Hands-on robots for Surgery

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Synopsis

Early commercial implementations of systems for robotic surgery have usually used an automated approach in which the robot automatically carries out the procedure in accord with the preliminary planning phase and without intervention by the surgeon. These have been particularly applied in orthopaedic surgery. Telemanipulator (master-slave) systems have also been used for some soft tissue surgery. However, more recently a new type of hands-on robot has been introduced which uses a force-controlled lever near to the tip of the robot where the tool is located. The surgeon holds the lever and controls the robot within a region specified in a pre-operative planning phase. This approach has been used at Imperial College for a neurosurgery robot and for a knee surgery robot. Details and benefits of these systems are given in the workshop.

Automated, or "Hands-Off" Systems

Traditionally, robotic systems have been used for surgery in an automated way. That is, once correctly positioned the robot has carried out the procedure automatically without intervention from the surgeon. A typical example of this is the PROBOT developed at Imperial College for prostate resection surgery[1]. In this procedure, the robot was used at the start of the operation to hold an ultrasound probe and scan this through the prostate to form a series of cross-section images. The outline of the prostate boundary to be cut was then identified by the surgeon on a computer display of the images. These slices were built into a 3D computer model and the pre-operative plan of robotic cuts was automatically produced for the surgeon. Once the surgeon was happy with this plan, the motions of the axes and the cutting sequence were passed to the robot automatically. The surgeon then positioned the robot cutter at the initial location and instructed the robot to proceed. The robot then carried out the sequence of cuts automatically whilst the surgeon observed a TV display of the endoscopic images of the cutter, together with a computer display of cutter and robot parameters relative to the tissue being cut.

An emergency "off" button was held by the surgeon to interupt temporarily or abort the procedure in the event of anything unexpected. However, apart from this emergency intervention, the procedure was automatic and the role of the surgeon was essentially that of an observer. Whilst this "hands-off" approach was welcomed by some surgeons as a reduction in stress and activity, others considered the lack of direct involvement in the patient care to be a disadvantage. There are also concerns about who is in charge of the procedure; is it the surgeon or the robot supplier. This can result in a number of legal issues for robot suppliers in the event that something goes wrong during the procedure, or even if patient outcomes are not as expected or hoped for! For this reason, some robot suppliers have declined to be involved in the provision of surgical systems. A further potential problem is that the sensing and modelling of the tissue to be resected is not generally in "real time", but is done pre-operatively.

Even in the instance of the PROBOT, where imaging is carried out at the start of the procedure and the patient is in the same state and orientation as a few minutes later when cutting takes place, the images of the organ are not taken in real time (ie at the moment of cutting). A further problem is that any intra-operative motion of the tissue to be cut is difficult to plan for pre-operatively. This can lead to a situation where, particularly for soft tissue, the cuts are different from those in the plan. Fortunately the prostate, by virtue of its anatomy, does not move much during the procedure and the process is primarily one of "debulking" and is not required to be accurate.

In other procedures, eg orthopaedics, the pre-operative CT scan and models are implemented on the patient, with the bone rigidly clamped and treated as a fixed object very much like a CNC machining tool[2,3,4]. This is the primary reason why robotic implementations of orthopaedic surgery have been so successful, although they involve an automated approach. Even for orthopaedics, however, the take-up by surgeons has been primarily dependent on the culture. Germany has seen a considerable acceptance of robotic orthopaedic surgery by both patients and surgeons, but in other countries the market penetration has been much slower.

Telemanipulator based Robotic Surgery

The use of telemanipulators (master/slave) systems for robotic surgery is well-established for holding and moving endoscopes, typically for minimally invasive abdominal surgery. In conventional surgery, an assistant stands close to the surgeon, moving the endoscope and camera, whilst trying to predict what it is the surgeon wishes to see on a TV display. The use of a "slave" robot with the "master" input operated by the surgeon, ensures direct control over what is being displayed[5]. The input system can be a simple "mouse", a head motion monitor or a voice control. The input is usually an open loop-system with each motion of the input giving a small increment in the appropriate direction. This relatively low-cost robotic aid to surgery is one which has had the largest market penetration.

