Study Report - Neuro-Endoscopic Manipulator

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Contents

Introduction

This report discusses the design, kinematics and dynamics of a hybrid parallel-serial manipulator for use as a surgical aid in Neuro-Endoscopic procedures. It also discusses possible force control approaches which may be applied to the manipulator, including the previously used Modified Damping approach and possible improvements on this concept. Finally the apparatus required to test the design of the manipulator and its control is specified and a Project Plan outlined for implementing this.

The basic requirements for the ROBOSCOPE project are set out in [1], and are paraphrased in this report.

This report is being reviewed and updated continuously, with the intention that it will form the basis of the MPhil->PhD Transfer Report and eventually the Thesis. As such this report is not complete at the time of writing.

Design Specification

The current state of the art in Neuro-Endoscopy involves the use of a hand-held endoscope which is guided to the site with the aid of pre-operative MR images. The site is identified by inserting a needle to the depth of the pathology and then following the tract with the endoscope. This procedure is performed through a cranial burr-hole, through which intra-operative Ultra-Sound imaging is also introduced when the endoscope is removed. The current procedure requires considerable dexterity and communication skills on the part of the surgeon and assistants, as the endoscope must be held by hand while procedures at the target site are performed through the instrument. To alleviate the dexterity and communications problems involved with the procedure, as well as improve the accuracy, a need has been identified for a force-feedback actively constrained robotic manipulator with intra-operative image guidance. In order to perform to the surgeons requirements the manipulator must be able to rotate and translate the endoscope in the manner shown in Figure 1;

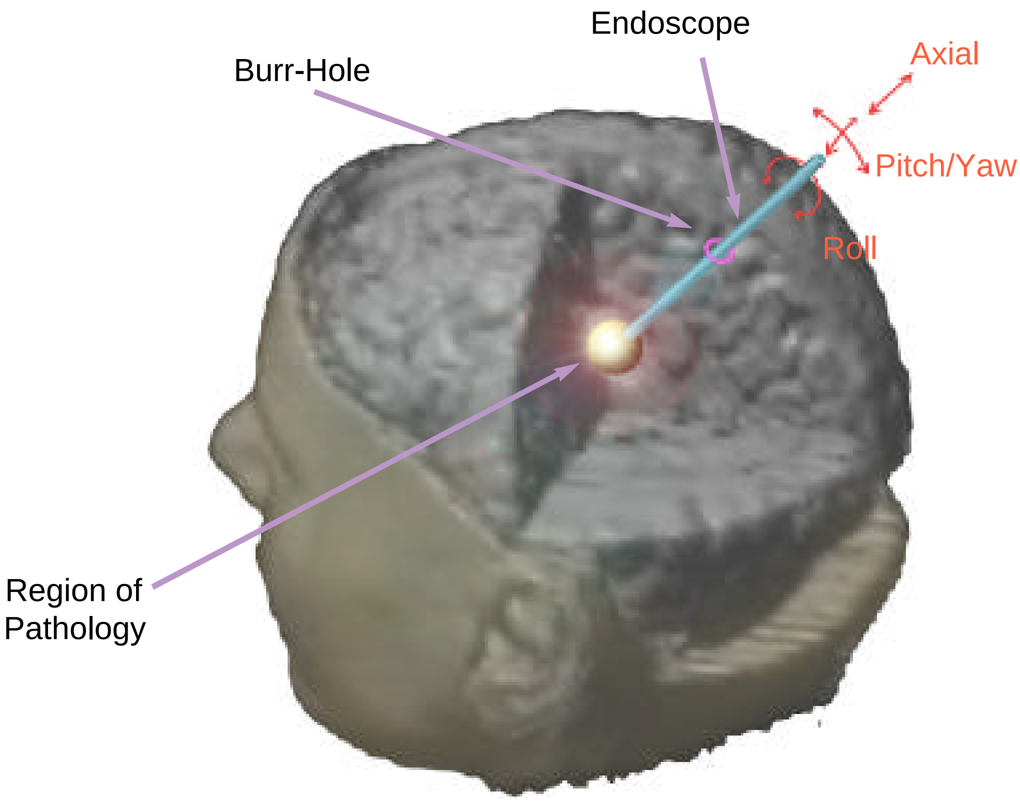

Figure 1 - Manipulator Positional Requirements

The endoscope must stroke a distance of 150 mm in order to reach deep-seated tumours and haematomas with an accuracy of 25µm. It must be able to rotate about a virtual fulcrum described at the surface of the brain (the Burr-Hole) by 45° in both pitch and yaw and must be able to roll about its axis through a full 360° (or at least 180° in either direction from a central position). It is desirable for all axes to exhibit equal force admittance so that the surgeon does not feel constrained to or from any particular set of motions. Note that the axes are represented in no particular order in Figure 1 - the order in which the axes are applied in the manipulator is important and will be discussed later (Force Control Strategy).

Manipulator Architecture

There are effectively two choices when considering the basic architecture of the manipulator. It can either have a standard serial architecture, where each degree of freedom is mounted on, and therefore dependent on and coupled with, the previous one or a parallel architecture involving several closed loop kinematic chains, which allow several axes of motion to be actuated in parallel.

Serial Manipulators

These correspond to the standard open kinematic chain of most robotic manipulators, including X-Y positioning systems (ink-jet printers, plotters etc.), SCARA type robots etc. The characteristic of a serial manipulator is that it involves an open kinematic chain. Two serial manipulators that have been used under active-constraint control previously are the 3-DOF SCARA robot used for drilling the tibial shape in the end of the tibia [2] and the 4-DOF ACROBOT [3] used for contouring the end of the femur, both of which are intended for precise machining in uni-compartmental knee replacement surgery. A serial manipulator configuration which would solve the positioning problem is shown in Figure 2;

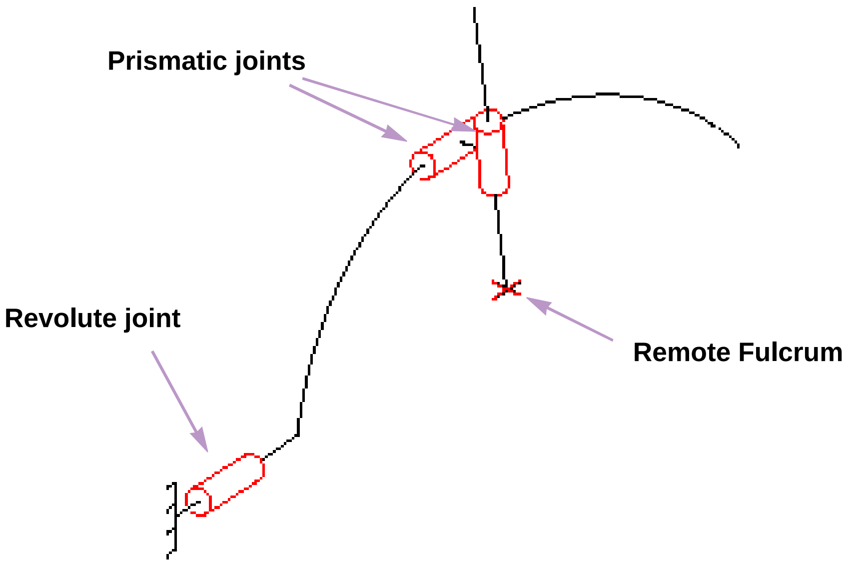

Figure 2 - Serial Architecture

The single advantage that this architecture has over any other is that a true remote fulcrum can be achieved. Unfortunately, this is at the expense of equal admittance between the axes of control, and presents problems related to the order of the axes under force-feedback control, which is discussed later (Force Control Strategy).

