visual feedback, the most important type of feedback is haptic information returned from sensors on the remote robot to the local pseudo surgical instruments.

One of the main disadvantages of the current generation of teleoperated master-slave systems is the lack of haptic feedback. The surgeon performing the procedure using remotely controlled robots is not able to feel the patient (Font et al., 2004).

Lindeman et al. (2002) showed that the accuracy achieved when performing intricate user interface manipulation tasks could be greatly improved when feedback channels, such as haptic and visual, are combined.

By using a combination of visual and force feedback, the surgeon can assess tissue structure. For example, by applying force and observing the deformation of a tissue, the surgeon can estimate the elasticity of a tissue. It has been shown that the combination of visual and force feedback is more reliable than using only visual or force feedback alone to assess tissue elasticity (Tholey et al., 2005).

Unlike visual and force feedback, tactile feedback is entirely lost with the use of laparoscopic surgical instruments. Thus the surgeon cannot make use of tactile feedback when performing a laparoscopic procedure.

However, the insertion of a robot between the surgeon and the patient means that there is a physical separation between the surgeon's hands and the surgical instruments, resulting in a loss of force feedback.

Although there have been many advances in the application of robots to laparoscopic surgery, there is still the problem of the lack of reliable haptic feedback (Lee et al., 2009). Haptic feedback systems for laparoscopic surgery are still at the development stage, but those that have been produced are impractical for clinical implementation (Okamura, 2009). The surgeon has only position and velocity information to help with the surgical procedure. When no force feedback is available to the surgeon, there is a possible risk of damage to the patient's tissue (Hashizume et al., 2002).

Some of the existing methods used to measure forces in laparoscopic surgery are discussed in the next section.

Force measurement in laparoscopic surgery

A review of the research literature shows that most force measurement systems for laparoscopic surgery incorporate strain gauges, which can be used to measure the forces applied

to structures. For example, strain gauges attached to a force-sensing sleeve fitted over the shaft of a standard surgical instrument have been used to measure forces up to 13 N (Prasad et al., 2003). The instruments were used in MIS with audio feedback to the surgeon corresponding to the measured forces. Strain gauges have also been used on the jaws of custom made surgical instruments (Wagner and Howe, 2007). The strain gauges were held in place with epoxy resin, and then sealed within a layer of silicon rubber. While they were not suitable for use in a surgical environment, they could be used in the laboratory to measure forces up to 1.5 N. Strain gauges have also been used on concentric shafts within the main shaft of a surgical instrument, which allowed forces acting in different directions to be measured (Trejos et al., 2009). The commercial da Vinci robotic surgery system (Intuitive Surgical Inc., Sunnyvale, CA, USA), which does not itself have force feedback, has been used with strain gauge-fitted surgical instruments in knot tying experiments, which used a maximum force of 3 N (Reiley et al., 2008).

Apart from strain gauges there are some other force measuring systems used in surgical equipment. For example, the MicroSurge robotic system measures the forces and torques applied to a surgical instrument by a Stewart platform 6-DOF force/torque sensor (Hagn et al., 2009). A different approach is to integrate miniaturized force sensors into a trocar (Zemiti et al., 2007). The forces on the instrument are therefore measured outside the patient. This has the advantage that the part of the instrument that enters the patient can be sterilized after a surgical procedure. A 3-DOF optical force sensor has been developed for use with a surgical instrument (Peirs et al., 2003). The sensor is built around a flexible titanium structure. When the structure is deformed, the amount of light that is reflected along three optical fibres changes. The amount of light passing along the fibres corresponds to the forces on the instrument. Forces up to 2.5 N have successfully been measured by this approach. A similar force-sensing system has been developed, which has a mirror attached to a sensing pin that touches the area to be examined (Mazid and Russell, 2006). Light from a light-emitting diode (LED) is directed down a fibre optic cable pointing at the mirror on the sensor. If there is no force deflecting the pin, the light is reflected up a second fibre optic cable to a phototransistor, which measures the light intensity. If a force deflects the pin then the mirror does not reflect all of the light from the LED into the second optic cable and the light level to be measured is reduced.

The next section proposes the use of quantum tunnelling composite (QTC) to measure the forces applied to a surgical instrument.

Force measurement using quantum tunnelling composite force sensors

In order to provide a force feedback channel the forces of interest have to be measured by sensors that rely on direct contact with tissue (Eltaib and Hewit, 2003). Research into the forces encountered by surgical instruments during a procedure showed that for scissors the maximum force was 15 N, as the scissors closed at the end of a cut (Callaghan and

McGrath, 2007). The force required to break the base of a skull was more than 20 N, which exceeded the calibration of the forceps being used (White et al., 2004). Other research has shown that a lung tumour could be localized using palpation with a probe capable of measuring 10 N (McCreery et al., 2007). Other tests have shown that many people perceive a force of 11 N to be a solid object (Massie 1993; Tavakoli et al., 2006). However, forces as small as 0.3 N have been measured during bypass grafts (Seibold et al., 2008). Following on from these results, the QTC force sensors used in this research should be capable of measuring forces in the 0.3–11 N range.

