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Intelligent multifunction myoelectric control of hand prostheses

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Intuitive myoelectric prosthesis control is difficult to achieve due to the absence of proprioceptive feedback, which forces the user to monitor grip pressure by visual information. Existing myoelectric hand prostheses form a single degree of freedom pincer motion that inhibits the stable prehension of a range of objects. Multi-axis hands may address this lack of functionality, but as with multifunction devices in general, serve to increase the cognitive burden on the user. Intelligent hierarchical control of multiple degree-of-freedom hand prostheses has been used to reduce the need for visual feedback by automating the grasping process. This paper presents a hybrid controller that has been developed to enable different prehensile functions to be initiated directly from the user's myoelectric signal. A digital signal processor (DSP) regulates the grip pressure of a new six-degree-of-freedom hand prosthesis thereby ensuring secure prehension without continuous visual feedback.

Introduction

Current myoelectric prosthesis controllers are available in different formats and are usually selected on the basis of user preference and operational success during the period of prosthesis fitment. Single or two site, two state systems are the most common forms of providing the user with muscular control over the opening or closing of the terminal device. Once activated, the device's motor voltage (or current) may be varied in direct proportion to the amplitude of the user's myoelectric signal (MES) thereby providing control of speed and pinch force [1].

The main disadvantage of myo-control is the lack of proprioceptive feedback that forces the user to rely primarily on visual information. Conscious grasping decisions that are based solely on visual feedback require the user to continuously monitor the prosthesis, leading to fatigue and handling errors [2]. Conversely the motion of body-powered prostheses enables the wearer to sense device actuation through cable tension and harness position. Thus direct feedback and potential control of the position, velocity and prehensile force of the device can be maintained in a manner known as extended physiological proprioception [3]. As proprioception is fundamental to the acquisition of motor skills, intuitive myo-control is therefore exceptionally difficult to achieve [4].

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Multifunction control

The limited functionality exhibited by commercial devices is not attributable solely to the method of control, but rather, remains rooted in their single-degree-of-freedom format. Users continue to request an increase in the number of possible grasping patterns and an improvement in the visual feedback of the object in the hand [5]. Historical solutions to this problem have centred on prostheses with multiple digits and an independent mobile thumb [6–9], yet none have reached successful clinical status in this configuration.

In order to achieve multiple grip patterns, the artificial hand must possess more than a single degree of freedom. This requirement has been addressed by the development of the new lightweight, six axis Southampton–Remedi hand prosthesis [10], which is designed to improve functionality by increasing the adaptability of the device. Four independent digits and a two-degree-of-freedom thumb enable the hand to form secure precision, power and lateral grip formations. However, the development of a prosthesis with mechanically enhanced prehensile function is not sufficient in itself. The user must be able to harness the device's grip potential without any additional psychological effort than is currently necessary for myoelectric control.

The difficulties of maintaining stable prehension through the use of visual feedback are particularly apparent in multifunction prostheses. The conventional command structure of powered upper limb prostheses requires the user to sequentially select a function (e.g. a powered hand, wrist or elbow), and then employ standard two-state myo-control. Artificial hands that are able to provide a range of prehensile patterns through multiple independent digits suffer from similar control difficulties due to the restricted number of user inputs available. The command and co-ordination of more than a single device or function is difficult, and is the primary cause for high-level amputees rejecting the prosthesis [11]. Hence the successful use of multifunction devices lies in the synergistic control of several actuators without increasing the number of inputs that a user must independently initiate.

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The Southampton Hand philosophy, first developed during the 1960s [2], centres on transferring the low level reflexes of prehensile control from the user to the prosthesis. The user maintains superficial myoelectric control in the conventional two-site manner, whilst a microprocessor and sensor system provide sufficient feedback for the prosthesis to self-regulate prehensile movement and grip force [12]. This hierarchical Southampton Adaptive Manipulation Scheme (SAMS) enables multiple-degree-of-freedom control without increasing the cognitive burden. However the various prehensile patterns afforded by the mechanics of the hand must be originated by specific sensor contact rather than by voluntary muscle function. For example, triggering a lateral force sensor on the fingertip would initiate a lateral grip posture. This method is neither a natural nor fluid movement as part of the grasping process.