Parallel Manipulators

The alternative is to use some kind of parallel architecture in which closed loop kinematic chains are involved. This allows several axes to be controlled in parallel, enabling more similar impedance between each axis as well as higher load carrying capabilities. Examples of this kind of manipulator include the Stewart platform (usually used as a flight simulator), the Clavel Delta Robot, the Hexa Robot and the Star Robot. The closed loop chain often results in some kind of redundancy (either as an extra actuator which provides no more motion than that provided by other actuators, or as non-actuated joints), which usually results in greater load bearing ability and accuracy. More importantly in this application, parallel manipulators can provide several axes of control which have similar admittance - ie; to move the manipulator in the direction of one axis requires similar forces to those required to move in the direction of another axis. There is a practical limit to this. Increasing the number of degrees of freedom in a parallel configuration usually involves severely restricting some of the axes of control. The Stewart Platform(figure 3), for instance, has 6 degrees of freedom, yet cannot move very far in any of these degrees. It also involves two redundant degrees of freedom in order to provide all four of those required in this task.

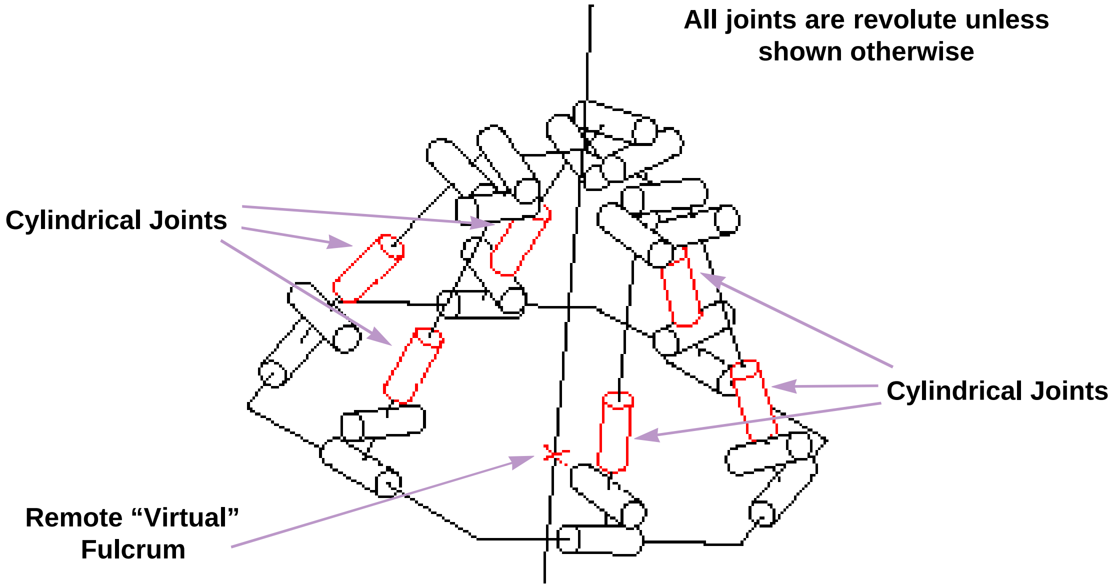

Figure 3 - Parallel Architecture (Stewart Platform)

Hybrid Architecture

It seems clear from the specification that at least the two axes of pitch/yaw must be parallel in order to provide equal admittance in these directions. However, the circumferential movement is relatively large and would be almost impossible to achieve if it had to be actuated in parallel to the pitch/yaw axes. A Stewart platform manipulator (figure 3) could achieve the desired degrees of freedom in a fully parallel configuration, but limits the movement in each degree, and would be incapable of providing full 180° roll. It also involves two redundant degrees of freedom.

In order to achieve the desired DOF without excessive redundancy, and allowing for the large movements required of the manipulator, a hybrid system is perhaps optimal (Figure 4);

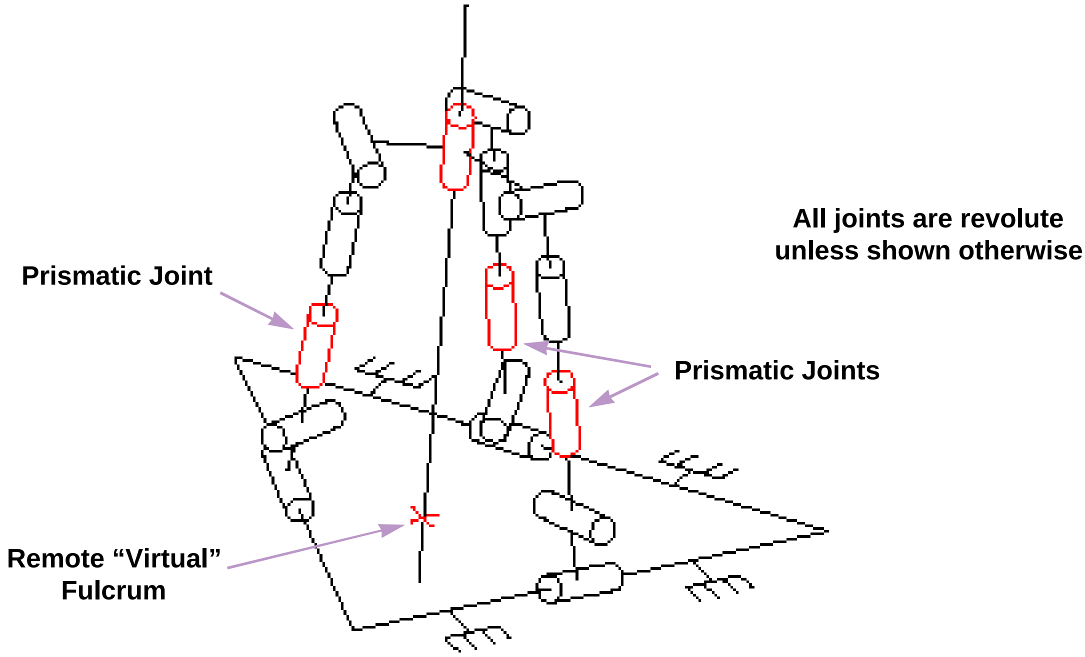

Figure 4 - Hybrid Parallel-Serial Architecture

This involves a parallel part which provides the pitch, yaw and axial motions (through the actuated joints shown in red), in series with a revolute joint which provides circumferential motion. In designing the manipulator with this architecture, a further useful side-effect is realised - the manipulator is intended to be mounted on a gross positioning stage, which by its very nature will involve some positioning error. This error is propagated to the fine positioning manipulator and needs to be compensated for. To a limited degree this can be achieved by the hybrid manipulator, by specifying the virtual fulcrum and the propagated error in the kinematics equations. This will be considered more fully later (Manipulator Analysis).

