Progress of a modular prosthetic arm

A.S. Poulton, P.J. Kyberd and D. Gow

1 Upper limb prostheses - design restraints

Active prosthetic devices to replace missing hands or arms have much in common with robotic dextrous manipulators for industrial tasks (Gruver, 1994). However, the design of an upper limb prosthesis presents a set of restraints which may differ considerably from those in other robotics applications. A mass-produced robot of standardised design may be usable in many different situations, while the needs of prosthetics users are highly individual. The degree of loss can vary from a partial hand up to a complete arm including the shoulder. Variants are needed to cater for different sizes and for the two sides. User surveys (Kyberd *et al*., 1998(1), Kyberd *et al*., 1999) have confirmed that a prosthesis should be light, reliable, functional, look natural, and be quiet in operation. This contrasts with the requirements of industrial robots where weight, appearance and noise level may be less important than repeatability. If the prosthesis does not make life any easier for the user, it is likely to be rejected. A functional prosthesis must, then, offer real advantages over a purely cosmetic one for it to be accepted. Indeed, the majority of users have one good hand, and become quite adept at performing tasks one-handedly, with little involvement of the prosthetic hand.

In engineering terms, prostheses have developed considerably in recent years. The motors and gearboxes used can be small and unobtrusive, and the batteries can be small, with the energy density increasing with each new development. Modern materials such as carbon fibre are used for strength and lightness. Cosmesis has improved, with realistic looking silicone gloves. However the major problem remains one of control. Powered prostheses are commonly controlled using electromyographic (EMG) signals, which are generated when muscles contract. It is often difficult to find a control strategy that works effectively, as the number of degrees of freedom to be controlled may be greater than the number of independent signals that the user can easily generate.

The introduction of microprocessors to prosthetic applications has greatly increased their potential and simplicity in fitting and maintenance (Poulton *et al.* 2000). Prosthetic controllers which can be adapted to different needs through field programming have been introduced by a number of manufacturers. They allow the prosthetist to try different control strategies or even invent completely new ones, using graphical software programming tools (Kurtz *et al.* 1999: Wallace and Williams 1999: Farnsworth and Stevens, 1999: Hanson and Farnsworth, 2001). However the current microprocessor solutions are added to existing prostheses, there is no systems based approaches and so the manufacuters have created a mixture of different technologies with little inter-joint or device compatibility. The ToMPAW solution attempts to address this porblem.

2 The control problem

Good dexterity requires individually movable digits rather than a simple open/close grip; and depending on the degree of loss, there may be wrist and elbow movement as well. Typically, everything has to be controlled through the employment of two muscle sites in the residual limb, which generate EMG signals or possibly actuate some other type of sensor or switch. This normally requires a period of training. It can be difficult to easily control two separable signals, and for these cases the users are limited to very basic control strategies. Additionally the EMG signals may not be very stable, as they can change as the user and prosthesis moves around or they sweat within the confining socket.

There are two main lines of attack to this problem. One is to get more information out of the EMG signals that the user generates. Multiple electrodes can be used, with the user maybe not able to control them individually, but able to generate a pattern of activity that can be detected by techniques such as neural networks. This was the basis of the Swedish SVEN hand (Herberts, 1978: Almstrom, 1981). At that time the computing power needed could not be built into a practical prosthesis, but recently several researchers have revived the idea, now that the technology is becoming possible (Hudgins, 1993: Fermo *et al.* 2000). Also, the raw EMG signals have been studied to see whether any improvement can be made over the standard technique of amplification, rectification and filtering to give a high level voltage signal that can be used for control purposes. Methods that have been studied include neural networks (e.g. Farry *et al.* 1996: Asres *et al.* 1996: Atsma *et al.* 1996), wavelet-based classification (Englehart *et al.* 2001), Hilbert transforms and fuzzy logic (Taffler 1999(a),(b)).