Multifunction control may also be achieved by the extraction of additional information from the user's MES input. One of the most notable advances is the multiple-degree-of-freedom controller developed by Hudgins *et al.* [11] at the University of New Brunswick. The system uses an artificial neural network to derive multifunction control inputs from the myoelectric signal. The main disadvantage of this controller is that the user must still use visual feedback to maintain prehensile and kinematic control.

The efficacy of each control philosophy has been well proven, yet both suffer from additional disadvantages that increase the cognitive effort on the part of the user when ensuring dynamic multifunction control of a prosthesis. However the development of a new hybrid control system enables the user to directly implement prehensile patterns from the usual two-site myo-signal input, whilst the process of maintaining a secure grasp remains automated thereby reducing the reliance upon visual feedback. Although primarily intended for application to the multiple-axis Southampton–Remedi hand, additional functions enable the controller to be used with other powered joints (such as wrist, elbow or shoulder).

UNB MyoController

The Institute of Biomedical Engineering at the University of New Brunswick in Canada has been developing and fitting myoelectric control systems since the 1960s. The research from this group has been primarily on single function control (UNB 3-state) and sensory feedback but recently, with collaborative funding from Hugh Steeper Ltd (UK), they have developed a three-degree-of-freedom myoelectric control system. This approach uses patterns in the instantaneous myoelectric signal to define a signature for a particular limb function.

The myoelectric signal is very complex as it is influenced by many factors due to the electro-physiology and the recording environment. It is the complexity of the MES that has presented the greatest challenge in its application to the control of powered prosthetic limbs. In most myoelectric control systems, information from the *steady-state* MES (produced during constant effort) is used as the control input. The steady-state MES, however, has very little temporal structure due to the active modification of recruitment and firing patterns needed to sustain a contraction [12]. This is due to the establishment of feedback paths, both intrinsic (the afferent neuromuscular pathways) and extrinsic (the visual system). In a departure from conventional steady-state analysis, Hudgins and co-workers [11, 13] investigated the information content in the *transient burst* of myoelectric activity accompanying the onset of sudden muscular effort. A substantial degree of structure was observed in these transient waveforms. Data was acquired during small but distinct isometric and anisometric contractions, using a single bipolar electrode pair placed over the biceps and triceps muscle groups. This arrangement was intended to allow a large volume of musculature to influence the measured activity. Figure 1 shows typical patterns corresponding to flexion/extension of the elbow, and pronation/supination of the forearm.

These patterns exhibit distinct differences in their temporal waveforms. Within a set of patterns derived from the same contraction, the structure that characterizes the patterns is sufficiently consistent to maintain a visual distinction between different types of contraction. Hudgins aligned the patterns using a cross-correlation technique and showed that the ensemble average of patterns within a class preserves this structure.

Subtle changes in the nature of a contraction, however, can introduce variability into the recorded MES. In an ensemble of patterns produced by similar contractions, there are visually perceptible similarities amongst waveforms, but the local characteristics may vary tremendously. Identifying this loosely defined structure is a challenging pattern recognition task. Hudgins used

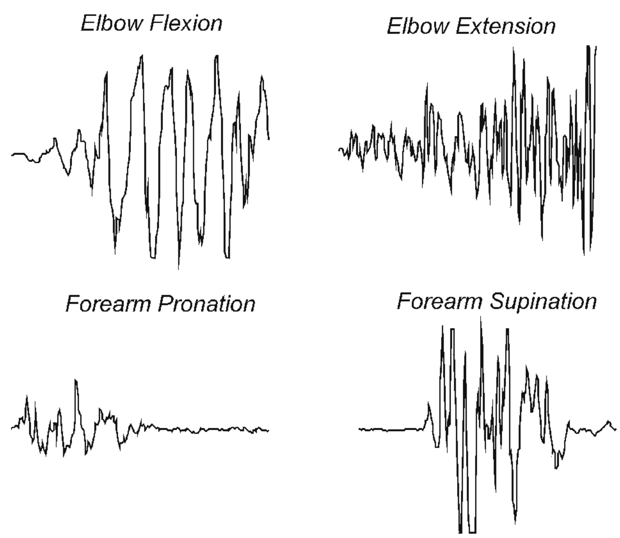

Figure 1. Patterns of transient MES activity recorded using a single bipolar electrode pair, placed over the biceps and triceps.

an approach in which the initial 240 ms of unprocessed MES following a threshold trigger is divided into several time segments as shown in figure 2.