Our force sensors have been developed incorporating a relatively new type of composite, QTC (Bloor et al., 2006). QTC is used in the form of pills, cuboid-like structures $3.6 \times 3.6 \times 1$ mm in size, each weighing 0.04 g. When the composite is compressed, stretched or twisted, the resistance falls from 10^{12} to $10^{13} \Omega$ to less than 1Ω in a smooth repeatable curve, with an exponential fall of resistance. Each pill has a hardness of 60 Shore A, which is similar to a car windscreen wiper blade (Substances and Technologies 2010). The pill can withstand forces in the range 0–100 N and has a lifetime of greater than 10^6 compressions. It has an operating voltage range of 0–40 V and a maximum current rating of 10 A. QTC has an operating temperature range of -20°C to $+120^\circ\text{C}$ and a humidity range of 0–100%. QTC pills are resilient to harsh environmental conditions and can exceed the International Protection Rating IP65, for dust and water ingress (Peratech Ltd, 2004).

After searching the research literature and reviewing the various force sensors that have been used, QTC sensors were selected for the following reasons:

- QTC pills are inexpensive, costing less than \$1 each.
- QTC pills are physically small, enabling compact force sensors to be produced.
- A QTC pill is robust, feeling like a thin slice of rubber, and does not have to be handled delicately.
- Peratech's literature shows QTC can be used to measure forces of at least 20 N.
- A simple electronic circuit can interface several QTC pills to a computer.
- Several QTC force sensors located at the base/handle end of a robot-held surgical instrument allows for the possibility of encapsulating the electronics and permitting the instruments to be sterilized after a surgical procedure.
- They can also facilitate use of single-use surgical instruments, as only instrument shafts are used and these can easily be changed after a surgical procedure.
- QTC pills are physically small allowing mechanical linkages located at the base of the instruments to provide force amplification for the sensors.
- A literature search revealed that QTC does not appear to have been used previously in the field of medical robotics.

QTC has been used in our earlier research into providing low-cost instruments for a virtual reality simulator (Mack et al., 2006, 2008) and force-sensing feedback system for laparoscopic surgery (Mack et al., 2009). QTC has also been used by NASA on their robotic astronaut, or Robonaut.

QTC sensors have been incorporated into a force-sensing glove, which fits over the hand of the Robonaut (Martin et al., 2004). The Media Lab at the Massachusetts Institute of Technology has also used over 1000 QTC sensors in the skin of their robotic teddy bear, the Huggable. The Huggable is a therapeutic companion, which is able to respond to human touch (Stiehl et al., 2005). QTC sensors have been incorporated into an upper body garment to record physical forces made to the body as an aid to exposing physical abuse (Whiton and Nugent, 2007). A modular quadrupedal robot has been developed for use in space exploration that has tactile capability because of the use of QTC sensors in the feet modules of the robot (Hancher and Hornby, 2006).

In order to be able to use QTC sensors to provide a force feedback channel as part of a robotic surgical procedure, it was necessary to determine accurately the range of forces that can be measured using these sensors. To do this, a test rig was developed incorporating electronic scales accurate to 1 g. A small area of 0.15 mm thick copper sheet was attached to the weighing pan of the scales to act as a fixed electrode. A QTC pill was then placed on top of the copper sheet, and forces applied vertically to the pill by means of a second electrode. This arrangement can be seen in Figure 2. The electrode-QTC pill-electrode formation created a QTC sandwich sensor, which was placed in series with a current limiting resistor, to prevent high current flow if the resistance of the QTC pill approached 0Ω . The QTC sandwich sensor and current limiting resistor form a potential divider and the voltage from this tap point was input to a logarithmic operational amplifier circuit to linearize the effects of the very large non-linear resistance variation between no compression and maximum compression. A schematic diagram of the test circuit is shown in Figure 3.

Force probes, which had different tip profiles and dimensions, were evaluated for sensitivity and force measuring range. The force-voltage characteristics for the 11 probe tips tested are shown in Figure 4, with the characteristics of the eight probe tips that had the smallest force measuring range shown in Figure 5. Each probe was compressed until the maximum 5 V output was obtained and readings taken as the force was reduced. Five pills were tested with each force probe.

