# MEASURING THE FORCES APPLIED TO A VIRTUAL REALITY LAPAROSCOPIC SURGICAL SIMULATOR WITH QUANTUM TUNNELLING COMPOSITE SENSORS

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Abstract: Abdominal surgery performed by laparoscopy requires a very high degree of skill in the surgeon. This skill level can only be acquired through practice and training. However, a virtual reality (VR) training simulator commands a high price. There is no reason for a VR simulator to be expensive, as a modern personal computer can produce high-quality graphics. If all that was required was good graphics, every surgeon could have a training tool within their laptop computer. What is missing is suitable low-cost human interface hardware – the equivalent of the computer game 'joystick'. This paper presents a design for a low cost device to address this issue. In order to provide force feedback, the forces exerted on the surgical instruments have to be measured by sensors mounted at various points. The sensors are constructed from quantum tunnelling composite pills which measure the pressure applied to them by the surgeon. The force feedback is produced by small direct current motors. The low cost design has been tested by both specialist laparoscopic surgeons and non surgical personnel to assess its benefits in training at different levels of expertise. A preliminary qualitative report is given which documents the findings from these initial tests.

## 1 INTRODUCTION

Laparoscopic, or minimally invasive, or keyhole surgery is well established among surgeons as a technique used to carry out surgery through small incisions as compared to larger incisions required for traditional surgery. However, while a singer, for example, can practice before a concert, a surgeon does not always have available the means to sharpen his/her skills before performing an operation.

The quality of the training equipment to which a surgeon has access largely depends on the amount of money a hospital has available for that purpose. At the low cost end of the market, a plastic box with a fabric top represents the body, with holes through which real surgical instruments are pushed to operate on rubber body parts. A camera looks through the side of the box and displays the 'operation' on an ordinary video monitor.

At the top end of the market the laparoscopic surgical trainer can be a pair of pseudo surgical instruments with force feedback and virtual reality software running on a computer which displays a depiction of the inside of a virtual patient and VR tool tips. The LapVR system from the Immersion Corporation allows the surgeon to learn essential skills through virtual reality training. The VEST systems from Select-IT VEST Systems AG allow for training in gall bladder removal and surgery in gynaecology. The SurgicalSim Education Platform from Simsurgery can be used for a wide range of training scenarios including trocar placement, camera navigation, suturing and knot tying.

VR training systems like these, and the one shown in Figure 1, can cost many thousands of dollars. However, the cost of such simulators need not be prohibitive, as personal computer (PC) game technology can deliver excellent, high quality, real time interactive 3D graphics that can easily meet any requirements of a VR laparoscopic simulator. If it was only an issue of graphics, then every surgeon could have a training and practicing tool on their laptop PC. It is suitable human interface hardware, the equivalent of the computer game 'joystick' or 'flight simulator yolk' that is missing.

Figure 1: A VR laparoscopic surgery application displaying a representation of the abdomen and two simple instruments.

When interacting with a 3D virtual environment the experience not only depends on the type of device used to provide the human interaction, but also on external factors such as feedback, whether this is visual, audio or tactile. Other factors also have to be considered, such as the number of degrees of freedom of the user interaction device, as well as subjective and ergonomic aspects. For example, (Kontarinis and Howe, 1995) demonstrated that high frequency vibrations played a significant role in manipulation tasks. (Lindeman, Sibert and Hahn 1999) showed that adding passive-haptic feedback to precise manipulation tasks appreciably improved user performance. (Lindeman, Templeman, Sibert and Cutler, 2002) demonstrated that adding vibrotactile feedback to visual and auditory feedback improved the user experience of virtual environments.

Force reflecting interfaces such as the PHANTOM Desktop Device from Sensable Technologies provide useful feedback, but their utilization is limited by their cost and the fact that it is difficult to customize them to fulfill a specific task.

Vibrating motors, like the ones in mobile telephones, can be used to provide low-cost vibrotactile feedback as demonstrated by (Cheng, Kazman and Robinson, 1996). Indeed vibration elements have been attached to a standard computer mouse by (Hughes and Forrest, 1996) to provide tactile feedback.

This research reflects the belief that integrated tactile and visual feedback must be implemented in surgical simulators. The visual feedback is readily available in real time and at low cost using advanced computer graphics. The tactile feedback is much more difficult to integrate into the simulator at low cost. This paper aims to resolve this issue by documenting the development of a low cost haptic device for use in a surgical simulator. Following on from this introduction, section 2 will outline the basic design of the mechanical hardware. Sections 3 and 4 describe the electronic system and interface protocols. The quantum tunnelling sensors are introduced in section 5 and section 6 illustrates how the concept was initially tested. Section 7 will then present conclusions from our work to date.