A control system based on Hudgins' work was designed at UNB. This system used a simple multilayer perceptron (MLP) artificial neural network as a classifier of the time-domain feature set (zero crossings, mean absolute value, mean absolute value slope and trace length) extracted from the single channel MES. The controller identified four types of muscular contraction using signals measured from the biceps and triceps. A block diagram of the UNB control scheme is shown in figure 3. A set of time-domain features is extracted from a transient burst of one-channel MES. A MLP classifier is trained upon an ensemble of patterns derived from contractions of (up to) four movement types.

Not only does this system provide multifunction control from a single site, but the control signals can be derived from natural contractions, thereby minimizing the conscious effort of the user. The control system was realized in hardware, and improvements to the original design have been suggested to allow it to be used for degree-of-freedom selection [14] and to improve its classification performance [15]. The current system uses two channels of myoelectric signal to derive control information. It has several modes of operation as shown in figure 4. Initially the control system is trained on the distinct MES patterns of the amputee. This information is downloaded into the control system. The control system can then be used to control a three-degree-of-freedom prosthetic arm or used to control a virtual arm simulation on a computer screen.

SAMS

The SAMS control structure resembles that of a simplistic model of motor control in the central nervous system. The lowest level of the hierarchy in the human body manages the position and force reflexes of the fingers. This is governed by the intermediate level of peripheral neural loops to coordinate the hand's shape and grip force in response to tactile feedback, whilst strategic control resides with the individual [16]. This organizational structure has been replicated in the SAMS controller by the user maintaining cognitive input, and the microcontroller implementing force or posture control based on feedback from sensors on the prosthesis [2]. The basic control states are POSITION, TOUCH, HOLD, SQUEEZE and RELEASE (see figure 5).

The POSITION state enables the hand to adopt the correct prehensile posture. The prosthesis acts in a voluntary opening manner, where extensor muscle activity on the part of the individual will cause the device to open in proportion to the MES amplitude using position feedback. Hence in the absence of user intervention, the hand will involuntarily close until an object is detected by sensors on each digit, at which