The first test was made with a square probe tip, which had the same area as the QTC pill. This effectively meant the pill was compressed between two electrodes, each equal to the area of the pill itself. It can be seen that a force of approximately 6.9 N was required to produce a voltage output on the voltage measuring circuit. A force of 20 N achieved the maximum voltage output of 5 V. Circular flat-tipped probes with diameters of 2.0, 1.5, 1.0 and 0.5 mm were tested. Reducing the area of the probe tip through which force was applied to the QTC pill had the effect of reducing the force required to produce an initial voltage. For the four circular tips, these forces were 1.5, 0.85, 0.67 and 0.41 N, respectively. The maximum voltage output for the circular probes was produced by forces of 4.2, 2.2, 1.5 and 1.2 N, respectively. The meant that the measured force ranges for the one square and four circular sensors, decreasing in area, were 13.1, 2.7, 1.35, 0.83 and 0.79 N, respectively. As the area of the probe was reduced, the

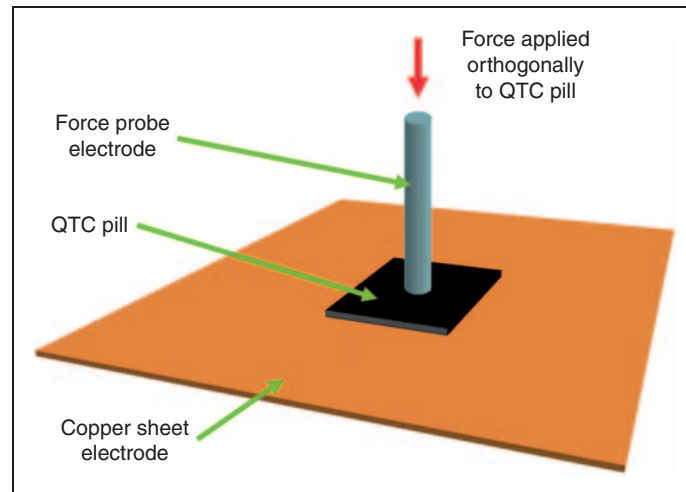


Figure 2. Quantum tunnelling composite (QTC) sandwich sensor.

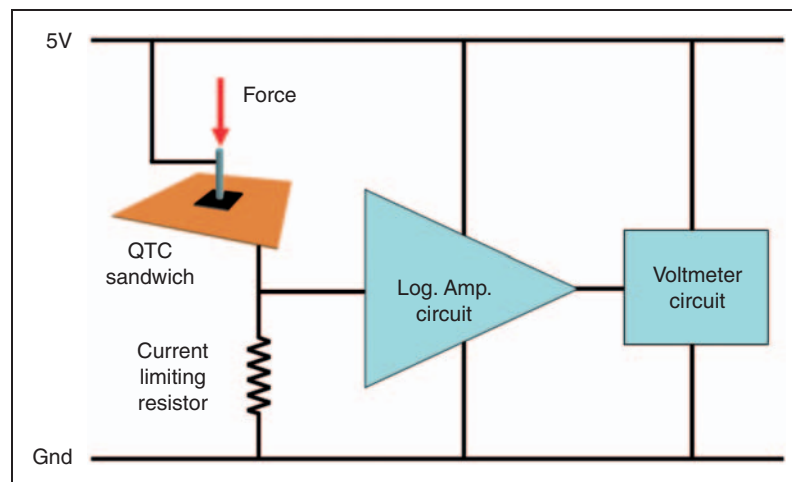


Figure 3. Schematic diagram of quantum tunnelling composite (QTC) test circuit.

initial force required to give a reading was reduced, but so also was the available force measuring range.

Cylindrical bar probe tips were tested, with the bar placed across the middle of the QTC pill and force applied vertically as before. For a 1.0 mm diameter bar, the initial force required to produce a voltage was 2.25 N, with a 5 V output being obtained when a force of 17.5 N was applied. With a 0.5 mm diameter bar the initial force was reduced to 1.25 N, and the maximum force reduced to 4.2 N. The force ranges for the 1.0 mm and 0.5 mm diameter bars were therefore 15.25 N and 2.95 N, respectively. It can be seen that changing from flat-tipped to bar probes changes the force–voltage characteristic curves. The bar probes have characteristic curves which produce less change in voltage for a change in force and therefore have extended force measuring ranges.

Two probes were tested, which had tips with radii of curvature of 2.0 and 0.5 cm. The 2.0 cm domed probe produced

an output voltage at 1.5 N, and the maximum 5 V when 8.5 N was applied. The 0.5 cm domed probe had an operating range from 0.75 N to 2.0 N. The response profiles were the same as for the flat-tipped probes.

A composite circular probe was tested, which had a 90° approach to a 0.2 mm diameter flat tip. This proved to be the most sensitive tip, producing a voltage change at 0.19 N, and the maximum output at 1.38 N. However, as the tip of the probe was effectively a point, it had the undesirable effect of damaging the QTC pill by puncturing it and causing a short circuit.

Although using a logarithmic amplifier between the QTC sensor and the analogue-to-digital converter produced a more linear output, it was not perfect. In an attempt to linearize the force–voltage characteristic, a force probe tip was given a quasi-domed profile with varying radii of curvature. This probe produced a voltage change at 0.6 N, and a maximum voltage when 2.9 N was applied. However, while the profile of

the tip is not perfect, the force–voltage characteristic can be seen to be more linear than for any of the other probes. Further research holds the possibility of producing a tip profile that would have a linear response over a range of operation.