The second, complementary, line of attack has been to approach the control problem from the other end and build some intelligence into the hand itself. It is not easy for the user to judge the amount of force applied to an object purely by visual feedback, and this requires concentration. The amount of grip force applied may be controlled automatically, as in the commercially available Otto Bock SensorHand™. Slip detection can be done by measuring changes in forces (Kyberd 1990, Winkler *et al.* 1992, Mingrino *et al.* 1994), or by detecting an acoustic signal with a small microphone (Salisbury and Coleman 1965, Chappell *et al.* 1987).

The type of grip pattern adopted may also be determined automatically, as in the Southampton Hand (Nightingale 1985, Kyberd and Chappell, 1994), which provided two basic forms of grip: precision (pincer) grip and power (fist) grip. The concept was later developed at the Oxford Orthopaedic Engineering Centre in the successful clinical version, the Oxford Intelligent Hand (Kyberd *et al*. 1998(2)). The type of grip adopted is determined by the point of first contact. If an object touches the palm first, a power grip is applied; while if the fingertips are touched first, a precision grip is used. The hand closes until the object is held in the lightest possible grip. If slipping occurs, this is detected by acoustic sensors in the fingertips and the grip is automatically tightened.

Current generations of clinical prostheses with microporcessor control have focused on the limited intelligence of detecting slip at a single point and controlling a single degree of freedom device, or in making the selection of simple control philosphies more easily avaialble to the clinical teams (Kurtz *et al.* 1999). Beyond the Southampton phylosophy, the research arena has only recently begun to discuss adding intelligence to the multi-degree of freedom prostheses (Stefan Shultz ISPO 2001).

3 The ToMPAW project

ToMPAW (Totally Modular Prosthetic Arm with high Workability) is a project to design and manufacture a set of modular and flexible standardized hand and arm prostheses, with a very high functionality and cosmesis. The system will be applicable to losses from a complete hand through to the upper arm, and will enable the users and the clinical teams to customise the device to the user with the minimum of effort and time. ToMPAW is a European Union project under the Telematics initiative.

3.1 Main features of the ToMPAW arm

The ToMPAW hand has four independently controllable digits (the fifth finger follows the movements of the fourth finger). The wrist has two degrees of freedom, flexion/extension and rotation. As well as having low weight and power consumption, a primary design feature of ToMPAW was that it should be as modular as possible, both physically and in terms of the control strategies that are supported. Reliability and ease of maintenance are key issues, and modularity helps to simplify servicing and reduce stock-keeping. For example, the fingers can easily be replaced individually. The modular approach of the mechanical system is reflected in a similarly distributed approach in the controllers. While it would have been possible to use one relatively powerful microprocessor to do everything, this would have meant that conductors from all the sensors and actuators would have to run along the length of arm. The cables and connectors that would be needed to carry all these signals would need to cross a number of active joints and this would be a significant weakness in a system where conductors are subjected to repeated

movement. The preferred option was to use a network of microprocessors, each controlling one or two joints. Each processor is close to the sensors and actuators that interface with it. There are only six conductors in the bus which links the processors, and this makes for a more reliable system. The distributed system also has some inbuilt robustness, in that it allows a degree of graceful degradation, where if one processor fails the others can continue. The form of control that was adopted is mainly hierarchical. This has the advantage that decisions are taken closest to where they are actually needed, maximising processing speed and avoiding communications bottlenecks. The distributed approach extends the advantages of modularity to the electronics as well as the mechanics. Any degree of loss from a hand to a complete arm can be accommodated using a small standard set of components. Stock-keeping costs are kept to a minimum and modules can be easily replaced.

3.2 The LONWORKS® protocol

Protocols for small scale networks supported by small low-power microprocessors were compared at the beginning of the design process. Echelon's LONWORKS® was adopted as it is a realization of the full OSI seven-layer communications protocol model rather than a 'cut-down' system. It is supported by Neuron® microprocessor devices from Toshiba and Cypress. Each device has two processors which are microcoded to operate the bus protocol, and these are inaccessible to the applications engineer. A third processor controls the applications, running programs that are written in a Neuron® C, a variant of C that provides multitasking and supports the I/O features of the Neuron® device. Thus the programmer needs to be concerned only with those elements of the system that are important to the application; the details of the communications protocol are invisible. Neuron® devices are capable of driving short network links between themselves on twisted wire pairs with few passive components, simplifying the hardware.