# 2 THE SURGICAL TOOLS

This section outlines the design and development of low-cost haptic devices for interaction with a surgical simulator.

## 2.1 The Mk1 Surgical Instruments

The hand grips, and spatial positions used in the pseudo-instruments, were constructed to match dimensions taken from actual surgical instruments. The instruments (the surgical tools) were mounted on pillars attached to a base. They could rotate from the horizontal to point down by 45 degrees, and from facing forward to point inwards by 45 degrees.

These instruments had no electronics attached, as they were produced solely to verify that the measurements taken had been translated into an accurate 3D model. Following initial field trials it was decided to make some alterations to the position of the pillars because, during an operation the tool-tips mostly remain within a 4cm diameter spherical volume. These changes had the advantage of allowing more space at the tool-tip end to mount some electronics in the Mk2 instruments.

## 2.2 The Mk2 Surgical Instruments

From our earlier research, Mack, Ferguson, Potts and McMenemy (2006), and discussions with practicing surgeons it was decided that each joystick or surgical tool should have six degrees of freedom. That is, they should allow for movement in the X, Y and Z axes, rotation about the Z-axis, rotation of the tool-tip about the Z-axis, and the opening and closing of the tool-tip. A Binary-Coded Decimal (BCD) thumbwheel switch was used to simulate the actual method of rotating the tool-tip. Five small rotary potentiometers were used to detect movement in the X, Y and Z axes, rotation about the Z axis and the opening and closing of the tool-tip.

For increased stability the instruments were mounted on a heavy wooden base as shown in Figure 2.

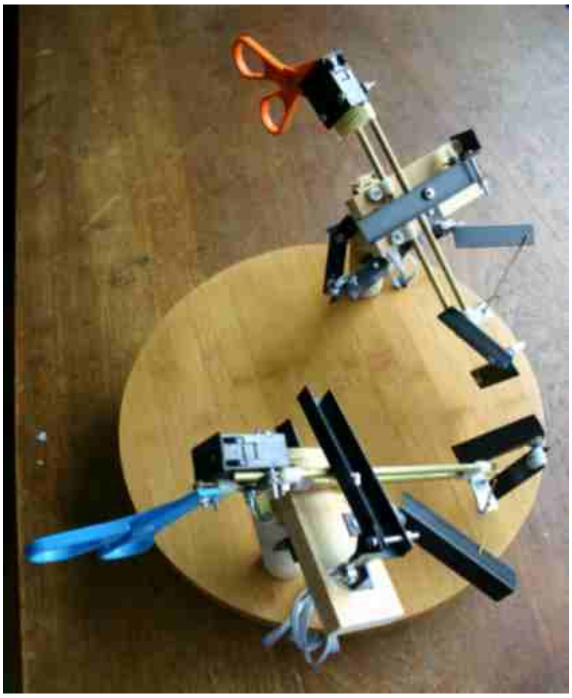

Figure 2: A pair of Mk2 instruments mounted on a wooden base.

# 3 THE USB INTERFACE

This section outlines the design and development of the Universal Serial Bus (USB) which was chosen to interface the instruments to the PC.

## 3.1 The Electronics

The 16C765 USB microcontroller from Microchip was selected for the interface because Microchip's MPLAB and Crownhill's Proton Development Suite provide a stable and comprehensive Integrated Development Environment (IDE). The PICs are cheap and employ re-usable re-programming technology, and require little in the way of additional external components to implement a working circuit. They have low power requirements and can therefore draw their power from the Universal Serial Bus itself.

Members of the Human Interface Device (HID) Class such as USB keyboards and mice are low-speed devices, and use interrupt data transfer.

The maximum possible transfer rate of data for this combination is 8 bytes per 10 milliseconds. This is quite sufficient for joysticks and similar devices such as the custom-made Mk2 pseudo surgical instruments because each surgical instrument's interface has only to send 6 bytes of data, one byte for each potentiometer and one byte for the thumbwheel switch on the pseudo surgical instrument.

The PIC was initially configured as a Human Interface Device without force feedback for the Mk2 joystick. Descriptor details for a HID device can be found in our earlier paper (Mack et al., 2006).

With the addition of force feedback, each interface would have to send force data to the PC and receive force feedback data from the PC. It was apparent that a HID class interface could not handle the data rates required. For a Mk3 joystick another method would have to be found to send and receive larger data bursts.