As the characteristics showed that the 1.0 mm diameter bar probe offered a wide force range and a relatively low initial operation force, this was the probe tip used in the surgical instrument sensors described later.

Force rendering

Locally, the forces have to be rendered for the surgeon, so that he can experience the forces on the surgical instruments attached to the teleoperated robots.

Vibrating motors, like those in pagers, can be used to provide low-cost vibro-tactile feedback (Cheng et al., 1996).

Force reflecting interfaces such as the PHANTOM Omni from Sensable Technologies have also been shown to provide useful feedback (Song et al., 2006). However, their utilization is often limited by their cost and the fact that it is difficult to customize them to fulfil a specific task.

In this research, a pair of PHANTOM Omnis have been modified with the addition of surgical instrument handles, which are held in a framework that can be used to simulate laparoscopic surgery more accurately. The PHANTOMS are not only used locally by the surgeon to direct the movement of the robots, but also to render the feedback forces applied to the surgical instruments attached to the robots, resulting in a more immersive experience for the surgeon.

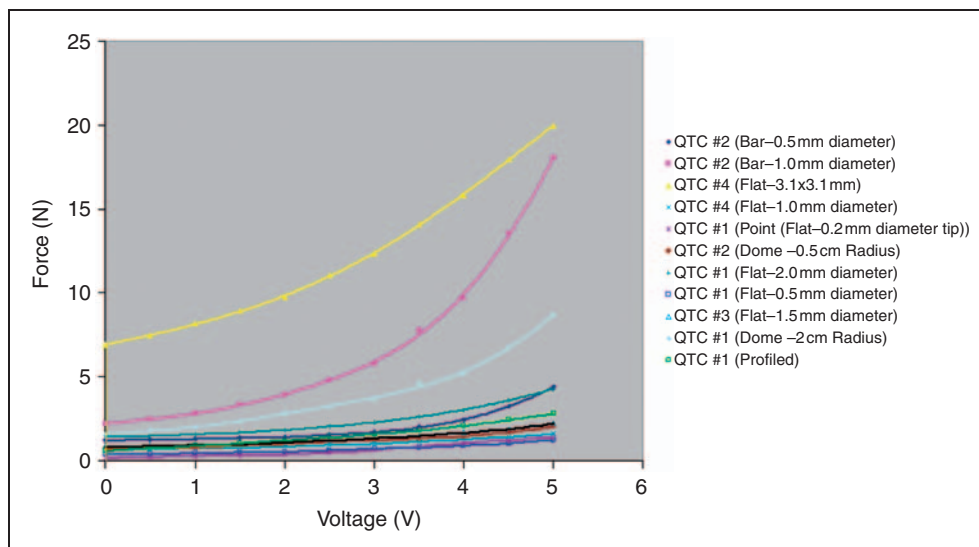


Figure 4. Force–voltage characteristics of 11 probe tip designs.

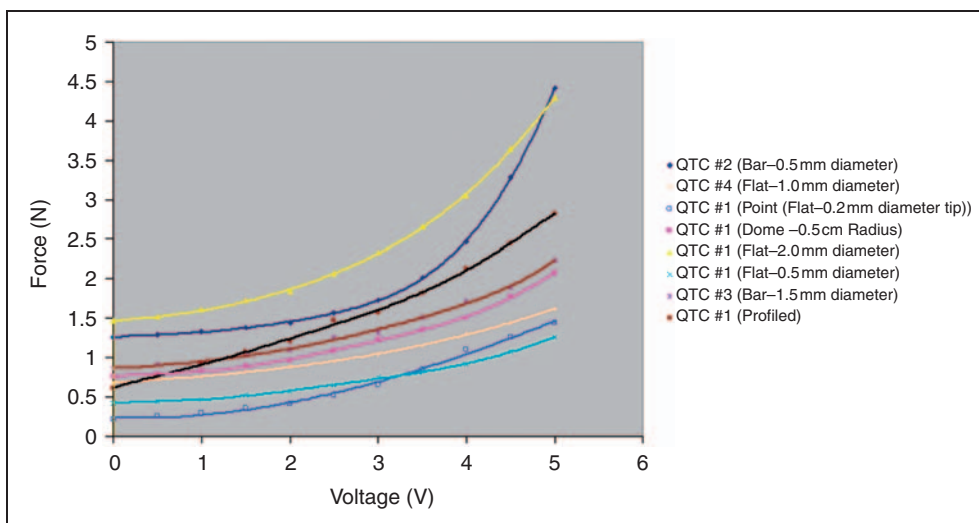


Figure 5. Force–voltage characteristics of eight small force range probe tip designs.

Surgical instrument design

The end effector of each robotic arm has a custom made surgical instrument attached to it, which has to measure the forces applied to it during a surgical procedure. The surgical instruments are the first stage of the force feedback channel. There are two aspects to the design of the instruments, mechanical and electronic. The mechanical design is of prime significance in providing mechanical amplification of the forces and in allowing the working end of the tool to maintain its traditional surgical shape and size. The accompanying electronics play an important role in eliminating noise and linearizing the sensor device characteristics. Prototype surgical instruments have been designed for attachment to the Mitsubishi robotic arms. The instruments incorporate force sensors, and the force data is sent over a network to be rendered on two PHANTOM Omnis, as shown in Figure 1.