For position control alone, this manipulator requires 3 linear motors and one rotary motor, with 3 linear encoders (one on each linear motor) and one rotary encoder. A total of 4 degrees of freedom. This would require an I/O board with at least four axes of control ie; 4 encoder inputs, 4 Digital to Analogue Converters and an on-board DSP controller.

Force Control Strategy

Previous attempts at Force-Feedback control of robotic manipulators [2,3], have concentrated on Implicit Force Control and Modified Damping Control, the latter of which was found to be most successful in controlling the serial manipulators involved. These strategies were modified from algorithms developed for force control in industrial applications, such as de-burring. In these operations the requirement is for a controlled force (usually constant) to be applied to the workpiece, while the position of the end-effector is controlled to perform the required task. This has been translated to orthopaedic surgery by measuring a control force and using this to modify the velocity command, in a Proportional-Differential type position control system.

Whatever control strategy is used, it is reasonable to assume that the system must measure a desired input force using some kind of multi-axis force/torque sensor. In order to understand the exact nature of the force control required, a free body diagram of the end-effector is examined;

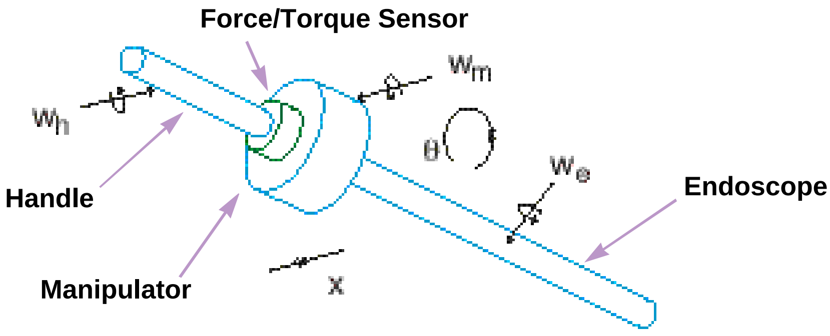

Figure 5 - End Effector Free Body Diagram

In this diagram the end effector is affected by three forces and three torques combined into three 6-dimensional *wrench* vectors. These are the wrench imposed by the environment on the endoscope, $\mathbf{w}_e$, the wrench applied by the surgeon to the handle, $\mathbf{w}_h$, and the control wrench applied to the end effector by the rest of the manipulator, $\mathbf{w}_m$. We would like to design our control law so that the wrench provided by the manipulator, $\mathbf{w}_m$, is some function of the control wrench, $\mathbf{w}_h$, and the position, $\mathbf{x}$, so that the manipulator has an *assistive action*, and a *constraining action*.

$$\mathbf{w}_m = f(\mathbf{w}_h, \mathbf{x})$$

Constraining Action

The positional constraint can take the form of a hyperbolic function. This function must be such that above a certain distance from the constraint boundary, d_c, the constraint does not affect the force control, while at the constraint boundary, it exactly cancels the assistive action. Beyond the constraint boundary, it must apply a wrench which returns the end-effector to within the boundary. Thus, the constraining action must be some modifier to the assistive action;

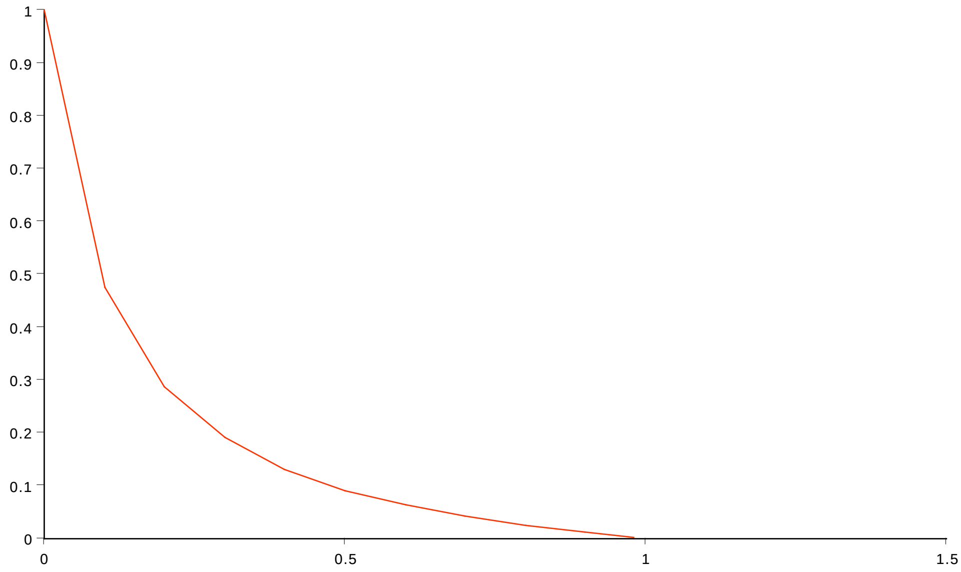

Figure 6 - Constraint modifier

Such a curve takes the form;

$$\mathrm{m}(x) = \frac{1}{(nx + a)} - b$$

where x is the ratio of the distance from the boundary, $|x|$, to the constraint depth, d_c, n is a design parameter (8 in this case), while a and b are determined to fit the curve (in this case; a = 0.89898, b = 0.11237244). Note also that the modifier must only work for x<1.

Thus, the control law becomes;

$$\mathbf{w}_{\mathrm{m}} = \mathbf{w}_{\mathrm{a}} - \sum_{i=1}^{n} \left(\left(\frac{1}{(n\bar{x} + a)} - b \right) \left(\frac{|\mathbf{w}_{\mathrm{a}}|^2}{\mathbf{w}_{\mathrm{a}} \cdot \hat{\mathbf{n}}_i} \right) \hat{\mathbf{n}}_i \right)$$

where $\mathbf{n}$ is the 3-dimensional unit normal to the boundary, $\mathbf{w}_a$ is the assistive wrench and the sum is performed over the part of the constraint which contains the end-effector.