Another type of telemanipulator is that in which the "master" is operated by a surgeon adjacent to the operating table, whilst viewing an endoscopic display and where the "slave" is mounted over the patient. The "master" usually comprises a complex linkage, whose joint motions are monitored and form an input to the slave arms which are usually kinematically similar to the master. Typically two arms are used for the above (eg, one to hold a gripper and the other scissors) in addition to a third arm that holds the endoscope and camera. The ability to scale the motions allows gross inputs at the master to result in fine motions and forces at the slave. The endoscopic camera can also provide 3D images which give the surgeon high grade magnified views, which partially make up for the current lack of a sense of touch. One example of such a system is the da Vinci system by Intuitive Surgical Inc, which has been used for "closed" (ie, minimally invasive) heart surgery as well as abdominal surgery[6]. Although it is not automated, and involves the input of a surgeon to generate motions of the slave, a telemanipulator is not truly a hands-on system since it requires the "slave" to be operated remotely from the "master" robot.

Hands-on Robots

The concept of a hands-on surgeon robot was first proposed by the author for robotic knee-surgery. The use of a hands-on concept would be very unusual in industrial robots, since it is usually desirable to have the operator some distance away from the reach of the robot, both to avoid dust and fumes resulting from the process being carried out and for safety. Thus, although industrial robots can be fitted with force sensors near the tip for, say, grinding the flashing from castings, the robot with fume extraction equipment is isolated in a cell whilst the operator is outside the cell. Thus the proposal to use a hands-on robot for surgery was novel. The concept was to place a 6 axes force sensor near the tip of the robot which carries a rotary cutter. The surgeon holds the force control lever and drives the robot within a region to machine appropriate shapes in the end bones of the knee that will allow a prosthetic knee implant to be accurately fitted. The robot servomechanism is programmed to provide compensation for resistance (eg due to gravity) so that it is easy for the surgeon to move. This hands-on robot is a special form of telemanipulator, in which the "master" (the force controlled handle) is placed directly on the robot "slave" output which it drives.

The use of a robot for knee surgery can consistently achieve a good accuracy of fit of the prosthesis over the knee and bones, requiring a minimal (or no) cement mantle for fixation. In addition, the femoral and tibial components can be correctly located relative to each other and to the leg as a whole, to give the desired knee alignment and degrees of valgus/varus. The use of a hands-on robot (called ACROBOT after Active Constraint ROBOT) gives the additional benefit of having the surgeon directly involved in the procedure so that his/her judgement and sensing can be utlised to best advantage, whilst the robot enhances safety by constraining the surgeon's action to a safe region and provides an accuracy of cut which would be difficult to achieve conventionally[7]. Thus the surgeon uses the robot as an intelligent tool and there is no doubt that the surgeon is in charge of the procedure and not the robot supplier. This eases many potential litigation problems and also helps overcome patient concerns.

A pre-operative plan of the procedure is produced by taking Computer Tomography scans of the leg, a few days prior to the operation. From these a 3D computer model is generated on a low-cost PC, onto which the CAD models of various types and sizes of prostheses can be overlaid. When the prosthesis and its location is correct, the required cutting plan is sent to the robot controller.

In normal industrial robots, the need for long reach, high speed and heavy payload requires that the robot is large with very powerful motors. The Acrobot concept, however, uses a gross positioner that carries and locates the Acrobot active system in the right position and orientation. The gross positioner can then be unpowered and locked off for safety, whilst the Acrobot is powered with motors just adequate for moving relatively slowly over a local region. This strategy avoids the need to move over large distances just to reach the target area, with a consequent need for high power motors. Whilst this approach introduces a degree of redundancy of motion, and hence increases cost and complexity, it is felt that it results in an intrinsically safer system. The special-purpose Acrobot has been designed mechanically to provide even and low impedance motion for all the axes, whilst the servo-control system has been configured to provide compensation for the gravitational and resistive loads, to allow the surgeon to move the cutter smoothly in all directions under servo-assist. The pre-operative plan not only provides the desired cutting planes on the end bones of the knee, it also provides a map of no-go regions which will result in damage (eg to ligaments). These "no-go" regions and the limits of the desired cutting planes thus provide a volume of "Active Constrain" within which the robot is permitted to move easily, using low force servo-assist. At the constraint boundary, the control system switches into high-gain position control, preventing radial motion into the no-go area whilst allowing a tangential motion around the constraint boundary or back into the allowed central region. The ability to achieve this transition using smooth stable motions, has been the result of considerable research.