From an early stage of the design process, the QTC force sensors were mounted at the handle/robot end of the surgical instruments, and not at the patient/tool-tip end. If force sensors are mounted at the instrument tips, the tips become rather bulky, as it is very difficult to produce miniaturized sensor mechanisms. Mounting the sensors at the base of the instruments means that size restriction is considerably reduced. This has the advantage that the forces are measured at a position where the surgeon's hand would normally be holding the instrument. Additionally, this would simplify the encapsulation of the instruments, allowing them to be utilized in a real surgical procedure and sterilized after use.

A QTC sandwich sensor using a bar probe can measure forces in the range 2.25–17.5 N. This does not correspond to the desired range of 0.3–11 N. However, the sensitivity of the QTC sensors was further increased by the use of a lever mechanism, which uses the principle of mechanical advantage:

$$\text{Mechanical advantage} = \frac{\text{Load}}{\text{Effort}} \quad (1)$$

The sensors on the main shaft for measuring Up/Down/Left/Right forces are operated as a second-class lever and have a mechanical advantage of 5.5. This has the effect of shifting the force measuring range to 0.41–3.2 N. The other sensors on the instrument for measuring In/Out/Clockwise/Anti-Clockwise/Open/Close forces have a mechanical advantage of 2, which shifts the force measuring range to 1.12–8.75 N. While this is not ideal, there is the prospect that a suitably profiled tip could improve this operating range. The mechanical advantage of each QTC sensor is shown in Table 1.

CAD model of the surgical instrument

An interactive CAD model of the surgical instrument was developed to test the feasibility of incorporating 14 force sensors. The instrument has four sensor tubes, three of which have four QTC sensors, and a fourth, which has two QTC sensors. Figure 6 shows the CAD model for a sensor tube with four QTC sensors. Figure 7 shows a view of the instrument with all four sensor tubes. The instrument jaws are opened and closed by a servo motor, which can be seen on

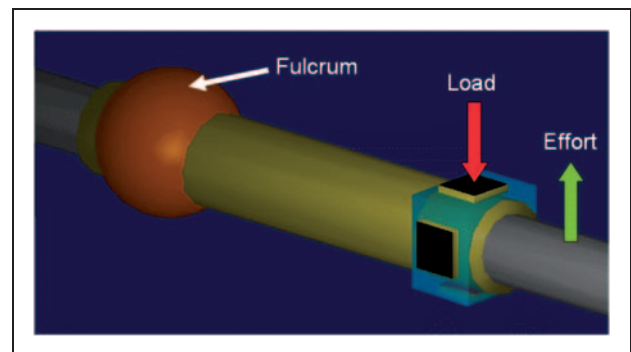


Figure 6. CAD model of quantum tunnelling composite (QTC) sensor tube showing the fulcrum, load and effort locations.

Table 1. Mechanical advantage of QTC sensors

Sensor tube	Sensor	Sensor number	Mechanical advantage
Shaft	Up	1	5.5
Shaft	Down	2	5.5
Shaft	Left	3	5.5
Shaft	Right	4	5.5
Top	In	5	2
Top	Out	6	2
Top	Rotate CW	7	2
Top	Rotate CCW	8	2
Bottom	In	9	2
Bottom	Out	10	2
Bottom	Rotate CW	11	2
Bottom	Rotate CCW	12	2
Jaw	Open	13	2
Jaw	Close	14	2

QTC: quantum tunnelling composite.

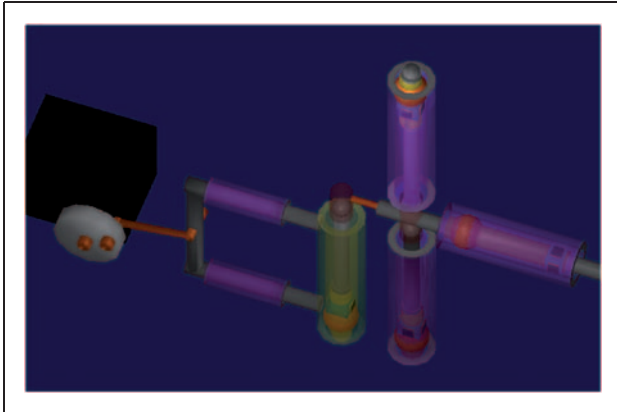


Figure 7. CAD model showing four sensor tubes and servo motor.

