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THE ROLE OF THE MECHATRONIC ENGINEER IN MEDICAL ENGINEERING

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Abstract. *Medical engineering and surgical robotics are relatively new subject areas in the field of corrective and preventative medicine, and as such there are tremendous opportunities for mechanical engineers to influence these particular fields. This is even more so for those mechanical engineers who have crossed the traditional boundaries and embraced the parallel disciplines of electronics, computer science and design. In truth the Mechatronic Engineer. Mechatronics is essentially a team or group approach to a problem whereby engineers, each with a broad background knowledge and maybe one area of specialisation, are able to visualise and appreciate the whole problem not just their particular specialisation. This is normally carried out in the now popular 'brainstorming' meeting. In this paper the authors will give examples of this approach to problems associated with surgical robotics applied to Minimal Access Surgery (MAS), orthopaedic surgery, surgical theatre design, rehabilitation robotics and to the design of medical aids for the Visually Impaired (VI).*

Keywords: *Mechatronics, medical engineering, rehabilitation robotics, surgical robotics.*

1. INTRODUCTION

Mechatronics is one of those hard to define subjects. If fifty engineers were asked for a definition, then they would in all probability give fifty different answers. Mechatronics is a group activity, a blending of traditional skills into a cohesive whole.

If we assume that there are three main engineering groups in an organisation, Electrical Mechanical and Computing, then the traditional approach has for each group to remain fiercely independent of the others only communicating when absolutely necessary normally when some crisis has arisen, or when passing on a project with the philosophy "We've done our bit, now do yours." (Figure 1). With the Mechatronic approach the traditional boundaries are still there, but with considerable overlap between them. It is this overlap that is the important difference with the Mechatronics philosophy, and it is this that makes the difference, not only to the product but also the overall working strategy of the organisation (Figure 2).

Definitions were mentioned earlier. Here are two fairly typical definitions of Mechatronics: "*Designing intelligent machines*" - about 25 of the hypothetical survey would have used this