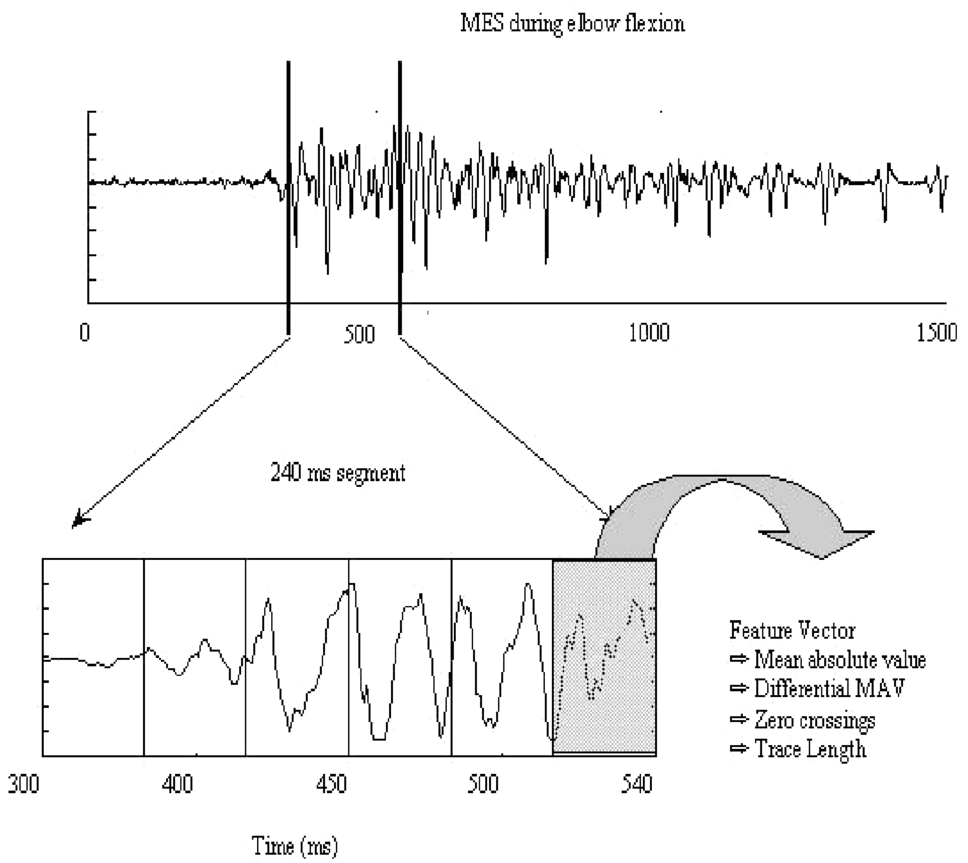

Figure 2. In Hudgins' approach the features are extracted from several time segments of the unprocessed MES.

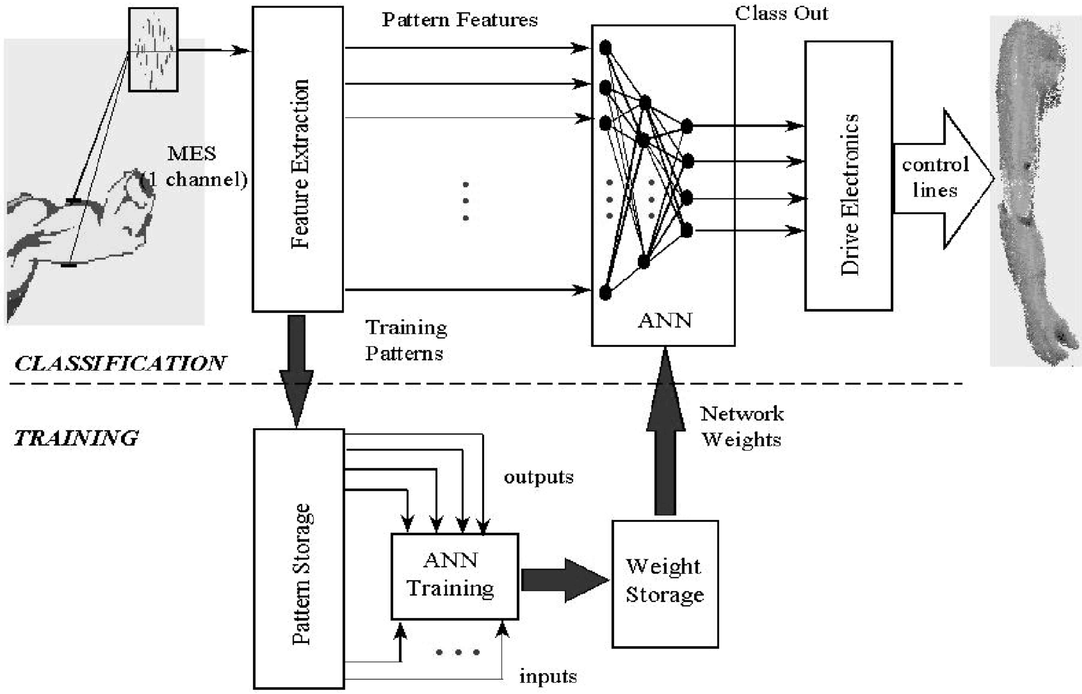

Figure 3. The UNB multifunction control scheme.