Other classes of USB devices were investigated to determine if any would be suitable for use in a force feedback interface. The Communications Device Class (CDC) specification from USB.org indicated that it could be used for bulk data transfer.

However, the 16C765 could only operate as a HID class device, so the 18F4550 was selected as it could operate as a Communications Class Device.

A PCB very similar to the one used for the Mk2 joysticks was designed for the new microcontroller on the Mk3 joysticks. Two of these circuit boards are required, one for each surgical instrument, and are mounted underneath the base of the instrument.

## 3.2 The PIC Descriptors

The Universal Serial Bus interface uses a serial protocol, and depending on how it is configured, can be low, full or high speed. The maximum data rates are 800 bytes per second for low speed, 1.2 Megabits per second for full speed and 53 Megabits per second for high speed.

When a USB interface is connected to a PC a procedure called enumeration takes place. During enumeration the interface must send descriptors to the PC which completely define the USB device's capabilities and how the device will be used.

If a USB device can be incorporated into a standard USB device class then there is a good chance that it can be made to work using the standard device drivers included with the Windows operating system. Configuring the interfaces as members of the Communication Device Class results in a twofold advantage. Firstly, the Proton+ compiler is able to use customizable descriptors provided by Microchip which allows the Communications Device to emulate RS232 serial protocol over a USB connection. Secondly, the device enumerates as a COM port on the PC and allows the use of a standard Windows device driver to establish communications with the device.

Although the descriptors define the interfaces as standard COM ports, this is only used as a convenient way to input data to and output data from the PC application via the Universal Serial Bus.

Details of the descriptors used in the Mk2 and Mk3 surgical instruments are explained in detail in internal documents entitled, “Descriptors required for a HID USB Interface”, and, “Descriptors required for a CDC USB Interface”, respectively.

# 4 THE PIC PROGRAM

However, to have any purpose, the USB devices must each run an application program.

The surgical instruments were originally developed without force feedback, and only fed position information to a Windows VR application, which can be seen in Figure 1. A different PIC application was developed for use with an experimental rig to test the setup for force feedback in one degree of freedom.

The data flow for one degree of freedom can be seen in Figure 3. The force feedback in the surgical instruments will be provided by small DC motors, which will provide a more tactile feel for the surgeon. A potentiometer at each pivot point provides position data. The force exerted by the user is measured by the use of pressure sensors produced from Quantum Tunnelling Composite (QTC) pills manufactured by Peratech.

Excluding the thumbwheel switch input, which is not suitable for force sensing or force feedback, four sets of data are required for the operation of each degree of freedom. Position data has to be sent from the joystick to the PC application, as does data regarding the force exerted by the user in two directly opposing directions. Force feedback data has to be sent from the PC application to the pseudo surgical instruments.

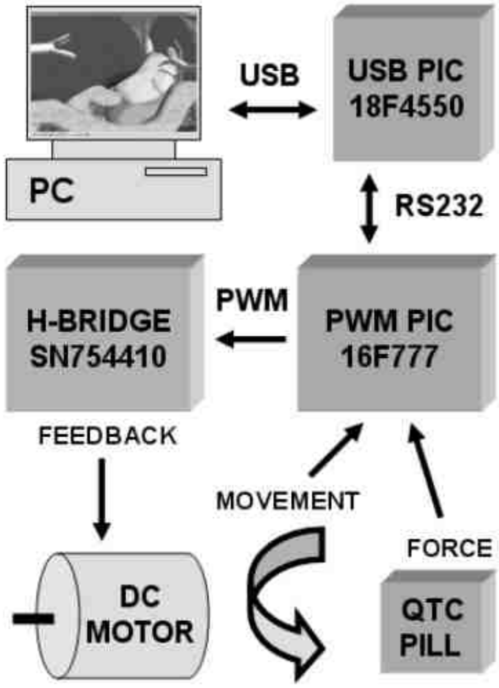


Figure 3: Data flow for one degree of freedom.

Small DC motors have been used in the development process. The motors have to operate in both forward and reverse, and this can be achieved by the use of an H-bridge circuit. The motor torque can be controlled by using Pulse Width Modulation (PWM) to vary the average current. A motor can be controlled by varying the duty cycle and/or the frequency of the PWM pulse train applied to it. Some PICs, such as the 16F777 used here, have hardware PWM channels which allow the pulse train to be produced in the background while the program is executing other instructions.

It was decided to produce separate modules which could control three degrees of freedom, with each module being controlled by a 16F777 PIC. The PIC also has the nine Analogue-To-Digital (A/D) converters required to sample three position and six force sensors. Each module sends data to the USB interface PIC and receives data from it to control the torque on three force feedback motors.