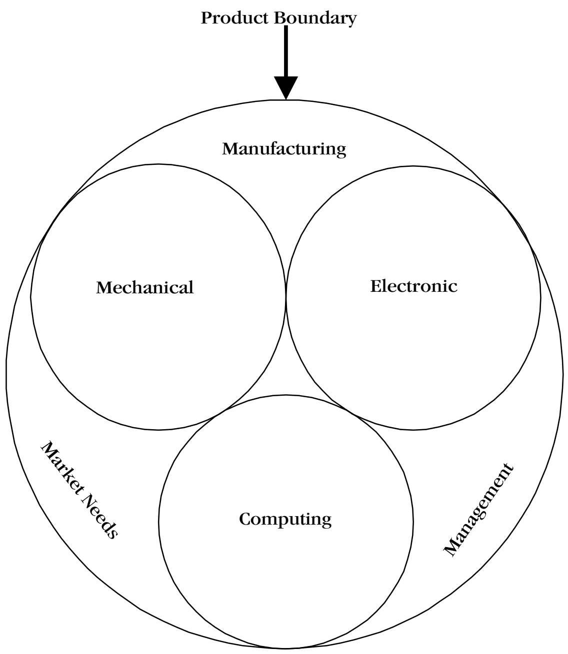

Figure 1: The traditional discipline boundaries

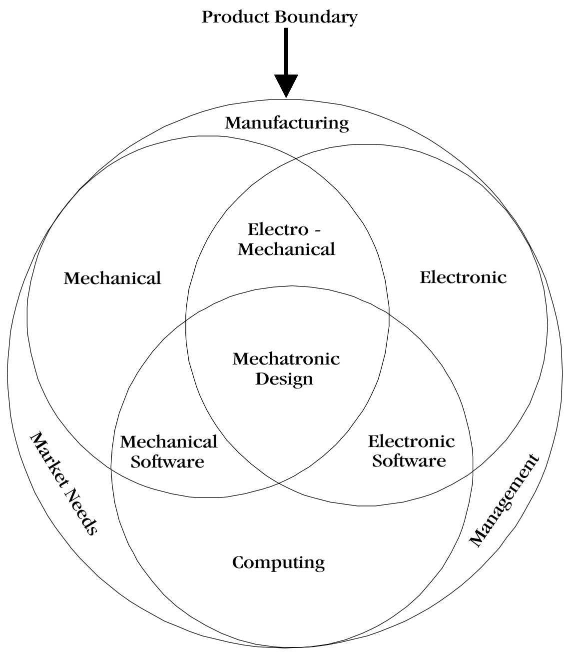

Figure 2: The Mechatronic discipline boundaries

form of definition; "*Product design fully integrating the electronic, mechanical and computing elements of the product*" - around 10 of the remaining group would have chosen this style of answer. For a fuller definition the Mechatronics Forum prefers "*The synergistic integration of mechanical engineering with electronics and intelligent computer control in the design and manufacture of products and processes*".

It is the word synergy that leads to the equation 1+1+1=4, where the missing or 'free' part is the Mechatronics kernal at the centre of the product. This equation could be re-written as:

Mechanical & Electrical & Computing = Ordinary or 'Dumb' product

Mechanical + Electrical + Computing = Mechatronic or 'Smart'' product

where & = ordinary add, + = Mechatronic combine.

As a further illustration of the Mechatronics concept consider for a moment the broad definition of an engineer, be it Mechanical, Electrical or Computing. It is often understood to mean someone with a deep knowledge of their own specialist subject but with a small breadth of general engineering knowledge. The Mechatronics Engineer, on the other hand, has a very broad general base of knowledge of all engineering subjects as well as a slightly deeper knowledge in one or more specialist areas. It is this broad base of knowledge that allows him or her to appreciate the problem from different viewpoints and to suggest and evaluate many differing solutions to the problem.

Robotics in surgery is a field in which Mechatronics design philosophies can flourish. The synergy obtained by the integrated design can allow the full power of computer-based intelligence and sensor-rich control to be applied to this sensitive and demanding role of protecting the health and prolonging the life of the patient.

The future of medical robotics is very exciting with many new ideas and possibilities being investigated, but undoubtedly the most exciting is in the field of small autonomous robots that can carry out investigative or small surgical operations without the need for patient trauma. This, in reality, means small pre-programmed robots that are at present only in the realm of science fiction, but with the help of Mechatronic Engineers could soon become science fact.

2. TELEMANIPULATOR FOR MINIMAL ACCESS SURGERY

A major problem facing the endoscopic surgeon is caused by the fixed rigid configuration of the endoscope which allows the surgeon to see only what is within the fixed field-of-view. This field-of-view cannot be altered relative to the endoscope axis. To change the field of view various different endoscopes are needed, one to view straight ahead and others to view at different angles to this. Ideally all these viewing angles should be accommodated in a single endoscope. At the present time the endoscope is held and controlled by a secondary surgeon who has to stand very close to the principle surgeon in order to place the endoscope near to the site of the operation. This very closesness brings with it its own special problems, not the least of which is the unavoidable contact between them so making the endoscope motion jerky. A solution to this problem could be to employ a robotic arm to hold and move the endoscope. But should the human operator be mimicked or should a special purpose robotic arm be designed?

Unfortunately it is often assumed that 'robotics' implies 'industrial robotics'. However, an industrial robot is not suitable for surgical applications. Industrial robots have been designed and developed following three basic criteria; namely-

1) They must be highly flexible (be capable of performing many different tasks)
2) They must have a high power to weight ratio to manipulate a useful payload at high speed
3) They must have a high degree of accuracy and repeatability.

Safety is not a primary concern as humans are excluded from the working envelope of an industrial robot. The design criteria for a surgical robot are very different.

1) Safety is the prime concern so as not to harm the patient, surgeon or theatre staff
2) The arm must not be capable of sudden or rapid movements
3) It does not require such a high power to weight ratio as the loads are much smaller.

Thus, the intrinsic safety of the surgical manipulator is paramount in the design, as is keeping it's operating envelope as small as possible so as to minimise interactions (intentional or otherwise) between the surgeon and theatre staff and the manipulator.