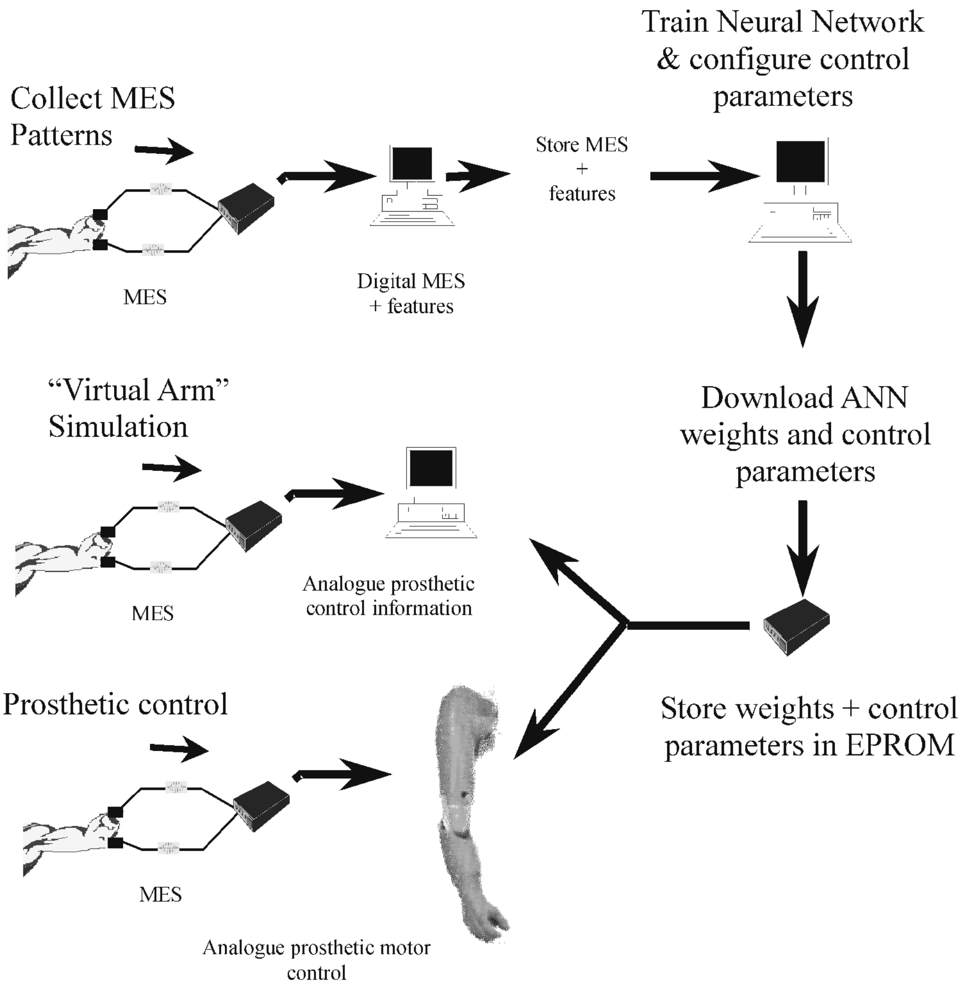

Figure 4. Modes of operation of the UNB multifunction control system.

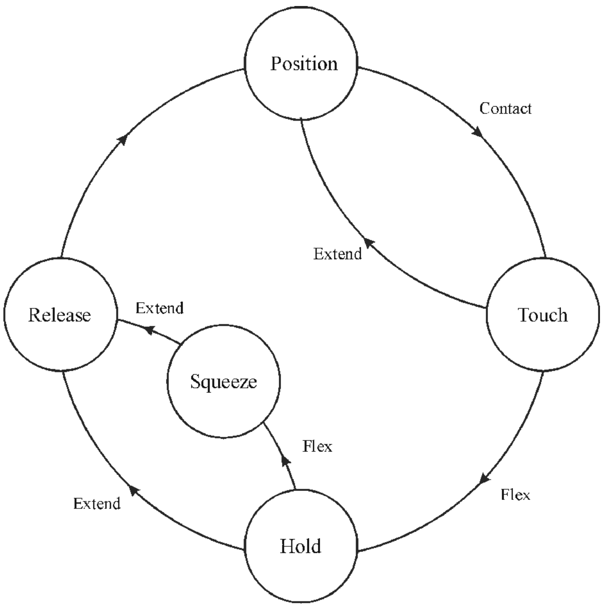

Figure 5. SAMS state diagram.

point the controller will move to a TOUCH state and terminate movement causing the prosthesis to exert only minimal grip pressure.

A burst of flexor myo-activity on the part of the user will cause a state change to HOLD whereby prehensile control is automated using slip sensors on the hand. The controller will maintain optimum grip pressure to ensure that the object does not slip from the grasp.

This state can be overridden by a further period of flexor activity (moving the controller to SQUEEZE) whereby the user is afforded direct control of grip pressure in proportion to the MES amplitude. During HOLD or SQUEEZE, extensor muscle activity above a pre-set threshold will cause the controller to return to its original state.