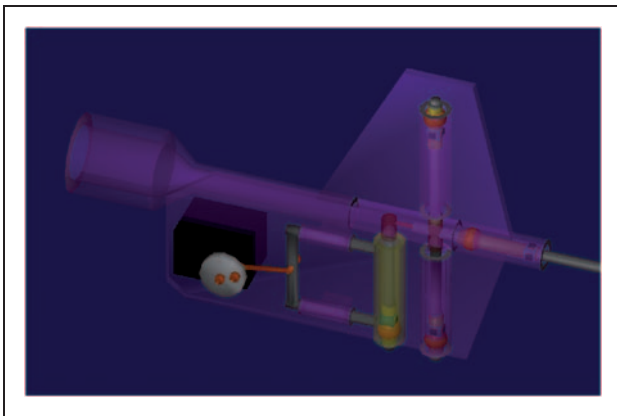


Figure 8. CAD model of complete surgical instrument.

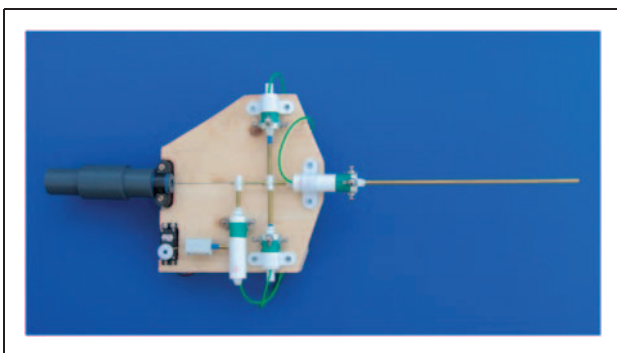


Figure 9. Working model of surgical instrument.

the left. The sensor tube nearest to the servo motor measures the opening and closing forces on the jaws of the instrument. The up/down/left/right sensors are in the sensor tube on the right of the figure. The two in/out and torque sensor tubes, incorporating eight sensors, are located one above the other, and between the other two sensors. The complete CAD model for the surgical instruments is shown in Figure 8.

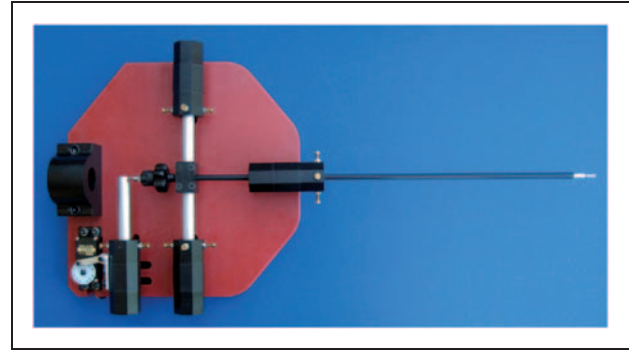


Figure 10. The prototype surgical instrument.

On completion of the design that fulfilled the functional requirements of the surgical instrument, a working model was built for evaluation and testing, before progressing to build the prototype surgical instrument. Figure 9 shows the working model of the surgical instrument.

Once the model had proved the concept, a prototype instrument was produced, and this is shown in Figure 10. The prototype surgical instrument incorporates the shaft and jaws from an actual medical instrument.

Electronic circuit implementation

Each surgical instrument has 14 QTC force sensors mounted at various points on the mechanism. As forces are exerted upon an instrument, the output voltages from the QTC sandwich sensors are fed to logarithmic amplifiers, as in the test circuit of Figure 3. The linearized outputs from the logarithmic amplifiers are then passed to the integral analogue-to-digital converters in four Microchip 18F4550 PIC microcontrollers. Each microcontroller circuit measures the voltage output from seven of the logarithmic amplifiers. The 18F4550 PICs also have integral universal serial bus (USB) interfaces, which provide a convenient way to transmit the force data to a server application running on a personal computer (PC). Firmware descriptors in the microcontrollers give each USB device a unique identity on the universal serial bus.

Each fully populated printed circuit board (PCB) has a minimal component count with only the microcontroller, crystal, capacitors, USB connector, and a resistor network and eight LEDs for testing purposes, as can be seen in Figure 11.

With custom surgical instruments attached to the robot arms, forces that the instruments experience during a surgical procedure can be measured by the force sensors and electronics interfaces. As shown in Figure 1, this force feedback data is sent from a server, PC #3, via a computer network to a client, PC #1, which enables the PHANTOM Omnis to render the forces for the surgeon to feel.