2.1 The Dundee University Minimal Access Surgical aSsistant (DUMASS)

In the design stages of the new type of laparoscopic manipulator, full account was taken of the problems experienced by all the operating theatre staff and careful evaluation of their requirements and needs were balanced with what can be achieved while still utilising the current operating theatre design and equipment. One of the prime aims was to increase the operating area available to the principle surgeon and to decrease the stress levels experienced by him.

The technique adopted was to use a design philosophy in which safety is the critical design constraint. This has led to the design of a very small, compact, semi-autonomous powered manipulator which still offers a full six degrees of freedom, a three axis manipulator and a three axis endoscope. This is illustrated in Figure 3 where axes X, Y and Θ are contained in the main manipulator and Z, x and y are contained in the endoscope.

The X and Y axes are so arranged that there is a fixed remote centre of compliance 65 mm below the body of the main manipulator i.e. the cannula insertion point, which means that provided the manipulator is correctly positioned no harm can come to the patient. By mounting the camera and lights distally on a steerable platform at the base of the main endoscope the surgeon now has the opportunity to see along various axes and even to look round the back of items of interest, something which was not possible before with the standard endoscopes. Furthermore, the endoscope is now held firmly and can be moved smoothly so that the picture

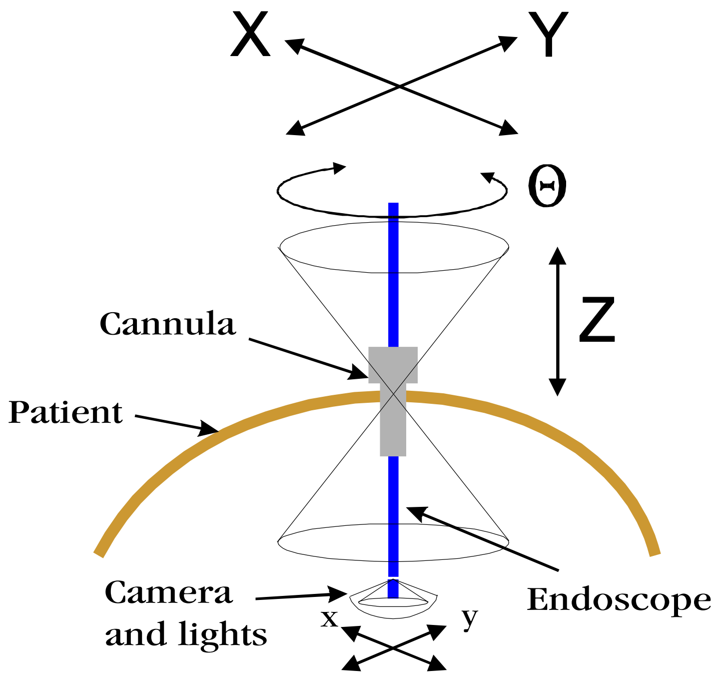

Figure 3: The six axes of the endoscope.

presented to the surgeon is not jerky and does not induce nausea.

Current endoscopes use a high power lamp (in the order of hundreds of Watts), fibre optic cable and fibre optic bundles around the outside of the rod lens system to bring a sufficient quantity of light to the viewing area. In terms of the power requirements for the light and losses through the fibre optics this is a very inefficient method of getting light to the viewing area, and the heat losses in the rod lens contributes to the build up in temperatures within the body cavity.

DUMASS utilises an array of small white LED's around the camera lens to provide the necessary illumination and these have the added advantages of requiring very little power to drive them (0.1 W) and consequently they do not heat up the body cavity.

The manipulator is coupled to a totally integrated, unobtrusive and natural multi input command system which is not limited in its expansion capabilities, therefore lending itself to other uses in theatre or in other fields requiring a natural, integrated command input.