Consequently the user may maintain stable prehension by minimal control input without the need for continuous visual feedback. Although the specific implementation of this control has varied according to sensor and microprocessor technology, the efficacy of this design is proven in its continued validity and use [17, 18].

Implementation of the hybrid controller

The hybrid SAMS–UNB controller requires the integration of two real-time microprocessor-based control solutions with multiple feedback systems and minimal hardware. The UNB system is used as a myo-classifier, producing up to four potential state outputs, although additional pattern classes may be achievable depending upon the discriminate muscle function of the individual. The SAMS system then implements a specific prehensile pattern or function (either lateral, precision or power grips in the Southampton–Remedi Hand, or operation of another device such as a standard myoprosthesis and active wrist). Once the function has been selected the hierarchical control system is initiated and any subsequent state change of the myo-classifier is disregarded. At any point during grasping, a maintained period of extensor activity on the part of the user will cause both systems to return to initial conditions.

The prototype controller has been implemented in two separate units, as the UNB myo-controller already exists in a clinically ready format. However, it is feasible and logical that future developments will see both systems integrated to a single microprocessor (thereby reducing hardware requirements and power consumption).

A fixed point digital signal processor† (TMS320F240) is used as the main prosthesis controller. This is comprised of the SAMS system and all input/output (I/O) routines to enable communication with the external hardware, which includes prosthesis drive units, sensor systems and the UNB myo-classifier. The TMS320F240 is optimized for motor control, and more specifically can be used for multiple drive systems due to the dedicated pulse width modulation (PWM) outputs, digital I/O lines, and analogue inputs. Although many subsystems exist on-board the digital signal processor (DSP), external hardware is required to power the motors and interface between the processor and position, force and slip sensor systems.

Power electronics

PWM is an efficient method of drive control whereby the mark/space ratio of a fixed amplitude rectangular waveform may be varied to control the voltage at the motor terminals. This duty-cycle variation is easy to achieve by microprocessor control, and the use of a H-bridge provides full 4-quadrant motor control. Commercial H-bridge packages were rejected due to excessive power consumption. Instead, discrete components were used to produce a more efficient and controllable design (whereby the independent control of N- and P-channel MOSFETs affords the opportunity of regenerative braking and software deadband control). The low drain–source resistance of the MOSFETs (0.04 Ω for P-channel devices and 0.02 Ω for N-channel devices) results in an i^2R power loss that is significantly less than that of the commercial packages (from 200 to 15 mW for a current of 0.5 A). This characteristic is crucial to optimizing the use of the hand's battery power supply, and also eliminates the need for heat sinks (thereby reducing size and heat dissipation requirements).

The PWM signal is used to control the logic-level P-channel MOSFETs by switching in the 6 V power supply according to the duty cycle. Forward or reverse digital control signals maintain the N-channel MOSFETs in the relevant on/off configuration (and also minimize

†Development hardware supplied under the Texas Instruments Elite Universities Programme.

the transient current spikes that would arise if both N- and P-channel devices were driven simultaneously by the PWM signal). The design includes a high-side motor-current sensor that can be used to provide information on dynamic grip force, and whether the motor is approaching stall.

Sensor systems

The SAMS control system requires either position, force or slip feedback in order to ensure stable and secure object manipulation. The POSITION and TOUCH states utilize closed-loop position feedback so that the hand's digits track that of the user's myo-signal demand. Force feedback is necessary to determine whether the prosthesis has come into contact with an object, and is also subsequently used during the SQUEEZE state to apply grip pressure in proportion to the user's MES. During object manipulation in the HOLD state, slip feedback ensures that optimum grip force is maintained.

The appropriate sensor system (or output of the UNB myo-classifier) is selected (or reset) from the microprocessor's address bus via a demultiplexer. Once selected, the processed signal is transferred to the 16 bit databus (see figure 6), or to the DSP's on-board 10 bit analogue-to-digital converters (ADCs).

