# *THE CONTROL AND SUPPLY OF A MULTIMOVEMENT EXTERNALLY POWERED UPPER LIMB PROSTHESIS*

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In the descriptions of externally powered arm and hand prostheses which have been published over the last twenty years, considerable importance has been attached both to the mechanical and to the electronic aspects of their design. Most of the attention which has been paid to the normal role and operation of the human limb for which the prosthesis is to substitute, however, appears to have been paid to the analysis of its physical movements and its action in consciously controlled tasks such as tracking; the more usual situation where the normal limb is performing routine movements unconsciously appears to have had a very cursory consideration by artifical limb designers. They have principally considered the efferent channels of nerve and muscle, almost entirely neglecting the afferent channels, apparently on the assumption that the afferent can be replaced by the user's vision; the undesireability of committing vision to the role of the feedback channel for a single limb at the expense of its role as monitor of the body's environment and relationships has almost invariably been glossed over. The problem of the increased complexity of the visual monitoring task which must occur when the simple rudimentary artifical limbs which have been described have an increased number of active movements incorporated in them has similarly been bypassed on the grounds that the human mind has great powers of adaption, and could therefore be trusted to compensate for the deficiencies of the control engineer.

There may be several reasons for this approach. The first may be a lack of appreciation of the major role played by proprioception in normal hand and arm control and of the very great amount of limb movement which is controlled unconsciously with little or no visual monitoring. The second may come from experience that almost every machine met in everyday life is controlled with varying degrees of success by an operator depending principally on visual feedback taken in conjuction with a corresponding underestimation of the vast difference beetwen the relative simplicity of the control of machines such as motor vehicles and complexity of the control of a multi-degree of freedom limb.

Similarly, the effect on the individual of the pre-emption of consciousness in time/velocity control at the expense of his capacity for indulging in intellectual activity at any but the trivial level may not have been appreciated because, with many machine relationships, the operator of the machine is the primary occupation of the man at that time; he is usually rewarded for his task,but other than repetitive sequences he must be resigned to paying most of his attention to it, and frequently deprived of the ability to enjoy serious discussion or creative thought. The conscious operation of the movements of a complex machine may provide a task which is stimulating and a challenge. If more than two degrees of freedom are involved, however, the enjoyment of this stimulation will deminish extremely rapidly; it would become an unattractive, and possibly unacceptable, way of life.

The normal person is not faced with this situation in the control of his hands and arms, but most of the time can leave the organisation of their movements to be carried out unconsciously. If every movement of the normal arm and hand to be consciously organised the difficulty of eating even a simple meal and enjoying it while steering spoons and forks between teeth would daunt the most ambitious gourment; it is not reasonable to expect the amputee to accept this situation, particularly when there is no need for him to do so and if he is provided with a prosthesis which makes these demands, his reaction will be to reject it.

In a complete arm prosthesis for the bilateral amelic person at least three inputs are required to position the hand relative to the body; for the rotational degrees of freedom it may be sufficient to restrict the active control to one degree giving a total of a minimum of four in addition to the control of prehension, and although this is a small number compared with the normal, by any standards the control of such a machine by visual monitoring would be an almost impossible task which even if practical would absorb all the operator's attention. As was mentioned above, however, the operation of an artifical limb is not the amputee's main task, he has to think while he writes at school, and wants to be able to talk while he has his meals, he wishes to enjoy his freedom; in providing him with a visual feedback control system the designer may have reduced his physical handicap a little, but he will have inflicted a new disability.

To prevent this occuring and to bring him into a similar situation to his peers, he must be provided not with an incomplete operating system but with a complete control system, and one which will be as similar as possible to the normal biological one. Then he will be able to forget his prosthesis and allow his hand/arm system to act as his servant /1/.

This is perhaps deceptively easy to acheive in practice, and has been described elsewhere /2, 3/ but in essence the method is to make the arm itself a position controlled device whose input signals are the positions of the two clavicles. The natural propriception in the shoulder girdle in effect, therefore, can code and transmit, in biological terms to the central nervous system, the position of the arm, because the arm position is always related to the position of the shoulder girdle; with an appropriate arrangement and choice of valves it can provide the central nervous system with data on position, velocity, acceleration and force relevant to four control channels.