A further feature unique to the DUMASS system is that it has been designed from the start to issue meaningful unambiguous audio information to the surgeon, instead of the usual 'beeps' or 'buzzes' normally associated with electronic equipment. Essentially the system is designed to 'talk' to the surgeon by way of a library of standard phrases which will convey meaningful messages to the surgeon and other theatre staff without causing them to look at a message on a monitor. This ensures the smooth flow of the operation by keeping all of the theatre staff fully aware of the current status of the controller. A specific part of this communication interface is to warn the surgeon if a requested movement is unattainable and to suggest a possible alternative.

3. ORTHOPAEDIC SURGERY ROBOTICS

A major problem with many robotically assisted surgical systems is in preventing the end effector from damaging vital tissues (muscle, blood vessels, brain cells, etc.) especially when cutting operations are being performed. This is caused by the generic problems associated with robotic arms in so much as that to achieve stiffness they are normally relatively large and heavy and this requires that large and powerful motors be used. The traditional method of overcoming these difficulties is to develop special purpose arms and manipulators that can only follow pre-defined paths of movement so reducing the possibility of harm to the patient and theatre staff.

At present medical robotics are primarily assistive, that is they are deployed to assist the surgical team (primarily the principal surgeon) in carrying out an operation and require constant communication between the surgeon and the manipulator to carry out their particular task. Fully active systems are still treated with suspicion by both patients and surgeons due to concerns over safety of the control system and robotic arm. There has been some research into automatic cutting of body tissue (Brett, 1995) (Yen, 1996) (Davies 1994) and bone (Graham, 1993) (Buckingham 1994) (Khobandehloo 1996) but these have not as yet been applied into main stream surgery and only limited trials have been conducted.

There are a number of problems associated with current manual / assistive bone cutting methods:

1) The saws are only capable of making planar cuts, whereas more complicated shapes, such as the intercondylar notch in total knee replacement (TKR), or the arched cut to re-align bones (dome osteotomy) are often required
2) Many procedures require that reasonable force be applied to the cutting tool while still maintaining control within the access afforded by the incision. An example of this is re-alignment of the socket of the hip joint, where an osteotome must be used with some force, despite the limitations of access imposed by the adjacent muscular, tendinous, nervous and venous tissues
3) Skilful use of the saw is required to ensure that the blade does not get hot enough to cause thermal damage to the bone cells.

By utilising a Mechatronics approach to the problems outlined above it has been possible to design an integrated saw system capable of solving many of the problems associated with these types of operation. The system utilises an adaptable sensor rich saw that can measure temperature, force, the vibration signature of the bone, and the overall system also contains a coolant dispensing system and a bone breakthrough detector. The saw blades are contra rotating to minimise holder vibration and so allow a lighter structure to be used to hold / manipulate the saw.

The saw heads are adaptable allowing one head to do the work of many previous tools, this speeds up the operation and also reduces the overall tool count and the cost of the unit.

As this is only a small part of an overall system, the controller and the software are PC compatible so that it can be used with a variety of different controllers, it has also been designed to provide a permanent archive of the parameters met during the actual operation and the actions taken.

4. SURGICAL THEATRE DESIGN

There is room for a great deal of improvement in the layout of current operating theatres when used for MAS. Undoubtedly a major problem is the lack of space around the patient caused by the enforced fixed locations of the surgeons and the ever increasing number of support systems being deployed. Considerable effort is required to optimise the present in-theatre arrangements, not only in the deployment of the instrumentation and staff employed but also in the actual design of the operating theatre itself.

A typical situation in theatre might involve the principal surgeon, second surgeon, an assistant surgeon (who normally acts as the camera/laparoscope operator) and a scrub nurse, all positioned around the patients torso. The equipment used by the anaesthetist is arranged at the head of the patient. There are also the video monitors used by the surgeons and, if the operation is to be used as part of a teaching/training regime, the video recording equipment. A typical view of an operating theatre using a state-of-the-art MAS system for laparoscopy is shown in Figure 4.

Figure 4. Typical view of an endosopic operation.