Position feedback enables the controller to determine the location of the prosthetic fingertip. The mechanics of the Southampton–Remedi hand possess little backlash, hence digit position can be accurately estimated without direct measurement at the base of the finger (as is necessary with many artificial hand designs). This has the benefit of reducing bulk and improving reliability by eliminating sensors from exposed areas of the hand. The motors for the six-degree-of-freedom prosthesis each have a digital magnetic encoder mounted to the drive shaft. The quadrature encoder output pairs are connected to six dedicated position decoders that produce a directional 16 bit count of shaft position. Once processed, the resultant signal provides an accuracy of approximately 0.03° of digit rotation.

Contact and grip force information is crucial to the success of adaptive manipulation and is often gained through the use of force sensitive resistors [18, 19]. These analogue sensors must be mounted on the digits of the prosthesis and are notable for output drift over time or due to temperature fluctuations. However, the motor-current sensors provide sufficient information to determine if the prosthesis has come into contact with an object, and also quantify the force that the digit is applying. The advantage of this system is that the sensors are an integral part of the electronic hardware interface. This is crucial to the minimization of lead length between the analogue sensor and signal processing components (thereby limiting noise interference from the motors), as well as eliminating the need for externally mounted devices which are susceptible to reliability problems. The output of the current sensors are amplified and filtered (using a two-pole low pass Bessel filter, $f_c = 10$ Hz) in order to eliminate high transient effects that are particularly noticeable at motor start-up. The processed signals are then input to the ADCs on board the microprocessor.

An evolution of the acoustic slip sensor used in the MARCUS hand [17] provides feedback if an object begins to slide from the hand during the HOLD state. The sensor consists of a Knowles hearing aid microphone sealed within a rubber tube, and is capable of detecting air movement which is highly coupled to fluctuations at the finger surface. Hence the signal

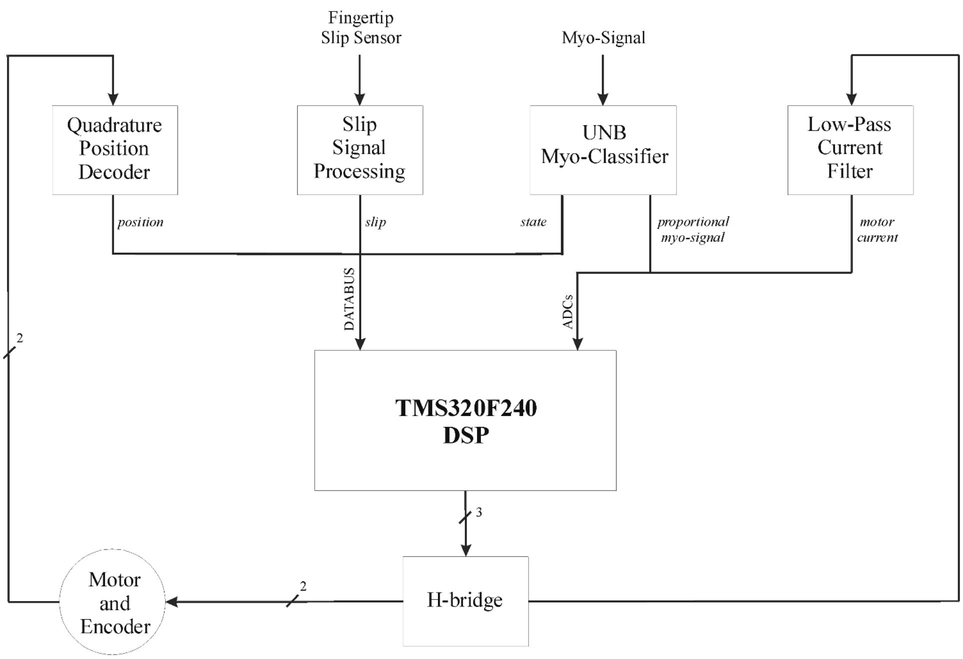

Figure 6. Hybrid SAMS – UNB controller and sensor systems.

resulting from an object sliding across the surface of the tube is much greater than any extraneous noise. This device has been integrated into the tips of the thumb, index and middle digits of the Southampton–Remedi hand, as only three slip sensors are required to determine object slip in any prehensile configuration. The slip signal produced by the microphone is broadband in nature with constant production at low frequencies; but it is the high frequency content which is dependent upon the speed of slip and the contact surface [20]. The signal is processed to extract this information and produces a slip pulse train which is used to increment a binary ripple counter. The resultant slip count is input to the DSP via the databus and forms a force demand which is proportional to the rate of slip.