The ToMPAW arm uses a LONWORKS® network to connect a number of Neuron® devices or "nodes". The node that handles top-level control is referred to as the proximal node, as in most cases it will be physically the most proximal (nearest the shoulder) node in the system. The other nodes are referred to as distal nodes. The data on the network is represented by standard network variable types. This data may be categorised as:

- outputs from distal nodes to the proximal node giving current actual positions, forces, and the state of any digital inputs. This data is supplied when requested by the proximal node.
- inputs to the distal nodes from the proximal node for variable data such as demanded positions or forces.
- digital control inputs to the distal nodes from the proximal node. These determine the control strategy to be adopted by the distal node.

The proximal node controller software takes user input, e.g. switch/EMG, and distributes the input over the network, possibly scaling it first to fit it to a standard range. The other nodes control the motors. One node can control one or two motors, so two nodes are needed for the four controllable digits of the hand. This requires positional feedback in each joint. The position of the joint is sensed by a high endurance potentiometer. The nodes in the hand take inputs from force and slip sensors. Force at the fingertips is detected by force sensing resistors, while slip is detected acoustically. Control strategies for each motor include: direct control of motor speed and direction by input variables from the network; proportional control to drive the motor to a desired angle; and control mediated by slip sensors, so that motor drive is incrementally increased in the event of slippage.

These are all tasks that can be scheduled for execution on a distal node without requiring much intervention from the proximal controller, apart from initiating the tasks and monitoring status. Traffic on the network is minimised by designing the system in this way, so that the network normally only needs to handle signals for high-level control. It does not need to transmit fast real-time signals related to EMG, motor control or slip detection.

3.3 External communication

The arm also needs to communicate with external systems. It needs to be able to be driven by the production staff during the initial build and later testing and repair of the system, by the prosthetist during customisation and the control/joint selection process, by the therapist for training, and possibly by the wearer for remote testing and diagnostics. This is done by linking the arm to a clinical support system which runs on a PC. The clinical support system displays the EMG data graphically in real time, and allows parameters such as operating thresholds to be varied. Transceivers for connecting a LONWORKS® bus to a PC are readily available, allowing fast traffic and providing isolation to certified standards. LONWORKS® can also be interfaced to TCP/IP, raising the possibility of remote diagnostics across the Internet. A radio link is another useful option, as the user is not then restricted by cables during setup and testing. This can be done with standard low-power transmitters and receivers which handle RS-232 serial data (Kyberd *et al* 2002). The conversion to this format is done by a Neuron® node. It may be that more advanced technologies such as Bluetooth™ will be used in future.

3.4 Practical implementation

The nodes were designed to make the best use of the functions provided by the Neuron® devices and at the same time meet the wider requirements of the project. The division of functions between three independent processors makes the device ideal for real-time applications of this nature. The I/O subsystem is also designed to be fairly independent of the application processor; it can generate PWM signals

for driving motors, and supports an I^2C serial bus for peripherals such as analog to digital converters (ADCs). From an analysis of the signals used in the system, it was concluded that two basic types of Neuron® node would be needed, one for motor control (with two motor drivers, and analog and digital inputs), and another with a fast parallel ADC for multiple EMG signals.

In the final design the controller functions were allocated to physical boards in such a way as to minimise the number of boards and interconnections required. Four-layer printed circuit boards using surface-mount components were produced. A hand board controls a complete hand with four active digits. It contains two motor control nodes, together with the interface electronics for force and slip sensing. A distal board drives two motors in the wrist, and a similar board drives the motor in the elbow joint. Because of the higher current demands of the motors used in these joints as compared to those in the fingers, drivers with a higher current rating (3A rather than 1A) are fitted on these boards. A master or proximal board accepts up to eight fast analog inputs and can be used for overall control of a system. However, the hand board can also accept two EMG inputs, so a hand prosthesis will not normally require a master board in addition. This allocation of nodes to physical functions means that the same node handles the motor and sensors associated with each joint. This keeps the network traffic between nodes to a minimum.