It is necessary that efforts should be made to carefully examine the role of each member of the surgical team to discover just what is the optimum level of personnel required for any particular type of MAS operation and to determine and develop the technical backup to ensure that MAS may be fully exploited both safely and economically. This approach has lead the authors to evaluate the problems associated with laparoscopic and rectal cancer surgery, this includes not only the layout of the operating theatre and all the equipment contained therein but also the instrumentation used and ways of improving the personal comfort of the staff, thus reducing the stress levels

A simple example of a requirement in theatre is that with nearly every piece of equipment if a dangerous situation is imminent, a button is pressed in error or a fault occurs, then the equipment merely ‘beeps’, and as all single beeps sound the same this means that the surgeon and theatre staff have to potentially check every piece of equipment to see which one requires attention. It would clearly be better if all the beeps were different (indicating different levels of status), and better still if the equipment could ‘talk’ to the surgeon and theatre staff

The two most common methods used to control the support equipment in theatre are front panel controls and foot switches, both of these are distracting to the MAS surgeon. Equipment with front panel controls requires that either the surgeon has to release the instruments he is working with and then change the control setting or ask an assistant to change the settings, hopefully to the surgeons requirements, and wait until it is done. One manufacturer is experimenting out with touch screen technology but the above comments still hold true for this as well, neither option lends to a smoothly flowing operation.

Control via foot switches has potential for causing even more disruption to the flow of the operation. If more than one foot pedal is in use (often with more than one control on each) the surgeon has to remember where each one is and then shuffle around trying not to disconnect any of the controls until he finds the appropriate control and then operate it. As the surgeon is standing up this means that he/she is then balancing on one leg whilst trying to carry out a possible complicated controlled movement with the other. If any of the controls have been accidentally moved out of reach of the surgeons foot, then the only options are for the surgeon to wait until an assistant puts it back into place or to let go of any instruments and step back and look to see where the controls are.

Both methods are very disruptive and can lead to further stress in the surgical team.

4.1 MAS operating theatre requirements

What is required is an integrated control structure whereby the surgeon, or an assistant, can control the equipment whilst still carrying on with the operation. Mechatronics design philosophy requires that the system has to viewed as a totality “a priori”. Only by doing so can true synergy be achieved. This has led to truly innovative solutions in the area of command and control and seeks to expand on this principle by developing a Surgical Control Area Network (SURCAN) whereby all the theatre equipment, including articulated operating tables, powered patient manoeuvring systems, lighting systems and physical supports for the staff, is linked into this network and the network controller would then provide meaningful audio information to the surgeon and theatre staff.

The primary command and control medium is based upon voice control. At the Medical Engineering Research Institute (MERIT) we have implemented a system whereby the surgeon can communicate with the robot arm controller and the theatre equipment using a specific set of command words (right, left, zoom, etc.). This set of recognised words and phrases can be increased as necessary. The system is trained to recognise individual surgeons’ voice patterns so that the system will only respond to one surgeon (or voice pattern) at any one time. Different surgeons may be added to the database of users by means of a training programme. This method of command is ‘hands-free’ and is hence particularly suited to MAS.

The system is based on a tree structure of dialogue whereby the control system prompts the operator for an input by a question such as “OK to switch on the motors?” and then waits for a response. The response is then checked against a list of acceptable words or commands, in this simple example it can only be “yes” or “no”, and the control systems will then proceed accordingly. Unrecognised words will cause the system to return to the previous branch of the tree and the question will be repeated. A list of acceptable words or phrases can be displayed at any time by the use of the keyword “menu”.

For fail-safe operation, any command/control system must avoid ambiguity. The voice command system is implemented in parallel with a unique fingertip actuation system developed at MERIT. This is called the FingerMouse. This consists of a miniature controller operating either as a ‘mouse’ or as a set of switches or joysticks which is worn rather in the manner of a thimble but underneath the surgeon’s glove. Using this, the surgeon is able to control the various instruments and assist devices without letting go of the operating instruments.

A further fail-safe feature is common to many MAS support systems known as ScreenPointer. The screenpointer developed by MERIT is attached to the surgeons head. Using slight head movements the surgeon is able to point to any desired area of the monitor screen and, via the Fingermouse or voice, to cause the endoscope manipulator to move to allow the surgeon to bring the desired view to the centre of the screen. In this integrated environment ScreenPointer has been shown to be far more effective than devices which rely on gross head movement, pure joystick manipulation or other obtrusive gestures and movements.