Real-time control

In order to achieve reliable and accurate control of the mechanical system, the motion controller must be implemented in real-time. Therefore I/O interfacing and control effort calculations are made within the bounds of interrupt driven software. The prioritized interrupt service routines (ISRs) are predominantly written in assembler to ensure fast execution times, and handle all data transfer between the controller and the prosthesis. These ISRs represent the lowest level of the hierarchical control structure, whilst the main program, written in C, executes the higher level 'cognitive' control states of the SAMS–UNB system.

If the controller is in normal operation then proportional and integral closed loop control is used with the appropriate feedback system to ensure a fast system response with minimal steady state error. The mechanics of the prosthesis are sufficiently slow during operation to provide stable prehension without the addition of a derivative control term.

There are two states in which this structure is bypassed: if the controller is in reset mode, the prosthesis is driven open-loop until initial conditions are met and all sensor systems can be initialized; or if a fast motor shutdown has been requested. The latter state acts as a safety harness to the control of the mechanics. Hence any requirement to cease activation of the prosthesis, either by user demand or by sensory feedback (e.g. the motor reaching stall current), is serviced in the shortest time period.

A demand characteristic resulting in a 'neutral' natural hand position [21] is set during an initialization state, prior to enabling closed loop operation and activation of the hierarchical SAMS control system. Any power failure, control error, or unknown mode of operation will cause the DSP to reset and commence the initialization routine.

Results and discussion

In the clinical setting, the UNB controller has been demonstrated to be highly reliable. After a short period of training, users are able to produce a correct function selection rate of over 90%.

The SAMS system has seen implementation in several hand prostheses [16–18] but clinical evaluation remains limited. Nevertheless increasing use of intelligent prehension in both developmental and commercial hand prostheses testifies to the efficacy of the original control hypothesis.

Preliminary evaluations of the Southampton–Remedi hand and hybrid controller have been carried out using tasks from a standardized and objective hand assessment tool [22]. The development format of the hybrid controller prohibits assessment by prosthesis users or wide scale normative testing at the current time. However, limited functional evaluations have demonstrated the ease of repeatedly initiating direct prehensile pattern control of the multiple degree of freedom prosthesis from a subject's myo-signal. In addition, the hierarchical automated grasping scheme has been shown to perform secure manipulation of objects of various sizes and compliance. Ongoing research is intended to develop the controller to enable clinical trials to commence.

Conclusion

There is a requirement for existing hand prostheses to provide improved functionality for the user, which primarily can be achieved through multiple degree of freedom devices. Myoelectric control is an effective method of enabling the user to provide input commands to these prostheses, however, current systems lack the proprioceptive feedback often achieved with the use of simple body-powered devices. Consequently the user is forced to rely upon visual information to ensure stable prehension. This increases the psychological effort necessary to maintain effective control of the hand, and is particularly evident in the use of multifunction devices where the movement of several degrees of freedom must be co-ordinated.

The Southampton Adaptive Manipulation Scheme (SAMS) is an established method of removing the reliance upon visual feedback during object manipulation, but requires the user to trigger external sensors on the prosthesis in order to initiate a range of prehensile patterns. Maintaining direct myo-control of the hand's posture would lead to a more fluid and natural movement. The UNB myo-controller achieves this by the extraction of additional information from the user's myo-signal for the effective control of multifunction upper limb prostheses. However this system does not possess the automated grasping characteristic of SAMS, necessary to reduce the dependence upon visual information. Consequently a hybrid SAMS–UNB system has been developed based on two digital signal processors, an array of position, force and slip sensors, and power electronic drives. Integration of these development systems to a single DSP with minimal hardware is expected to produce a solution suitable for clinical use.

There are clear indications that the hybrid controller would be effective for a range of prosthesis users. Although multiple degree of freedom hands currently remain confined to development status, the demand for increased functionality is likely to result in commercial availability in the near future. The main disadvantage of these systems to date has been the increased cognitive burden placed upon the user. However by integrating multifunction and intelligent prehension myo-control, this boundary may be removed.

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