The value of the two coordinates of $\Theta$ and $\Phi$ of each clavicle are sensed by using a light, specially designed, low friction, Bowden cable to transmit the displacement of each acromion relative to the arm mounting harness. The displacement is then transmitted by the cable to the valve - actuator - feedback assembly, each cable inner and outer acting respectively either to signal the valves or to add in the feedback, depending on the particular joint. If an actuator is restrained from movement, the inner cable can only move to the extent permitted by the allowable error signal at the valve system; the shoulder is thus restrained so that it is kept within that distance of the "no phase difference" position of the arm. The proprioceptive information emanating from the shoulder is therefore always accurate, within these limits with the perceived arm position.

Versions of control systems embodying this extension of physiological proprioception (e. p. p.) have now been routinely in use in this Centre for seven years and are no longer experimental; They have had a dramatic effect in the reduction of the learning time to a few hours and in the acceptance of the arms.

This control system has been applied to pneumatic arms but could easily applied to electrically powered arms provided a similar mechanism of "unbeatable" servo were incorporated to restrict phase difference between input and output and maintain a constant relationship between arm and shoulder proprioception.

With the achievement of an acceptable system which appears to allow a rate measure of unconscious limb control, the major hurdle to be faced becomes the support of the prosthesis in its role as a "body part" in the establishment of a routine clinical service. Although providing a system which is acceptable to the patient and matches his control characteristics was the first obvious target, the adopting of externally powered prostheses in clinical practice is impossible unless there is a considerable investment in the appropriate service which can be provided for the patient. In fitting a child, therefore, with a complex prosthesis it has to be born in mind that unless it can be maintained in action, not only is it unrewarding but can cause great disappointment.

A prosthesis can fail because it runs out of gas, because it brakes down, or because no refill cylinders are supplied. The first essential is the supply of energy, without it the arm is "dead". At present the largest tank which is available in the United Kingdom is the new BAJ 150g $CO_2$ cylinder which can be comfortably and inconspicuously housed in the passive arm; a cylinder of greater capacity would be unlikely to be acceptable to a child of the main group we are dealing with at present, about 10 to 11 years of age. One change of cylinder per day, however, does not present a major difficulty and so the designer can consider a gas consumption of about 300g of $CO_2$ a day or approximatly 30g per hour. This would be considerably exceeded by differential area or standard double acting actuator systems but is achieved here by using for each actuator a double acting cylinder and piston and regulating the gas supply to each half cylinder by two force damand valves mounted back to back; (Fig. 1) the signal input is applied differentially to these two valves and is the error signal produced between the control position and the actuator position. When a command is presented to the actuator the pressure which must be delivered by the force demand valve concerned is that required to produce movement against the load and the required direction and although the pressure in the driven side may rise to .85 of the "supply side" pressure /4/, the supply pressure as seen by the actuator is that delivered by the force demand valve relating to that actuator and not the line pressure delivered by the regulator on the storage tank of the system. If no load is presented this may be as low as 10% of line pressure. If the actuator needs opposition the input signal applies more force to the valve and therefore greater pressure to the actuator and thus what is effectively a load dependent gas consumption is acheived neglecting the losses due to seal function, etc. When movement occurs the feedback works to reduce the force, and therefore the pressure, so that the actuator does not lead the input. The return of an actuator is produced by a spring acting at the valve end of the system to restore the input lever. At either end of the actuator stroke, when no further movement of the actuator is possible, the valve input could drive the pressure in one or other side up to full line pressure in attempting to produce further movement, thereby filling the actuator with gas at full line, high, pressure and destroying the effects of the economy produced by the feedback. To obviate this another feedback system is provided which is fitted with preset stops which remove the valve lever from the approptiate valve just before the end of the actuator travel in either direction, and thus prevent this happening.