Should the surgeon so desire he can also control the theatre equipment via menus on the monitor screen with ScreenPointer.

This work is seen as central to the total integration of the operating theatre into the hospital and eventually the complete health care system and a schematic is shown in Figure 5.

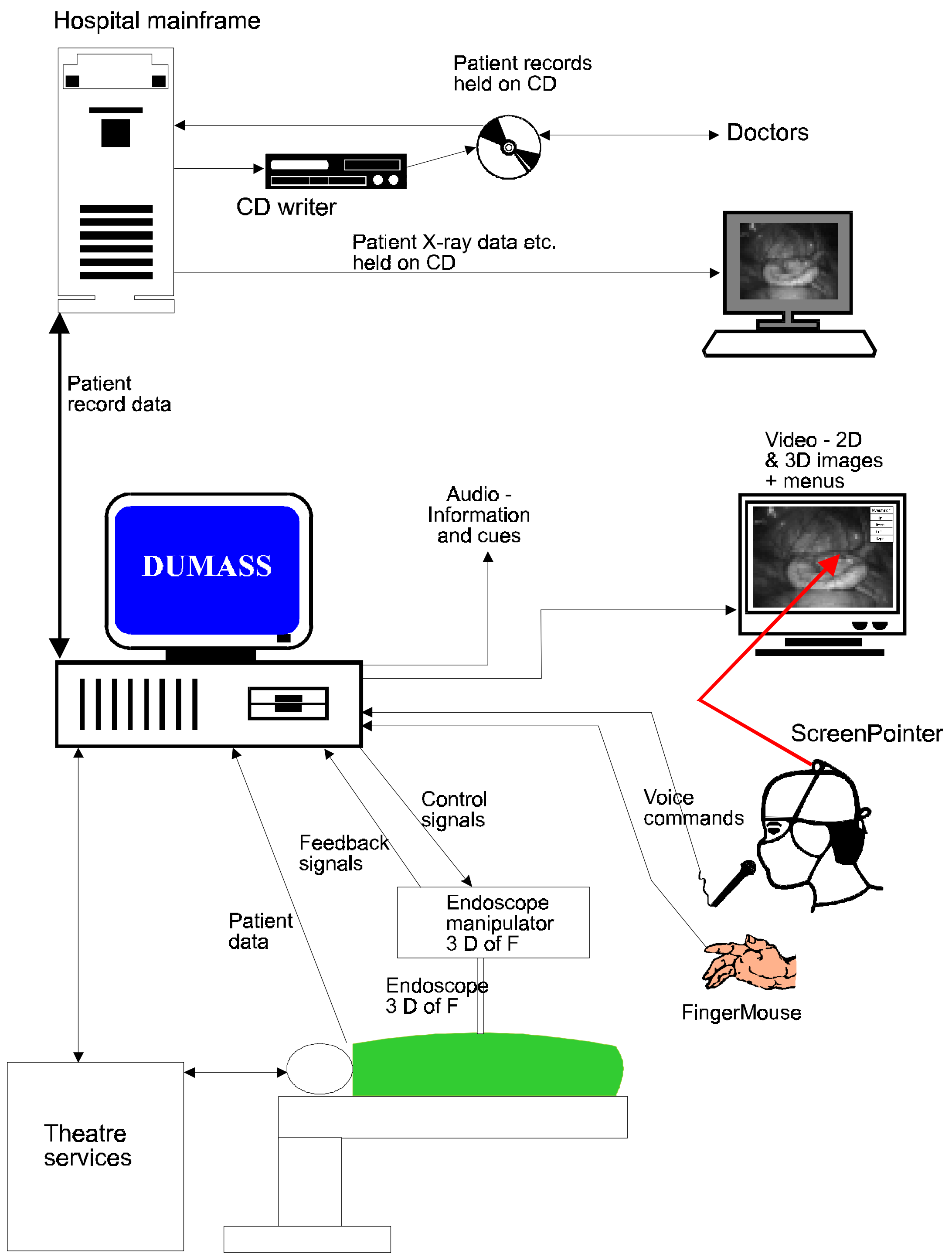

Figure 5. A schematic of the proposed control structure around the MAS surgeon.