Assistive Action

We would also like an element of force feedback, so the handle wrench, $\mathbf{w}_h$, is some function of $\mathbf{w}_e$(when the constraint is not affecting the control, ie when x>1)

$$\mathbf{w}_{\mathrm{h}} = \mathrm{f}(\mathbf{w}_{\mathrm{e}})$$

Now, the wrench measured by the force/torque sensor can be found by decomposing the free body diagram further;

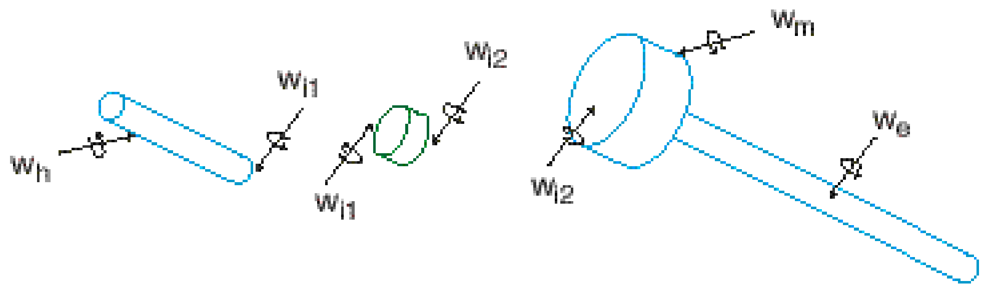

Figure 7 - Free body diagram - Sensor wrenches

So, the sensor will measure the interaction wrenches;

$$\mathbf{w}_{meas} = \mathbf{w}_{i1} = \mathbf{w}_{i2}$$

Now;

$$\mathbf{w}_{i1} + \mathbf{w}_{h} = 0$$

$$\mathbf{w}_{i2} + \mathbf{w}_{m} + \mathbf{w}_{e} = 0$$

which shows that the wrench the surgeon applies will be equal to the manipulator plus environment wrenches, and will be the measured force/torque. If the manipulator is controlled such that it provides forces proportional to this measured handle wrench, less force will have to be applied to the handle in order to overcome the environment wrench, as well as dissipative wrenches and the inertia of the manipulator (although these effects should in fact be removed by decoupling them in the control law). The proportionality can be greater than or less than unity. If greater than unity, the manipulator will lessen the environmental feedback, which would be useful if the environment is stiff or highly damping (orthopaedic surgery); alternatively, if less than unity, there will be greater feedback from the environment, which would be useful in low stiffness / low damping environments (soft tissue surgery). Thus, we have achieved the aim in a very simple manner - that of providing force feedback which is related to the environment;

$$\mathbf{w}_{h} = \mathbf{w}_{m} + \mathbf{w}_{e} \qquad \mathbf{w}_{m} = k_f \mathbf{w}_{h}$$

$$\mathbf{w}_{h} = k_f \mathbf{w}_{h} + \mathbf{w}_{e}$$

$$\boxed{\mathbf{w}_{h} = \frac{\mathbf{w}_{e}}{(1-k_f)}}$$

Hands-Off Mode - Position Control

The procedure also requires a hands-off capability - that is the ability to move the manipulator to a particular position under force control and then lock it in that position while the operator performs another task. Under such circumstances the control law must switch into a different mode. At the point of being commanded to lock in place, the manipulator must use pure position control to maintain its pose, under whatever forces are applied to it. This is necessary as it is likely that the operator will want to pass tools down the endoscope while in such a state, and the procedures to effect this will undoubtably impose wrenches on both the handle and from the environment. It is unlikely that simply counteracting any measured forces would be sufficiently accurate to maintain position. A joint-based PI control law is proposed to effect the Hands-Off mode, as this will allow simple position control and will integrate out any standing error due to external forces (no de-coupling is required as coupling terms usually involve velocity, which is zero in this case);

$$\mathbf{w}_{\mathrm{m}} = k_p(\theta - \theta_{\mathrm{d}}) + k_I\left(\int \theta - \theta_{\mathrm{d}}\right)$$

Thus, we can now describe the entire control system with the aid of a diagram as follows;

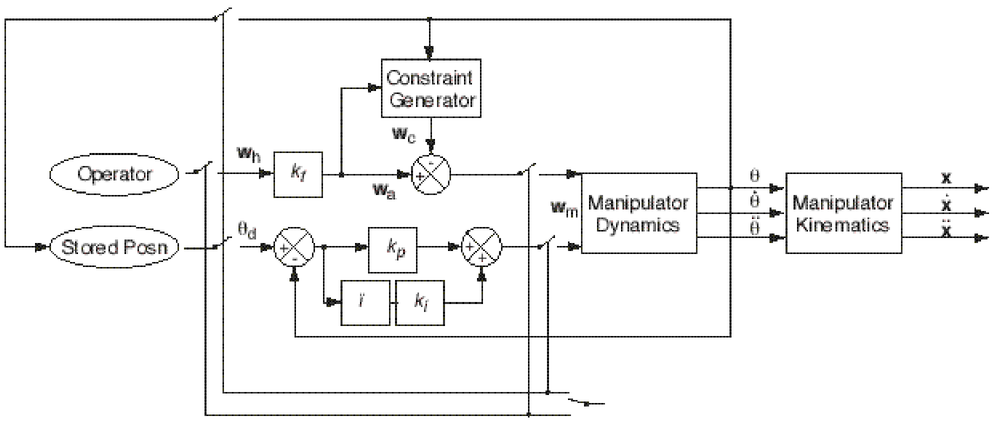

Figure 8 - Constrained - Assistive Force Control with Locking Mode

Note that, although a pre-operative conversion of task-space to joint space needs to be performed, no on-line calculation of either the DKP or the IKP need be done for the basic control algorithm. Although this will provide the basis of the control of the manipulator, there are further issues which will need to be taken into account. Gravity and dissipative forces, such as friction, will need to be de-coupled in the control law and the exact form of the constraint will need to be decided.

Manipulator Analysis

The concept design of the manipulator is shown in Figure 9. As can be seen, this is based on a standard Cosman-Roberts-Wells Stereotactic Frame, with the hybrid manipulator mounted as the end-effector instead of the standard tool-holder. Thus, the gross positioning of the endoscope is performed manually (in this prototype) by the 5-axis Frame, which is locked off once in place, to allow the fine positioning stage to work.