Control, system operation and testing

Communication between the local and remote sites is made via a standard computer network. Data is sent from servers

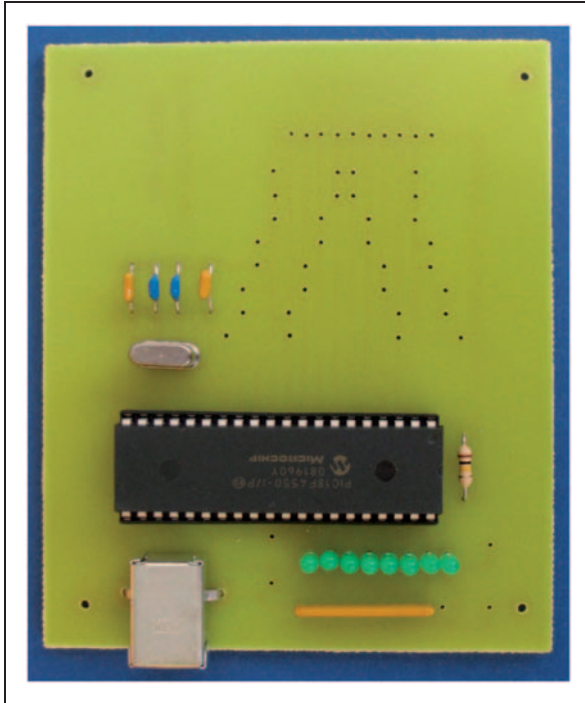


Figure 11. One of the four Microchip 18F4550 PIC microcontroller printed circuit boards (PCBs).

and received by clients using UDP protocols and software from the virtual reality peripheral network (VRPN) libraries (University of North Carolina, 2009).

Robot positioning

At the control site, the surgeon can perform two-handed procedures by moving two PHANTOM Omnis, which are connected to a PC by Firewire interfaces. A PHANTOM Omni is shown in Figure 12.

The PHANTOMS are normally controlled by holding the pen and moving it to the desired position and orientation. However, this does not look or feel like a surgical instrument. A mechanism was therefore developed, which allowed the handles from real surgical instruments to operate the PHANTOMS, and this apparatus is shown in Figure 13.

Three co-ordinates specify the position of a PHANTOM's pen and three angles specify its orientation. Again, with reference to Figure 1, a VRPN server application on PC #1 streams this position data from the PHANTOMS. At the remote location, PC #2 runs a VRPN client, which is connected to the robot control units. This control computer extracts the position and orientation data from the PHANTOM devices, which is then used in the CCD algorithm to determine the angles required to move the robot so that the force-sensing surgical instruments attached to the robot are in the required position as determined by the surgeon. As the surgeon moves the instrument handles attached to the PHANTOMS, the surgical instruments attached to the remote robots mimic his actions. A robotic simulator was developed to ensure that the PHANTOMS would properly control the robots, and its output is shown in Figure 14.



Figure 12. A PHANTOM Omni.

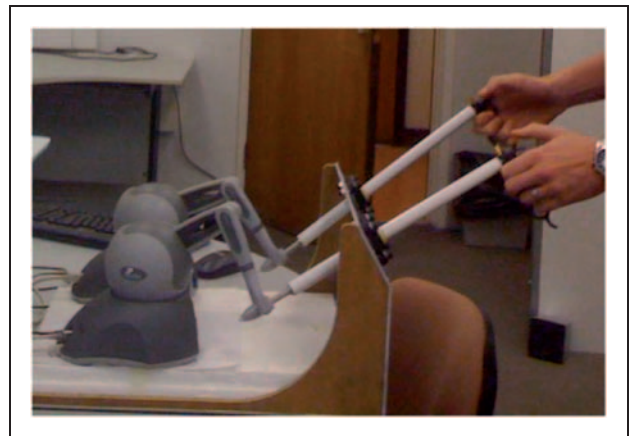


Figure 13. Surgeon using PHANTOM Omnis with instrument handles attached.

Figure 15 shows a pair of force-sensing surgical instruments attached to the pair of Mitsubishi PA-10 industrial robots, which were used in this research.

Force feedback

At the operating site, the surgical instruments are moved to touch objects by a program listening for commands from the control computer, PC #2. The integral QTC force sensors on the robots are connected to another computer, PC #3, by their USB interfaces. A VRPN server application on this computer streams this force feedback data from the surgical instruments. At the control site, the computer used by the surgeon, PC #1, runs another VRPN client which receives the data from the force sensor computer. This information is passed to the PHANTOMS to render the feedback forces for the surgeon to experience.

Visual feedback

A third VRPN server streams video data from a webcam placed between the two robots to a local PC running a

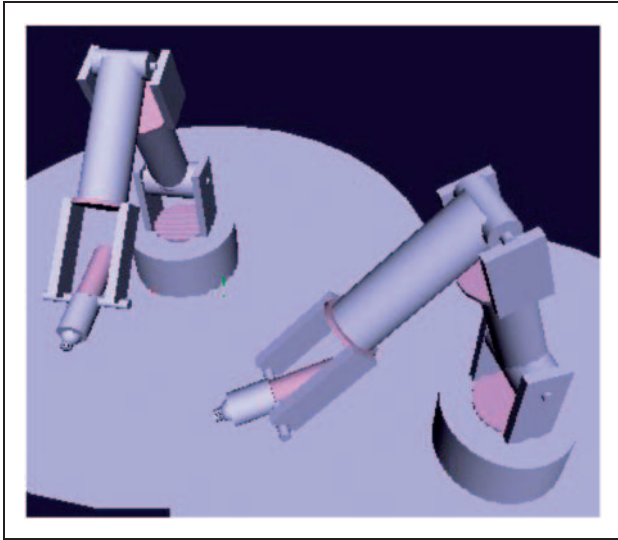


Figure 14. Robotic simulator.