Another hands-on robot with active constraint control has been designed for neurosurgery and has been researched at Imperial College as part of the EC funded project Roboscope[8]. This project aims to use intra-operative ultrasound images to give real time updates of pre-operative MR and CT merged images. These are used to provide Active Constraint boundaries which are outlined by the surgeon and passed to the robot control system. The active constrain control robot (called Neurobot) is being jointly researched with Fokker Control Systems of Amsterdam.

Like Acrobot, Neurobot consists of a gross positioning system that can be locked off whilst the relatively small active system is used. The gross positioner consists of a simple x,y base table with a z motion provided for the head clamp. The active system consists of a 5 bar link mechanism that holds the neuroendoscope in a collet clamp. The use of a 5 bar link permits a remote-centre for the pitch and yaw motions about the skull entry point. An in/out motion of the endoscope about the pitched/yawed position is achieved by moving the horizontal bars vertically on the base links. A fourth degree of freedom (the axial rotation about the endoscope axis) is also provided. A 6 axes force-control ring, located around the top of the endoscope, allows the surgeon to manipulate the endoscope with very small input forces. The use of a foot-pedal allows the force control system to be switched off at any location to permit the endoscope to be locked in position, so that tools can be deployed through the working channel. Active Constraint control allows the endoscope to be moved smoothly from an entry point to a target tumour in a straight line with minimal damage during transition, and then to move easily within the pre-defined boundary of the tumour to be excised whilst preventing entry into more critical regions of the brain at the periphery of the tumour. The use of the hands-on robot, together with Active Constraint control, ensures that the surgeon can adapt, on-line, during surgery to changes in soft tissue location due to interaction with tools much more readily than more automated robot surgery.

Conclusions

Robotic surgery is still in its infancy. Whilst automated surgery gives benefits of accuracy in location and in applied forces, hands-on systems have the potential to be more user and patient friendly allowing easier adaptation on-line to changed circumstances such as tissue motion. There is also less confusion about the surgeon being in charge of the procedure, with all the reassurance for the patient (and for the robot supplier) that this conveys.

It is anticipated that in addition to the above applications, medical robots will in future begin to target procedures that require a small and precise robot for tasks such as spine surgery or eye surgery. An additional area of activity will be in robotic systems that will benefit a larger population such as the GP in a local group practice. An example of this is the Bloodbot, being developed at Imperial College, which uses a force-control strategy for taking blood from patients automatically.[9] Systems of this type, which use robotic principles, can be produced in large numbers at relatively low cost to benefit many patients.

Since they are so recent in implementation, there is no objective evidence of the relative benefits of hands-on medical robots versus automated systems. However, their merits are intuitively convincing. It may not be possible to predict whether, in future, the majority of medical robots will prove to be hands-on or automated. However, one conclusion that may be drawn is that medical robots will be available in the next few years in large numbers and for an increasing number of procedures.

References

1. Davies, B L, Harris S J, Arambula-Cosio, F, Mei, Q, Hibberd, R D, "The Probot – An Active Robot for Prostate Resection". J. Eng. In Medicine, Proc H. of IMechE Vol 211, H4, pp 317-326, MEP Ltd, September 1997.

2. Wiesel, U, Lahmer, A, Borner, M, Skibbe, H, "Robodoc at B.G. Frankfurt – experiences with the pinless system." Proc. of 3rd Annual North American Prog. On Computer Assissted Orthopaedic Surgery. UPMC Shadyside, Pittsburgh, Pennsylvania, USA, pp133-117, June 1999.