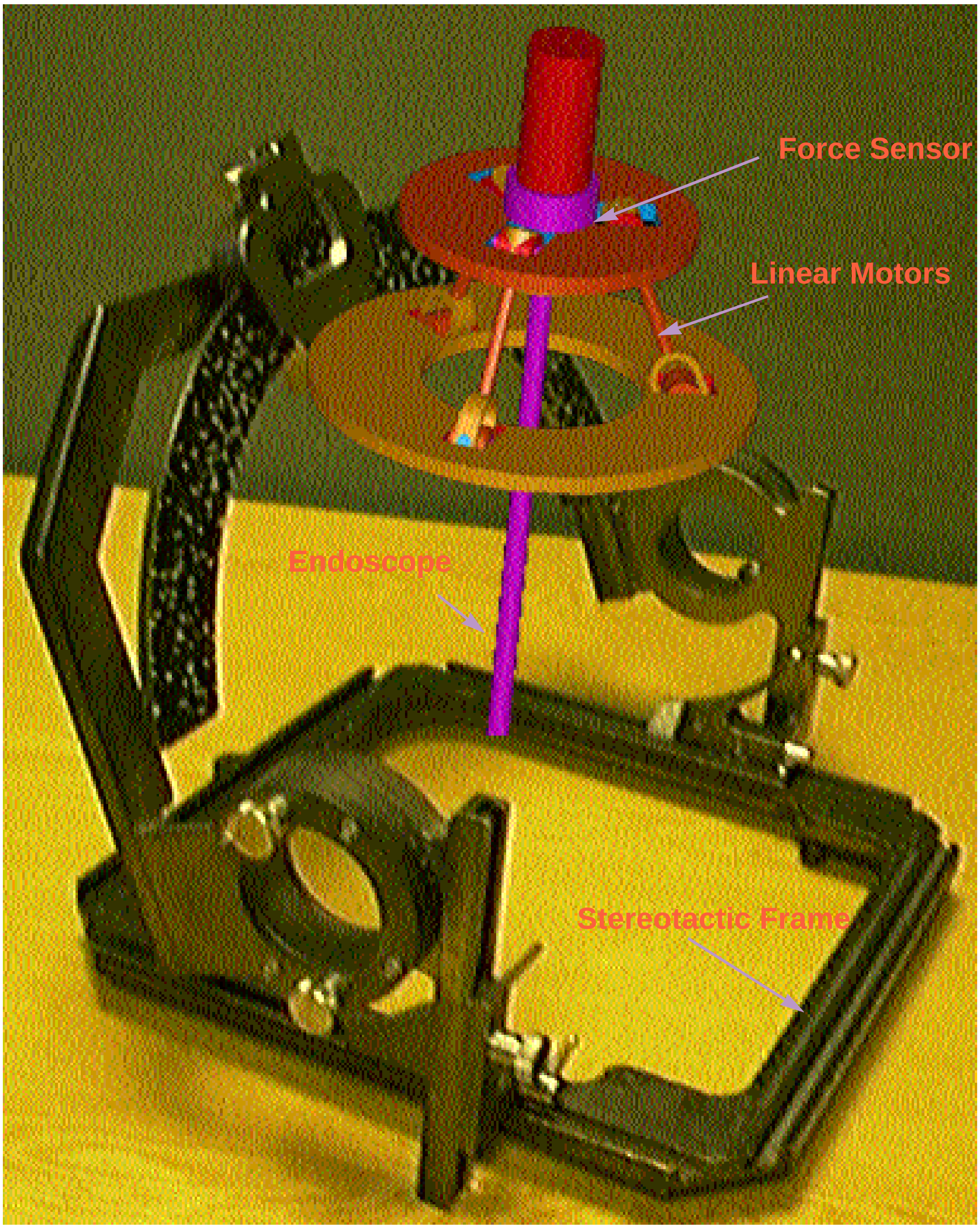

Figure 9 - ROBOSCOPE Prototype Concept

The specification requires the manipulator to be able to hold a position to an accuracy of 25 μm with a maximum force acting on the tip of the handle of 1N. The design of the manipulator is analysed in this section in order to ensure that it will meet the specified targets.

Procedures for solving the Inverse Kinematic Problem and Direct Kinematic Problem are also detailed here.

Manipulator Architecture

Considering one leg of the manipulator;

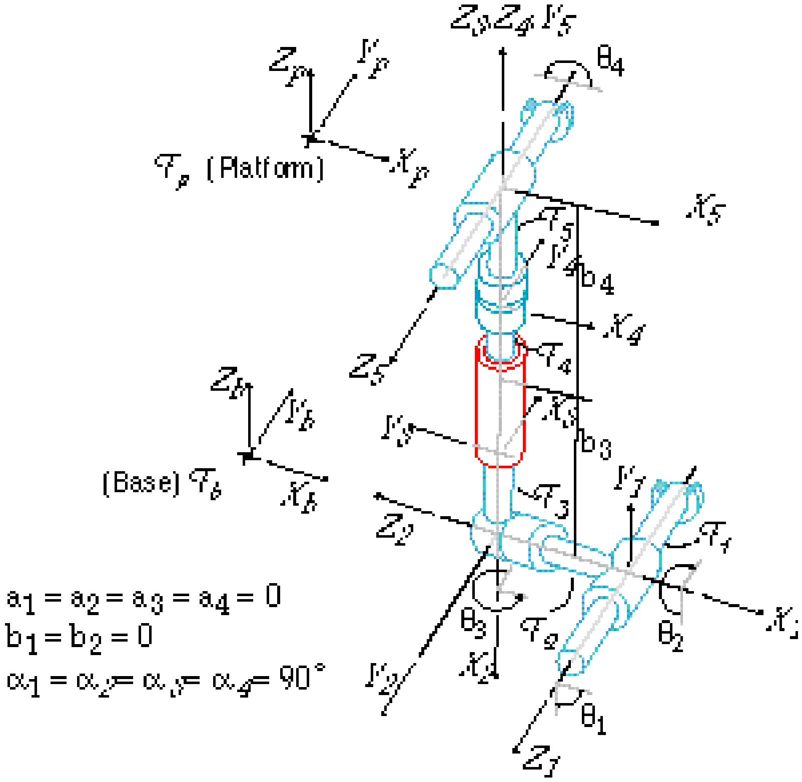

Figure 10- Single Manipulator Leg

From this one can see that the leg can be described by the Denavit-Hartenburg parameters;

Joint	ai	bi	ai
1	0	0	90°
2	0	0	90°
3	0	q_i	0°
4	0	b_4	90°
5	0	0	90°

Table 1 - D-H Parameters of the Leg of Figure 10

To completely describe the manipulator, we also need to calculate the frame transformation from the base frame, $\mathcal{F}_b$, to the first frame of each leg, $\mathcal{F}_{1j}$, and from the last frame of each leg, $\mathcal{F}_{5j}$, to the platform frame, $\mathcal{F}_p$, as shown in Figure 11;