5. REHABILITATION ROBOTICS

People who have undergone sudden, severe trauma such as may be experienced in sports or road traffic accidents or those who have suffered a heart attack or stroke are often in need of specialised remedial treatment which would normally be supplied by a physiotherapist. By the very nature of the trauma, people who need the services of a physiotherapist are those who are least able to travel to the hospitals or health centres to receive treatment. The simplistic solution to this problem is to employ and train a vast number of physiotherapists, but given the present economic climate this solution is never likely to happen.

In the majority of cases patients require very similar treatment, that is the exercising of upper or lower limbs to prevent stiffness and to promote muscle recovery and growth. Weight training exercises are one of the conventional methods of providing this. This is a perfectly acceptable solution for a otherwise fit and healthy person but is of no use to an elderly or severely impaired person.

Mechatronics can supply the answer though in the form of pseudo-physiotherapists. A working party from MERIT have proposed a solution whereby smart machines can be installed in the patients home or at specialised therapy centres. These machines can be operated in either the assistive or passive mode depending on the individuals requirements and are linked to a home monitoring system. This is a remote link from the hospital or health centre to the patients home and via smart card technology is able to track the patients progress and modify the machine parameters depending upon how the patient is responding to treatment.

To give an example of the possible use of the machine, say for a lower limb. The machine is a able to be used in passive mode whereby the patient would operate it in much the same way as a bicycle exercise machine, the difference being that only one limb is exercised at a time. As with a conventional exercise machine the loading can be adjusted to increase the effort required to turn it, but in this case it is under computer control via a pre-defined programme from the physiotherapist via the remote link. All the data taken during an exercise session, that is length of time used, when used, speed, trend (i.e. did it speed up or slow down), is stored ready for remote retrieval by the physiotherapist so that the patients progress can be monitered.

If it is used in the assistive mode the machine would exercise the patients limb via a pre defined routine by the physiotherapist and again controlled by the on-board computer. All the data taken from the exercise period is again stored ready to be read by the physiotherapist remotely. The patient is able to override the system and shut off the power at any time.

6. MEDICAL AIDS FOR THE VISUALLY IMPAIRED

Two percent of the UK population (approximately 1 million people) are diabetics, additionally, at least 2% of pregnancies develop gestational diabetes. In order to control their condition suffers need to monitor their blood glucose levels and administer insulin accordingly. This involves lancing a finger, placing a sample of blood on a transducer and taking a reading from a meter attached to the transducer. This process is awkward, particularly for those with visual impairment (VI), a condition common to diabetics and for those with physical disabilities, e.g. motor skills impairment.

Sufferers with VI may not always manage to get sufficient blood onto the transducer making the reading innacurate necessetating a repeat of the process. Diabetics also tend to have poor circulation so making the process even more difficult.

Glucose monitoring is, therefore, unpleasant and many patients fail to do it adequately or sufficiently frequently, which can have adverse effects on their diabetes control and hence give rise to earlier onset of the long term disabling complications of the disease such as retinopathy, neuopathy, nephropathy and cardivascular disease. These in turn can lead to blindness, renal failure and leg amputation.

Personnel from MERIT are working on ways to address the above problems, and initial tests and results are promising.

7. CONCLUSIONS

Medical Engineering has many diverse problems ranging from the design of new types of instrumentaion for endoscopic surgery, aids to help patients recover from trauma to the inegrated development of totally new operating theatres for Minimal Access Surgery. Each one a considerable challenge in its own right and possibly almost impossible to solve if the engineer works in isolation and does not emprace the Mechatronics approach.

There are many problems still be be solved in the field of Medical Engineeering, but by employing the Mechatronic approach, solutions to many diverse problems can be found as have been outlined in the above examples.

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