3. Grueneis, C O R, Ritcher, R H, Hening, F F, "Clinical Introduction of the CASPAR system. Proc of 4th Symp. On Computer Assisted Orthopaedic Surgery, Davos, Switzerland, March 1999.

4. Davies, B.L., "A review of Robotics in Surgery". J. Eng. in Medicine, Proc. H. of IMechE. Special Millennium Issue Vol 214, H1, pp.129-140M.E.P. ltd., Jan 2000.

5. Finlay, P A, Ormstein, M H, "Controlling the Movement of a Surgical Laparoscope". IEEE Engineering in Medicine and Biology Magazine, Vol 14, No 3, pp 289-291, May 1995.

6. Carpentier, A, Loulmet, D, Aupecle, B, Berrebi, A, Rellard, J. "Computer Assisted Cardiac Surgery", Lancet, Vol 353, pp 379-380, 1999.

7. Davies, B L, Harris, S, Jakopec, M, Fan, K L, Cobb, J, "Intra-Operative Application of a Robotic Knee Surgery System"." Lecture notes in Compueter Science 1679m pp 116-1124. Springer Verlag, September 1999.

8. Davies, B L, Starkie, S, Harris, S J, Agterhuis, E, Paul, V, Auer, L M "Neurobot: a special-purpose robot for Neurosurgery." Proc IEEE Robotics and Automation Conf, ICRA 2000, San Francisco, USA, April 2000.

9. Zivanovic, A, and Davies, B L, "A Robotic System for Blood Sampling", IEEE Trans. on Information Technology in Biomedicine. Vol4, No 1, pp.8-14, March 2000.