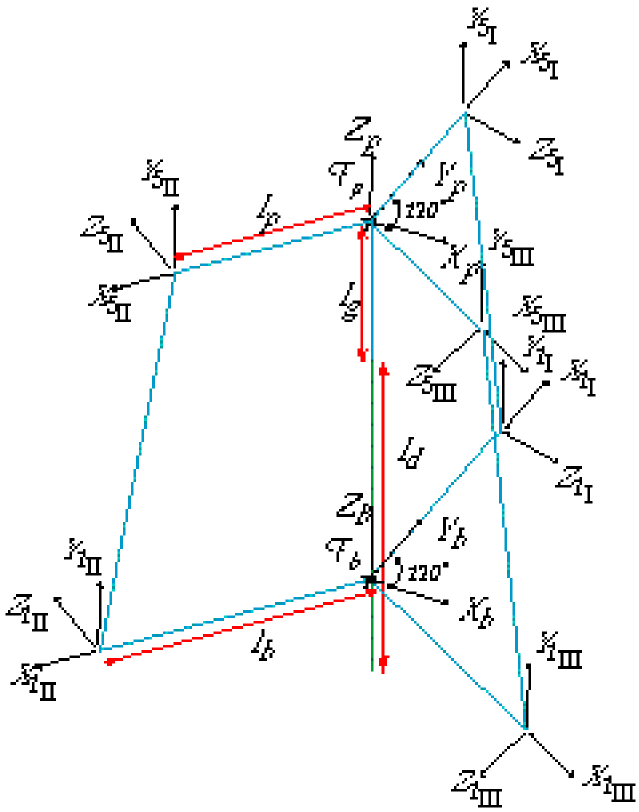

Figure 11- Frame Transformations; Base - Leg - Platform

In the figure l_d is the length of the endoscope, l_p and l_b are the design parameters of the platform and base, and it is assumed that the optimal configuration will be when the legs are equidistant around the manipulator. The distance lg is a design parameter, which is included to allow for various items hung from the bottom of the platform such as the revolute motor assembly and valves, conduits etc running away from the endoscope ports. It is also worth noting that b_4 (Figure 10) cannot be reduced to 0, due to the nature of the bottom joint in this design. This will become apparent in the part and assembly drawings of the final design.

Inverse Kinematic Problem

In order to design the manipulator in detail we require a solution to the Inverse Kinematics Problem(IKP). It is also necessary to convert the entire task space of the procedure into joint space at the start of the operation. Thus, an efficient algorithm is needed to calculate this conversion from World co-ordinates (a frame attached to the remote fulcrum and parallel to the base frame) and the joint variables. In this particular case, the manipulator admits a closed form solution to the IKP;

Referring back to Figure 10, it can be seen by inspection that the length of the leg from the origin of the first frame to the origin of the last is;

$$l_L = b_3 + b_4$$

where b3 is the joint variable q of each leg j, so;

$$q_j = l_{L_j} - b_{4_j} \qquad \text{-(1)}$$

Now, referring to Figure 6, the co-ordinates of the 1st Frame of each leg (I, II, III) in terms of the base frame, can be expressed as;

$$\{\mathbf{a}_0\}_I = \begin{pmatrix} 0 \\ l_b \\ 0 \end{pmatrix} \qquad \{\mathbf{a}_0\}_{II} = \begin{pmatrix} -l_b\cos30° \\ -l_b\sin30° \\ 0 \end{pmatrix} \qquad \{\mathbf{a}_0\}_{III} = \begin{pmatrix} l_b\cos30° \\ -l_b\sin30° \\ 0 \end{pmatrix}$$

Whilst the co-ordinates of the last frame of each leg can be expressed in terms of the platform frame as;

$$\{\mathbf{a}_5\}_I = \begin{pmatrix} 0 \\ l_p \\ 0 \end{pmatrix} \qquad \{\mathbf{a}_5\}_{II} = \begin{pmatrix} -l_p\cos30° \\ -l_p\sin30° \\ 0 \end{pmatrix} \qquad \{\mathbf{a}_5\}_{III} = \begin{pmatrix} l_p\cos30° \\ -l_p\sin30° \\ 0 \end{pmatrix}$$

The rotation of the first and last frames of the jth leg in terms of the base frame and platform frames can be expressed as follows;

$$\{\mathbf{Q}_{1,5_j}\}_{b,p} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{pmatrix} = \begin{pmatrix} \cos\beta & 0 & \sin\beta \\ \sin\beta & 0 & -\cos\beta \\ 0 & 1 & 0 \end{pmatrix}$$

where for j=I ; $\varphi = 90°$
j=II ; $\varphi = 210°$
j=III ; $\varphi = 330°$

This is essentially a rotation of the frame through 90° about the x-axis, followed by a rotation by φ about the y-axis. Thus, expressed in homogeneous co-ordinates, the frame transforms of the 1st frame of each leg, referred to the base frame are;

{To be completed}

In order to ensure that the endoscope always passes through the virtual fulcrum, we can find the IKP in two steps. First we need an expression for the pose of the endoscope, in terms of the pitch, yaw, axial and roll variables which are measured in terms of the base frame. The virtual fulcrum is defined as being at the origin of the base frame, and so it can be offset in the z-axis of the frame to give clearance between the manipulator and the patient, by supplying z terms in the positions of the first frames of the three legs (this offset will be termed o from now on).

The endoscope pose (ie a frame attached to the tip of the endoscope) consists of a rotation, θ, about X_b (as defined in Figure 11), the Pitch;

$$\{\mathbf{Q}_{\theta x}\}_b = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{pmatrix}$$

a rotation, φ, about Y_b, the Yaw;

$$\{\mathbf{Q}_{\varphi Y}\}_b = \begin{pmatrix} \cos\varphi & 0 & \sin\varphi \\ 0 & 1 & 0 \\ -\sin\varphi & 0 & \cos\varphi \end{pmatrix}$$

a rotation, λ, about Z_b, the Roll;

$$\{\mathbf{Q}_{\lambda z}\}_b = \begin{pmatrix} \cos\lambda & -\sin\lambda & 0 \\ \sin\lambda & \cos\lambda & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

and a negative shift, l_z, along Z_b, the axial displacement;

$$\{\mathbf{a}_z\}_b = \begin{pmatrix} 0 \\ 0 \\ l_z \end{pmatrix}$$

So, in homogeneous co-ordinates, the transform from the base frame to the endoscope frame, for required pitch, yaw, roll and axial displacement is;

$$\{\mathbf{T}_e\}_b = \begin{pmatrix} c\varphi c\lambda & -c\varphi s\lambda & s\varphi & 0 \\ s\theta s\varphi c\lambda + c\theta s\lambda & -s\theta s\varphi s\lambda + c\theta c\lambda & -s\theta c\varphi & 0 \\ -c\theta s\varphi c\lambda + s\theta s\lambda & c\theta s\varphi s\lambda + s\theta c\lambda & s\theta c\varphi & -l_z \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Now, the endoscope to platform transform will merely consist of the rotation, -λ, about Z_e and the shift of the length of the endoscope, l_e, along Z_e;