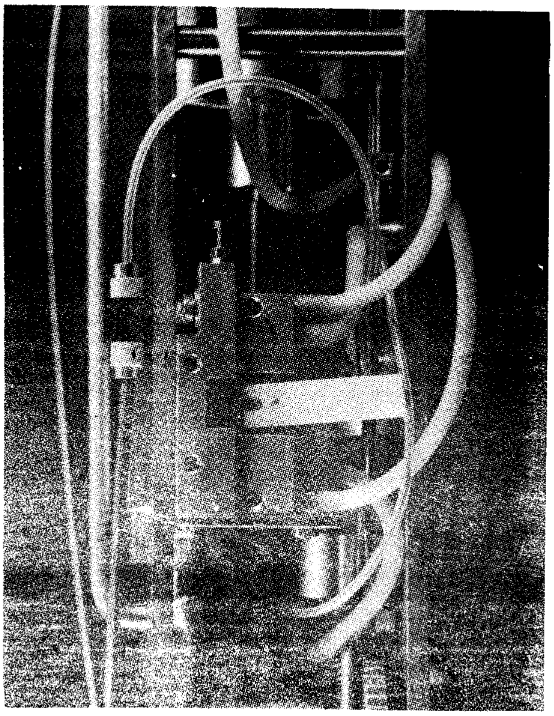

Fig. 1.

Mounting block for two force demand valves. The valve lever is the white block in the centre. The double acting actuator is to the left of the illustration.

The second requirement is the provision of a system for servicing and repairing the arms and for this it is essential that each oatient is provided with two complete sets of prosthesis and a transit box. Not only must servicing be carried out but parts break down due to wear and to accidents such as playgound falls. Occasionally more bizarre causes of damage occur, such as being caught in swinging doors, or by breaking wood with a prosthesis karate chop! If there is a breakdown the arms are dispatched by post with a pre-addressed, prepaid label, and in the majority of cases can be repaired in one working day and returned to the user. Transit times plus repair, on average, mean that the patient is without one of his pairs of arms for about seven days.On arrival, and before this patch, as well as the repair of the breakdown, each arm is thoroughly inspected and any worn parts replaced.

Similarly the back up for the gas supply is acheived by using a postal service, this time organized by the Department of Health and Social Security in conjuction with the Scottish Home and He-

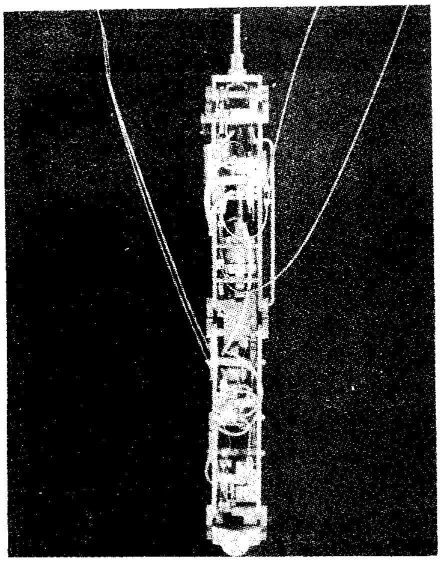

Fig. 2. The complete Series II arm prosthesis with separate position servo control of $r$, $\Theta$, $\Phi$, of the hand and hand rotation about a horizontal axis.

Fig. 3. The Series II arm fitted on the right side and hollow arm on the other side to carry the gas tank.

alth Department. Transit boxes each containing three of the 150g cylinders or ten of the 34g cylinders are supplied to the family or school and the cylinders are replaced in the box and dispatched for refilling as soon as each boxful has been used. These too, have prepaid and pre-addressed labels and, on arrival at the refilling depot, the box is emptied and filled with full cylinders and returned.

Fifteen children attending this Centre have powered limbs at present. Of these two are of the multimovement Series II type of complete limb; (Figs. 2, 3) two are of the above elbow version of the same limb; two others are very simple limbs for particular disabilities and the remainder are fitted with the Series I version of the e. p. p. arm (Fig. 4). The maintenance of these children in arms requires the continuous attention of four people, one of the major requirements being the constant refitting on the harness as the child grows. Each child, therefore, may have to have both sets of harnesses refitted twice in one year, giving a total of about thirty fittings per year, or one every seven or eight working days throughout the year.

Fig. 4. Series I arm with hand raise/lower movement, wrist rotation and grip. Gas is carried in a hostler.

With such a major staff involvement it becomes increasingly important that the arm is designed to be easily serviced. Unnecessary delays must be avoided and this can best be done by the storing of spare parts, and, more importantly, replacement assemblies. Acceptance of a prosthesis by a child means that the prosthesis will have hard wear and will have to take its share of the falls and bruises which are normal to the child. Unfortunately artifical limbs have no natural repair mechanism; unless the bio-engineer accepts that he must organize this he would be better not to have started to design in the first place.

## References

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