The arm can be powered by lithium polymer batteries, which are light in weight, safe, and have a high energy density. Power is conserved by putting the Neuron® microprocessors into low-power “sleep mode” when the arm is inactive. This is important as the prosthesis, as studies have shown that users need a prosthesis that runs all day without needing to change or recharge the batteries (Kyberd *et al.* 1998(2)).

4.0 Practical Application

The electronic subsystems of the arm were tested prior to integration with the final mechanical hardware, using a development system which consisted of the existing mechanical assemblies of the Oxford Hand and the Edinburgh Arm (Gow 2001), suitably modified. The modularity of the electronics and control allowed the different systems to be integrated easily. Two users operated the hand alone and two further users employed arm systems composed of hand, wrist and elbow. The control of the arms was very different with one user employing ON-OFF operation with an EMG amplifier and the second employing proportional control. Both used a pull switch to switch between the different axes. Training progressed over several visits, and the adaptability of the system allowed different strategies to be tested in an effort to find the best one for the particular user. The second user could produce myoelectric signals from two muscle sites, but he could not fully separate the two channels and there was some co-contraction. In this case, a “winner-takes-all” strategy was created so that the signal that was smaller in

magnitude was ignored, and the larger magnitude signal was used for control. This continued until muscles relaxed and both signals fell below pre-set thresholds.

Assessment of the device is based on a range of criteria. The users infrormal comments are of use in determining their general satisfaction, also directed questions based on the findings of surveys made prior to the design phase (Kyberd *et al.* 1999) enable more precise evaluations to be made. Finally, the functional assessment will be made using a hand function assessment protocol that is based on both abstract object handeling as well as simulated activities of daily living (Light et al. 1999).

Figure 1. Hybrid Edinburgh/Oxford Arm using ToMPAW electronics and control software.

References

Almstrom C, Herberts P, Korner L (1981) Experience with Swedish multifunctional prosthetic hands controlled by pattern recognition of multiple myoelectric signals. International Orthopaedics 5 (1): 15-21 Berlin: Springer-Verlag

Asres A, Dou H, Zhou Z, Zhang Y, Zhu S (1996) A combination of AR and neural network technique for EMG pattern identification. 18th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, Amsterdam: 1464-1465.Atsma W, Hudgins B, Lovely D (1996) Classification of raw myoelectric signals using finite

impulse response neural networks. 18th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, Amsterdam: 1474-1475.

Chappell PH, Nightingale JM, Kyberd PJ and Barkhordar M (1987) Control of a single degree of freedom artificial hand. J. Biomed. Eng., 9, July 1987, 273 - 277.

Englehart K, Hudgins B, Parker P (2001) A wavelet-based continuous classification scheme for multifunction myoelectric control. IEEE Trans Biomedical Engineering 48 (3): 302-311.

Farnsworth T, Stevens G (1999) Clinical experience with programmable controllers. MEC '99 Myoelectric Controls Symposium, Fredericton, NB, Canada.

Farry K, Walker I, Baranuik R (1996) Myoelectric teleoperation of a complex robotic hand. IEEE Trans. Robotics and Automation 12 (5): 775-788.

Fermo C, De Vincenzo C, Bastos-Filho T, Dynnikov V (2000) Development of an adaptative framework for the control of upper limb myoelectric prosthesis. Proceedings of the 22nd Annual EMBS International Conference, Chicago IL. 2402-2405.

Gruver W (1994) Intelligent robotics in manufacturing, service and rehabilitation: an overview. IEEE Transactions on Industrial Electronics 41(1): 4-11.

Gow D, Douglas W, Geggie C, Monteith E and Stewart D (2001) The development of the Edinburgh modular arm system. Proc Instn Mech Engrs Vol 215 Part H: 291-298. Hanson W, Farnsworth T (2001) New digital control technology for powered prosthetic elbows. ISPO 2001 10th World Congress, International Society for Prosthetics & Orthotics, Glasgow.