$$\{\mathbf{T}_p\}_e = \begin{pmatrix} c\lambda & s\lambda & 0 & 0 \\ -s\lambda & c\lambda & 0 & 0 \\ 0 & 0 & 1 & l_e \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Thus, we can now express the origins of the last frames of the three legs in terms of the base of the manipulator;

$$\{\mathbf{a}_{5_j}\}_b = \{\mathbf{T}_e\}_b\,\{\mathbf{T}_p\}_e\,\{\mathbf{a}_{5_j}\}_p$$

$$\{\mathbf{a}_{5_j}\}_b = \begin{pmatrix} c\varphi & 0 & s\varphi & s\varphi l_e \\ s\theta s\varphi & c\theta & -s\theta c\varphi & -s\theta c\varphi l_e \\ -c\theta s\varphi & s\theta & s\theta c\varphi & s\theta c\varphi l_e - l_z \\ 0 & 0 & 0 & 1 \end{pmatrix} \{\mathbf{a}_{5_j}\}_p$$

which, as expected contains no roll terms. From this we can now find the lengths of the three legs in terms of the required variables. First, the origins of the last frames of each leg in terms of the base frame are;

$$\{\mathbf{a}_{5_I}\}_b = \begin{pmatrix} s\varphi l_e \\ c\theta l_p - s\theta c\varphi l_e \\ s\theta l_p + s\theta c\varphi l_e - l_z \end{pmatrix}$$

$$\{\mathbf{a}_{5_{II}}\}_b = \begin{pmatrix} -\frac{\sqrt{3}}{2}c\varphi l_p + s\varphi l_e \\ -\frac{\sqrt{3}}{2}s\theta s\varphi l_p - \frac{1}{2}c\theta l_p - s\theta c\varphi l_e \\ \frac{\sqrt{3}}{2}c\theta s\varphi l_p - \frac{1}{2}s\theta l_p + s\theta c\varphi l_e - l_z \end{pmatrix}$$

$$\{\mathbf{a}_{5_{III}}\}_b = \begin{pmatrix} \frac{\sqrt{3}}{2}c\varphi l_p + s\varphi l_e \\ \frac{\sqrt{3}}{2}s\theta s\varphi l_p - \frac{1}{2}c\theta l_p - s\theta c\varphi l_e \\ -\frac{\sqrt{3}}{2}c\theta s\varphi l_p - \frac{1}{2}s\theta l_p + s\theta c\varphi l_e - l_z \end{pmatrix}$$

Thus, the vectors from the origin of the first frame to the origin of the last frame of each leg, in terms of the base frame are;

$$\{\mathbf{a}_{1\text{-}5_I}\}_b = \begin{pmatrix} s\varphi l_e \\ c\theta l_p - s\theta c\varphi l_e - l_b \\ s\theta l_p + s\theta c\varphi l_e - l_z - o \end{pmatrix}$$

$$\{\mathbf{a}_{1\text{-}5_{II}}\}_b = \begin{pmatrix} -\frac{\sqrt{3}}{2}c\varphi l_p + s\varphi l_e + \frac{\sqrt{3}}{2}l_b \\ -\frac{\sqrt{3}}{2}s\theta s\varphi l_p - \frac{1}{2}c\theta l_p - s\theta c\varphi l_e + \frac{1}{2}l_b \\ \frac{\sqrt{3}}{2}c\theta s\varphi l_p - \frac{1}{2}s\theta l_p + s\theta c\varphi l_e - l_z - o \end{pmatrix}$$

$$\{\mathbf{a}_{1\text{-}5_{\mathrm{III}}}\}_b = \begin{pmatrix} \frac{\sqrt{3}}{2}c\varphi l_p + s\varphi l_e - \frac{\sqrt{3}}{2}l_b \\ \frac{\sqrt{3}}{2}s\theta s\varphi l_p - \frac{1}{2}c\theta l_p - s\theta c\varphi l_e + \frac{1}{2}l_b \\ -\frac{\sqrt{3}}{2}c\theta s\varphi l_p - \frac{1}{2}s\theta l_p + s\theta c\varphi l_e - l_z - o \end{pmatrix}$$

The length of each of these three vectors can be found easily, and substituted into equation (1), to find expressions for each of the joint variables;

$$q_{\mathrm{I}} = \sqrt{\begin{pmatrix} s^2\varphi l_e^2 + l_p^2 + l_b^2 - s(2\theta)l_p l_e + 2s^2\theta c^2\varphi l_e^2 - 2c\theta l_p l_b - 2s\theta l_p o + \cdots \\ \cdots + 2s^2\theta c\varphi l_p l_e - 2s\theta c\varphi l_e(l_z + o - l_b) + o^2 - 2s\theta l_p l_z + 2l_z o + l_z^2 \end{pmatrix}} - b_{4_{\mathrm{I}}}$$

$$q_{\mathrm{II}} = \sqrt{\begin{pmatrix} +\cdots \\ \cdots + \end{pmatrix}} - b_{4_{\mathrm{II}}}$$

$$q_{\mathrm{II}} = \sqrt{\begin{pmatrix} +\cdots \\ \cdots + \end{pmatrix}} - b_{4_{\mathrm{II}}}$$

Finally, the roll of the endoscope is driven by the corresponding revolute joint directly.

The second step, involves finding the pitch, yaw and axial motions required to reach a particular point in World Space with the tip of the endoscope. The only orientation parameter required is the roll which must therefore be provided directly. This is allowable, because only the position is actively constrained. The roll of the endoscope is entirely under simple force feedback control, and not subject to any constraint.

In the actual implementation of the IKP, the second step would be performed pre-operatively (off-line), by converting the entire task-space (constraint space) of the task into control space, so that the constraint is defined in the same space as the control of the manipulator is performed. This cuts down the complexity of the problem, allowing faster computation.

Direct Kinematic Problem

The Direct Kinematic Problem needs to be solved as a prelude to finding expressions for the manipulator dynamics.

Manipulator Dynamics

The dynamics of the manipulator needs to be studied in order to determine the decoupling parameters for the control law.

Tissue Characterisation Experiment

In order to provide force/torque data for the detailed design of the manipulator, it is proposed that an experiment be carried out to characterise the forces/torques encountered during a typical endoscopic procedure. In consultation with neuro-surgeons it has been decided that animal experiments would be ethically suspect for such a small gain in understanding and not entirely relevant either. Cadaveric brain material is considerably different from live brain tissue and so not suitable. It is therefore proposed that a force/torque sensor be fitted to a standard endoscope and used in a real operation to determine the characterisation. A sensor and its associated equipment must be developed and thoroughly tested prior to such a trial. Testing should be carried out using a mock-up subject head involving moulded gelatin as a substitute for the brain.

Apparatus and Materials

The purpose of this phase of the project is to build apparatus to prove the effectiveness of the manipulator design and the control strategy adopted in its implementation.