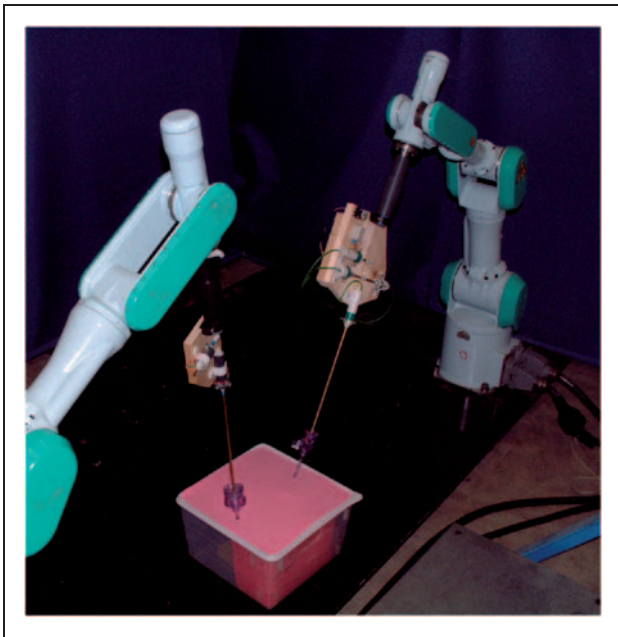


Figure 15. Instruments attached to Mitsubishi PA-10 robots.

client, which displays the video on a monitor. This enables the surgeon to view his actions as executed by the remote robots. The use of a separate video channel reduces the workload and internet traffic to/from the computers controlling the PHANTOM devices and the robots.

The remote camera has to be positioned carefully so that it produces a perspective that promotes intuitive operation by the surgeon.

Testing

The research has reached the point where the system elements have been tested and evaluated in the laboratory. In this

operating environment, network congestion or inter-site communications delays are not an issue.

The video feedback server and client can display the scene at the remote site without any perceptible delay. The PHANTOMS, with their instrument handle mechanism, position the remote robots with minimal tracking errors during small-scale movement. (Wild, i.e. large-scale or rapid movements, are prohibited by the safety routines in the robot control software.) The force feedback server and client have again demonstrated that they are not subject to network delay and data update rates of 30 Hz have been achieved.

The initial working model instruments were subject to some mechanical instability and consequent errors in the force measurement sensors. However, the precision-engineered functional prototype is much less prone to errors in force measurement and this gives confidence that even better results could be obtained in a production version.

Now that the research has proved the concept of the systems, the next stage will be to move to user testing and this will be carried out in collaboration with the team of laparoscopic specialist surgeons.

Conclusions

The aim of this research has been to add a force feedback channel to a teleoperated robotic surgical system, which allows a surgeon to control the forces being applied to the remote patient, whilst feeling the effect of his or her work. For certain types of procedure, this offers the benefit that the surgeon is no longer exposed to stray X-radiation used to visualize the internal working site. The two-handed robotic system allows the surgeon to perform intricate dextrous positioning movements as though he was performing the procedure directly on the patient.

Custom surgical instruments designed with integral QTC sensors to measure forces being applied to the surgical instruments form the key contribution by this research. Prior to this research, the measurement of forces on surgical instruments using QTC had not previously been reported. Most of the previous designs to measure the forces on surgical instruments use strain gauges or force/torque sensors. Indeed, in a recent review of haptic feedback systems for laparoscopic surgery, it was reported that they were either still at a development stage, or had not been used for clinical implementation because of their impractical nature (Okamura, 2009).

The main advantage of the QTC sensors is their miniature scale and sensitivity, which allows for 14 different forces to be measured at different points on each instrument. Because the forces are not measured at the tips of the instruments, but at the handle end, shafts from actual surgical instruments can be used. This leaves open the possibility of encapsulating the sensor end in latex and therefore specialized sterilization would not be required. Indeed disposable instrument shafts could be employed, or alternative instruments could be selected during a procedure by the use of a robot tool changer.

The PA-10 robots have 7-DOF and therefore do not have limited dexterity. Robotic surgery is normally restricted by size limitations. However, the PA-10 with 7-DOF has redundancy and therefore the elbow can be positioned to avoid

causing an obstruction or being obstructed in the operating theatre.

With a good sensitive feedback mechanism, this design of a two-handed teleoperated robotic surgery system could have other advantages. For example, by the appropriate use of filtering, it is possible to reduce the hand shake of surgeons.

Although this research has been aimed at laparoscopic/endoscopic surgery, it is equally valid in other fields. Teleoperated robots with force feedback could prove to be of value in bomb disposal, in nuclear plants handling radioactive waste, in underwater wreck exploration, controlling a telescope in space or indeed a rover vehicle on another planet.

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