Herberts P, Almstrom C, Caine K (1978) Clinical application study of multifunctional prosthetic hands. The Journal of Bone and Joint Surgery 60-B (4): 552-560.

Hudgins B, Parker P, Scott R (1993) A new strategy for multifunction myo-electric control, IEEE Trans Biomed Eng, 40-1:82-94.

Kyberd PJ, (1990) Algorithmic control of a multifunction hand prosthesis. PhD thesis, University of Southampton.

Kyberd PJ, Chappell P (1994) The Southampton hand: an intelligent myoelectric prosthesis. Journal of Rehabilitation Research and Development 31(4):326-334.P.J.Kyberd, D.J.Beard J.J.Davey and D. J. Morrison (1998) A Survey of upper limb prostheses users in Oxfordshire. Journal of Prosthetics and Orthotics, Volume 10, Number 4, Fall pp 85-91.

Kyberd PJ, Evans M, te Winkel S (1998) An intelligent anthropomorphic hand, with automatic grasp. Robotica 16: 531-536.

Kyberd PJ, Gow D, Scott H, Griffiths M, Sperling L, Sandsjo L, Almstrom C, Wartenberg C, Jonsson S (1999) A comparison of upper limb prostheses users in Europe. MEC '99 Myoelectric Controls Symposium, Fredericton, NB, Canada.

Kyberd PJ, te Winkel S, Poulton A (2002) A Wireless Telemetry System for User Training of Artificial Arms Prosthetics and Orthotics International, *Submitted for publication.*

Kurtz I, Heim W, Bauer-Hume H, Hubbard S, Ramdial S (1999) Programmable control: clinical experience at Bloorview Macmillan Centre. MEC '99 Myoelectric Controls Symposium, Fredericton, NB, Canada.

Light CM, Chappell PH and Kyberd PJ Quantifying impaired hand function in the clinical environment. In: MEC'99 Symposium Upper limb prosthetic research & consumer needs: Narrowing the Gap, Fredericton, NB, Canada, 25-27 August 1999. ISBN1-55131-013-9.

Mingrino A, Bucci A, Magni R, Dario P (1994). Slippage control in hand prostheses by sensing grasping forces and sliding motion. Proceedings of the IEEE/RSJ/GI International Conference on Intelligent Robots and Systems IROS '94 Vol 3: 1803-1809

Nightingale JM, (1985) Microprocessor control of an artificial arm. Journal of microcomputer applications. 8, pp 167-173.

Poulton A, Boman A, Gow D, Stodne F, Sandsjo, L, Kyberd, P (2000). Use of microprocessor technology in upper limb prostheses. 2nd International Conference on Advances in Osseointegration, Surrey.

Salisbury L.L. and Coleman AB, (1967) A Mechanical Hand with Automatic Proportional Control of Prehension, Medical Biological and Engineering. 5, pp 505-511.

Shultz S, Pylatiuk C and Bretthauer G (2001) A Lightweight Bionic Hand Prosthesis, Proceedings of the 10th World Congress of the International Society of Prosthetics and Orthotics, Glasgow 1 - 6 July 2001.

Taffler S, Kyberd PJ (1999) The use of the Hilbert transform in EMG analysis. In: MEC'99 Symposium Upper limb prosthetic research & consumer needs: Narrowing the Gap, Fredericton, NB, Canada, 25-27 August 1999. ISBN1-55131-013-9. pp 94-99

Taffler S, Kyberd PJ (1999) The use of fuzzy logic in the processing of myoelectric signals. In: MEC'99 Symposium Upper limb prosthetic research & consumer needs: Narrowing the Gap, Fredericton, NB, Canada, 25-27 August 1999. ISBN1-55131-013-9. pp 100-105.

Wallace C, Williams TW (1999) New clinically-useful control strategies made possible by the Varigrip II™ multi-device controller. MEC '99 Myoelectric Controls Symposium, Fredericton, NB, Canada.

Winkler W and Berwirth W (1992) The use of a gliding detector for the control of Prostheses-Hand Proceedings of the 7th World Congress of the International Society of Prosthetics and Orthotics 28 June - 3 July 1992, p 188.