At this stage of the research it was decided to work on only one degree of freedom on one surgical instrument.

The applications for the USB and 16F777 module PICs were written in Basic and compiled using the Proton Development Suite.

## 5 THE QTC SENSORS

When deformed, Quantum Tunnelling Composites transform from a near perfect insulator to a conductor similar to metal. This transformation can be as a result of compression, stretching or twisting the composite.

Each QTC pill is sandwiched between two electrodes, and the user force applied perpendicularly to the flat face of the pill, as shown in Figure 4.

The circuit for measuring user force is a simple potential divider with the sensor in series with a current limiting resistor. Under no pressure the sensor appears open circuit, while under pressure it appears short circuit.

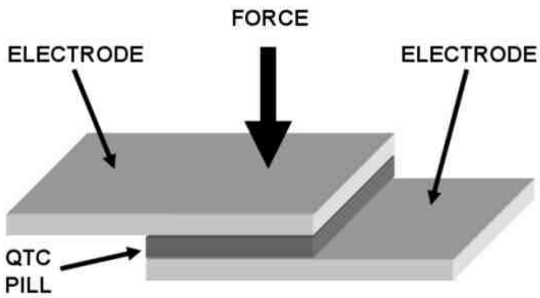


Figure 4: A QTC sandwich sensor.

## 6 TESTING THE CONCEPT

Figure 5 shows the rig used to evaluate the force feedback setup. For the sake of clarity it is shown before wiring.

A simple front-end program, written in Visual Basic (VB) is used to control and display the output from the experimental test rig.

Figure 5: The force feedback test rig.

Four bytes of data specify the motor behaviour. The application program allows forward or reverse motion to be selected. It is also possible to interactively control the PWM signal sent to the motor through the simulated RS232 protocol over the USB interface to the 18F4550 PIC. The 18F4550 sends the data to the 16F777, to configure the H-bridge and hence control the DC motor, thus providing force feedback.

The tests proved that a single personal computer could act as output generator for force specification and simultaneously acquire and act upon signals from the pressure sensors in real-time.

## 7 CONCLUSIONS

This paper presented a design for, and practical realization of, a low-cost laparoscopic surgical training tool that offers the possibility of incorporating force sensing through the novel use of quantum tunnelling composite force sensors.

Several electronic interfaces have been developed, culminating in a fully implemented USB design that emulates a traditional PC COM port. A test rig for a one degree of freedom force feedback axis has been produced which sends position and force data via one of these USB interfaces to a driver program in a host PC. Data from the driver program has been returned to the test rig to control a force feedback motor. It is the ultimate aim of this research to have twelve such motors controlled in the final version of the surgical instruments.

Two instruments give a surgeon the opportunity to practice realistic procedures, and our design offers the possibility of highly accurate force sensing and feedback in the future. The tight interaction between force sensing and feedback afforded by the quantum tunnelling sensors will alleviate some of the problems that arise in conventional haptic rendering applications, for example the need for a very high sampling rate in the servo loop.

When combined with the realistic graphics that current Graphics Processing Unit (GPU) based rendering hardware offers it will be possible to offer a very effective training package that could be made widely available.

Two surgeons and two non-specialists tested the Mk2 instruments in conjunction with the virtual reality software and they were very favourably received. Both groups found the instruments easy to use, with the surgeons able to perform simulated surgery on a gall bladder. With force sensing, force feedback and collision detection algorithms, surgeons will be able to practice realistic surgical procedures with a good level of authenticity.

The development of force feedback systems that are actually used by surgeons requires close teamwork between medical staff and researchers. It is hoped that the development of this VR trainer will result in a laparoscopic simulator which will be acknowledged by the medical profession and lead to an enhancement in the safety of patient care.

The original aim of making a pair of low-cost pseudo surgical instruments for a VR laparoscopic simulator is well on the way to a successful conclusion. The component cost of the Mk2 instruments is approximately 0.4% of the cost of the Virtual Endoscopical Surgery Training (VEST) simulator without force feedback from Select-IT VEST Systems AG. The Mk3 training instruments, when they have force sensing and force feedback implemented will have a projected component cost of 1.1% of the cost of the VEST force feedback system. While our costs do not include the cost of manufacturing the instruments they compare very favourably with commercial equipment. Indeed we could include a laptop computer with pre-installed laparoscopic simulation software, which could also be used independently as an ordinary PC, and still cost only 1.5% and 1.7% of the commercial non force feedback and force feedback systems respectively.

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