In order to build apparatus to test the force control techniques and overall mechanical design, the following materials will be required;

Supplier	No.	Description	Part Number	Cost/ Unit	Total
National Instruments	1	PCI-FlexMotion-6C (MacOS)	777625-01	£ 1960.00	£ 1960.00
RS	5	Force Sensors		£ 35.00	£ 175.00
RS	1	Force Sensor Mountings		£ 5.00	£ 5.00
Workshop	-	Structural Aluminium	-	-	-
Already owned	-	Force Sensor Amplifiers	-	-	-

Only those items that affect the near future of the project have been fully detailed.

Project Planning

In order to complete my PhD in good time and to requirements, several milestones and deadlines have been identified;

- Start PhD - 29.9.97
- First Presentation - 30.1.98
- Study Report & Project Plan (1st Draft) - 15.4.98
- Study Report & Project Plan (2nd Draft) - 1.9.98
- MPhil -> PhD Transfer Report - 18.12.98
- Study Report & Project Plan (3rd Draft) - 1.4.99
- Study Report & Project Plan (4th Draft) - 1.9.99
- Study Report & Project Plan (5th Draft) - 1.4.2000
- Thesis Submission - 1.10.2000
- Finish PhD - 1.12.2000

As well as these academic requirements, the project itself has its own goals. These are explored in depth in Figure 10, which is a GANTT chart of the entire three years. Only, the period up to the submission of the MPhil->PhD Transfer Report has been given in detail, as the remaining time depends on the outcome of the research up to this point.

The next stage of the project involves acquiring force/torque data from an operator in order to determine the motor and amplifier parameters and to complete the design of the manipulator. It would be advantageous to fully test the control board and force sensing equipment through this stage.

References

[1]Institute of Applied Sciences in Medicine, *ROBOSCOPE - Ultrasound-Image-Guided Manipulator-Assisted System for Minimally Invasive Endo-Neurosurgery*, 1997.

[2]Ho, S.C., Hibberd, R.D., Davies, B.L., *Robot Assisted Knee Surgery*, IEEE Engineering in Medicine and Biology, vol 14, no3.

[3]Jakopec, M., *Acrobot - MPhil - > PhD Transfer Report*, 1998.

Activity Name	Start Date	Finish Date	Length	Actual Start	Actual Finish	%
ROBOSCOPE PhD						
Initial Concept Design						
Initial Literature Search	29/9/97	29/12/97	91.00	29/9/97	29/12/97	100%
ManipulatorConcept Development	3/11/97	3/4/98	151.00	3/11/97	3/4/98	100%
Force Control Concept Development	5/1/98	3/4/98	88.00	5/1/98	3/4/98	100%
First Presentation	30/1/98			30/1/98		100%
Decide Basic Manipulator Design	6/4/98	7/4/98	1.00	6/4/98	7/4/98	100%
Decide Basic Force Control Design	6/4/98	7/4/98	1.00	6/4/98	7/4/98	100%
Write Study Report	7/4/98	17/4/98	10.00	7/4/98	17/4/98	100%
1st Study Report & Project Plan	17/4/98			17/4/98		100%
Wrench Sensor Development						
Specify & Order I/O Card	20/4/98	24/4/98	4.00			0%
Specifiy & Order Force Sensors	20/4/98	24/4/98	4.00			0%
Wrench Sensor Detail Design	20/4/98	30/4/98	10.00			0%
Acquire Amplifiers	20/4/98	24/4/98	4.00			0%
Acquire Aluminium	24/4/98	30/4/98	6.00			0%
Machine Wrench Sensor Parts	1/5/98	6/5/98	5.00			0%
Assemble Wrench Sensor, electronics & I/O card	6/5/98	11/5/98	5.00			0%
Software Development	1/5/98	21/5/98	20.00			0%
Wrench Sensor Calibration & Test	22/5/98	27/5/98	5.00			0%
Tissue Characterisation Study						
Initiate Contact with Surgeons	14/4/98	24/4/98	10.00	14/4/98		10%
Design Experiment	27/4/98	19/5/98	22.00			0%
Endoscope Clamp Detail Design	8/5/98	30/5/98	22.00			0%
Machine Parts for Clamp	1/6/98	12/6/98	11.00			0%
Acquire Sundry Hardware	1/6/98	12/6/98	11.00			0%
Assemble Experimental Hardware						
Software Development	21/5/98	19/6/98	29.00			0%
Decide Experiment Date	27/4/98	29/5/98	32.00			0%
Pre-Experiment Testing	22/6/98	3/7/98	11.00			0%
Experiment	7/7/98					0%
Manipulator Development						
Gather Design Information	2/2/98	10/7/98	158.00			0%
Manipulator Detail Design	10/7/98	24/7/98	14.00			0%
Specify & Order Linear Motors	10/7/98	15/7/98	5.00			0%
Specifiy & Order Linear Encoders & Gauges	10/7/98	15/7/98	5.00			0%
Specify & Order Motor Amplifiers	10/7/98	15/7/98	5.00			0%
Acquire Aluminium	19/7/98	24/7/98	5.00			0%
Specify & Order Sundries	19/7/98	24/7/98	5.00			0%
Machine Manipulator Parts	25/7/98	14/8/98	20.00			0%
Assemble Manipulator, Wrench Sensor & I/O Cards	15/8/98	29/8/98	14.00			0%
Test Individual Components	30/8/98	1/9/98	2.00			0%
Write 2nd Study Report	20/8/98	25/8/98	5.00			0%
2nd Study Report & Project Plan	3/9/98					0%
MPhil - > PhD Transfer Report						
Write Transfer Report	18/11/98	18/12/98	30.00			0%
Submit Transfer Report	18/12/98					0%
Control Software Development						
Write Utility Classes	3/11/97	2/1/98	60.00	3/11/97	2/1/98	100%
Design Software Structure	24/5/98	11/9/98	110.00			0%
Write Position Control Code	11/9/98	31/10/98	50.00			0%
Test Position Control Code	31/10/98	5/11/98	5.00			0%
Write Force Control Code	5/11/98	25/12/98	50.00			0%
Test Force Control Code	25/12/98	30/12/98	5.00			0%
Write Human Interface Code	30/12/98	20/3/99	80.00			0%
Test Human Interface Code	21/3/99	26/3/99	5.00			0%
Write 3rd Study Report	27/3/99	1/4/99	5.00			0%
3rd Study Report & Project Plan	1/4/99					0%
Constraint Space Research						
Research	2/4/99	25/6/00	449.67			0%
4th Study Report & Project Plan	1/9/99					0%
5th Study Report & Project Plan	3/4/00					0%
Thesis						
Final Literature Search	26/6/00	18/9/00	84.00			0%
Write Thesis Structure	3/7/00	23/7/00	20.00			0%
Write Thesis Chapters	7/7/00	29/9/00	84.00			0%
Submit Thesis	2/10/00					0%

Figure 10 - Project Pla