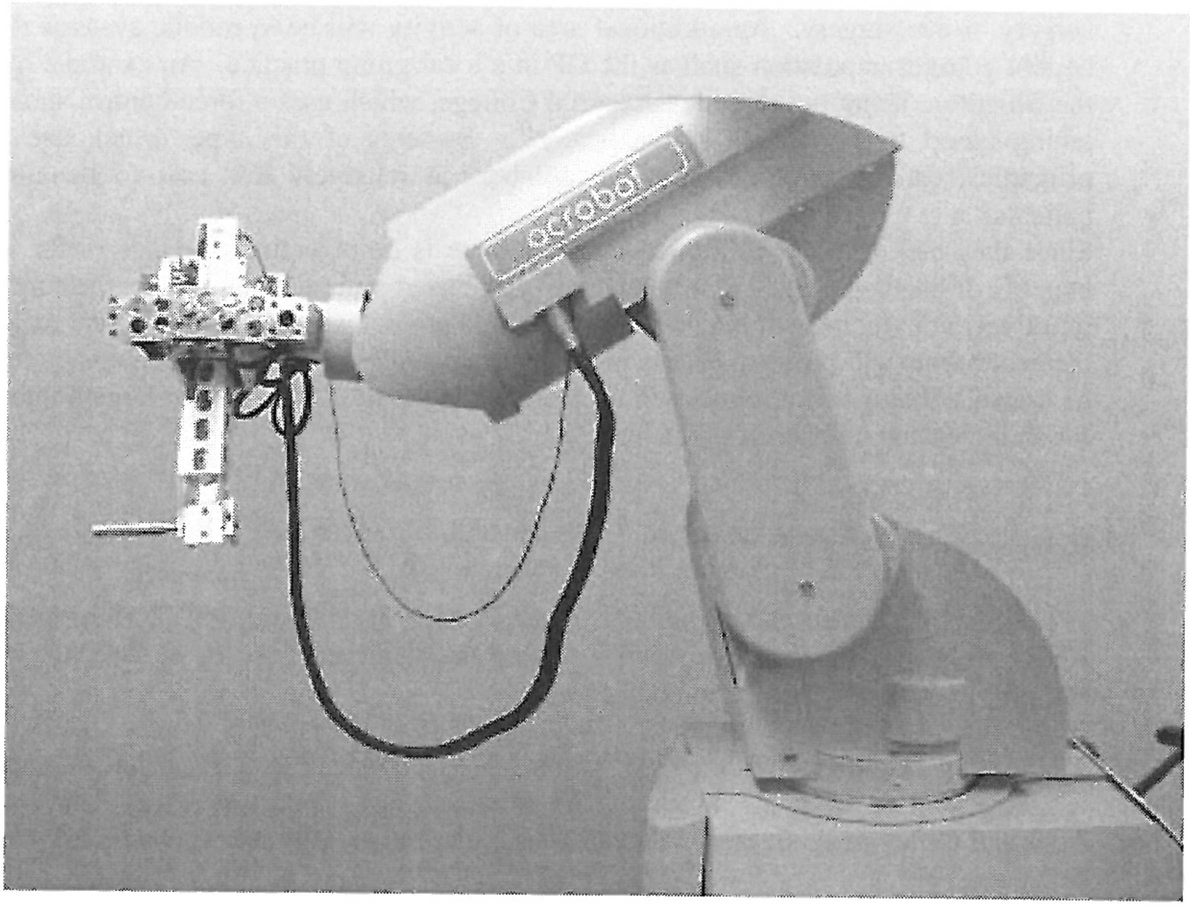

Fig 1. The IC Acrobot robot for knee surgery

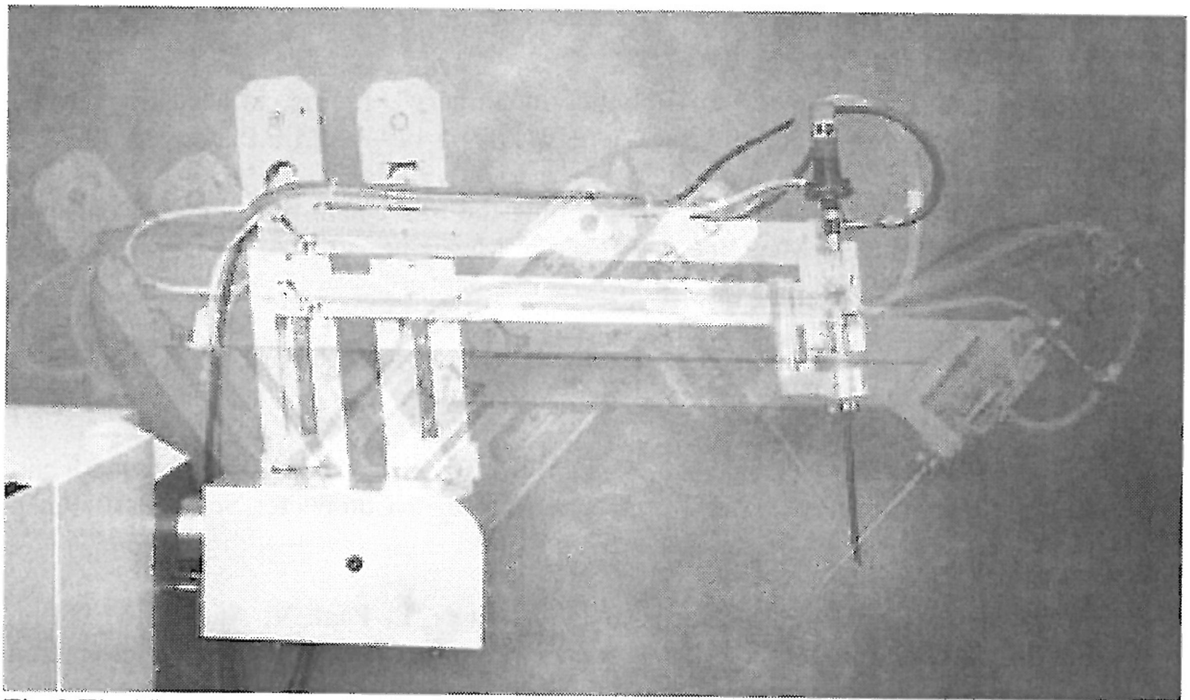

Fig 2 The Neurobot robot for Neurosurgery