THE DEVELOPMENT OF AN ADVANCED MULTI-AXIS MYO-PROSTHESIS AND CONTROLLER

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ABSTRACT

Commercial myo-electrically controlled prostheses are currently single degree of freedom devices with highly restrictive function. These artificial hands warrant high grip forces due to their planar pincer movement to ensure stable prehension, thereby inherently requiring precise and conscious effort on the part of the wearer to ensure optimum grip.

The Southampton Hand has demonstrated the ability to devolve low-level user control to the hand prosthesis itself by the use of the Southampton Adaptive Manipulation Scheme [1]. Until recently these multiple-axis prostheses have lacked clinical significance due to poor reliability and user-oriented design [2].

The development of the latest device is centred on the hypothesis of enhancing stable prehension by increasing the adaptability of the prosthesis, whilst simultaneously minimising the necessary grip force. This is to be achieved by increasing the number of independent degrees of freedom of the device without compromising user-effort by utilising the Southampton hierarchical control system. Constraints such as modularity, low weight and power consumption are factors that have been adhered to throughout the design process.

The six independent axes of the hand are controlled by a single microprocessor. The limiting factor in the advancement of artificial hands has frequently been the integration of technology to the device. Consequently several accurate sensing systems were implemented in this design to enable a more comprehensive control of the adaptable hand prosthesis.

INTRODUCTION

Conventional hand prostheses utilise proportional control methods for the user to directly control the position (or velocity) of a single degree of freedom hand via their EMG signals. The inherent disadvantage of these systems is the conscious effort a user must make to ensure the stable and optimum grasping of an object. This form of control frequently results in the user overgripping to ensure that the object does not slip from the hand. Utilising such a method for a multiple degree of freedom prostheses would result in an unacceptable control burden for the user.

The hierarchical control of the Southampton Adaptive Manipulation Scheme (SAMS) forms the foundation of an adaptive intelligent prosthesis philosophy [1], whereby the low-level control of the hand is transposed from the user to the device. The control scheme has been applied to several prototype prostheses (usually four degree of freedom devices), but has only recently seen clinical fitment in the form of a two axis device [3], with separate movement of the thumb and fingers. Use of a microprocessor ensures stable prehension by measuring force, slip, and digit position from the prosthesis.

This paper outlines the development of the latest Southampton hand (funded by the Rehabilitation and Medical Research Trust, Remedi).

A new mechanical prosthesis has been developed along with the SAMS controller implemented on a digital signal processor (provided by Texas Instruments under the Elite Universities Program) in combination with the

UNB myoelectric controller. When put into effect with multiple sensing systems, this design is to result in a highly adaptable and functional prosthesis without additional burden to the user.

MECHANICAL DESIGN

Conventional hand prostheses have limited object stability during prehension. Hence it is hypothesised that an increase in the number of degrees of freedom will improve the adaptability and grip stability of the artificial hand whilst minimising the necessary grip force.

The index and middle fingers of the natural hand are used to oppose the thumb during precision grips, whilst the ring and little finger are vital in strengthening prehension [4]. The lack of these functions is reflected in commercial hand prostheses by a notable absence of stability during power grips, usually only compensated for by the skill and experience of the user. Consequently the number of degrees of freedom in the Southampton-Remedi hand have been increased from the single axis found in a conventional device, to six independent movements, exhibited in the form of four fingers, and a dual axis thumb (to ensure maximal dextrous range during precision grip tasks).

The design of any hand prosthesis must adhere to a number of constraints, and factors such as cosmesis, reliability, modularity, weight and power consumption, must be optimised. These elements are reflected in the design of the Southampton-Remedi hand.

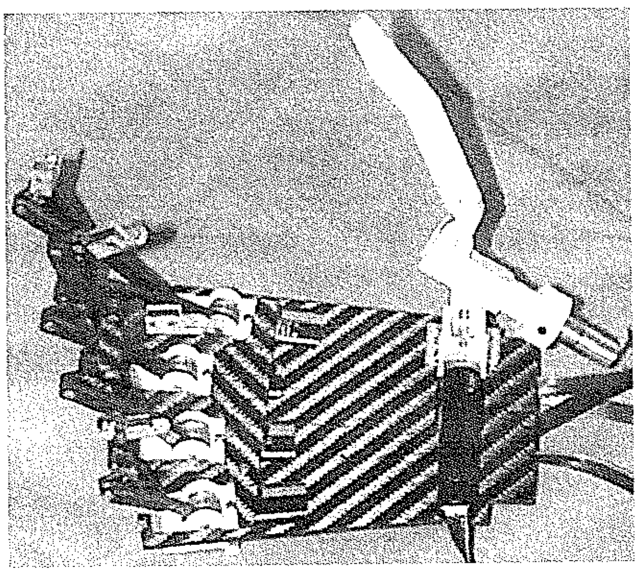

Figure 1 - Prototype Southampton-Remedi Hand

Mechanical linkages have frequently been used for the implementation of artificial hand digits [5,6] in order to produce a 'natural' curling action. A notable exception to the conventional linkage configuration is a 6-bar planar design [7], optimised for mechanical efficiency and trajectory (to reflect that of a naturally curling finger). Mathematical modelling was employed, and prosthesis design constraints imposed, to modify this design for use in the prototype hand. The result is a modular linkage made from carbon fibre (see Figure 1), driven via a motor and worm-wheel system to ensure a passive grip can be maintained without the constant application of power to the motor drive system.

The natural hand's dexterity is centred on the ability of the thumb to oppose the fingers. Indeed it is clinical consensus that a loss of thumb function causes a minimum of 50% of the hand's subsequent disability [8]. Given the role of the thumb as an opposer in the vast majority of grip scenarios, the single axis device currently found in commercial prostheses must severely impinge on functionality. A biomechanical study of the natural thumb revealed an optimum solution of a 2-axis system within the prosthesis. The circumduction and flexion axes in the artificial digit (see Figure 1) illustrated a compromise of the five degrees of freedom exhibited in the natural thumb whilst maintaining a broad range of dextrous opposition. The design exhibits a similar modularity to that of the artificial digits, with the dual axes being powered by motor and worm-wheel drive systems.

These modular components are integrated to the prosthesis through the carbon fibre palm. The biomechanical arches displayed in the palm of the natural hand form a template for adaptation during prehension, whilst the soft tissue and muscle groups enable sufficient compliance for the hand to actually effect an adaptive grip. Unfortunately it is not possible to replicate these palmar arches in the hand prostheses without advanced 3D modelling software to study the effect of digit interaction. However a limited form of oblique flexion (necessary for the thumb to oppose the little finger), and digit opposition, has been achieved by the spanning of the fingers (along with the mobility afforded by the dual axis thumb).

CONTROLLER DESIGN

The SAMS hierarchical state control scheme requires only simple user inputs from the forearm flexor or extensor muscles (see Figure 2). Extensor tension causes the controller to initiate the proportional opening of the hand, or if the exertion is sufficient, to trigger a RELEASE state. The prosthesis operates on a voluntary-opening, involuntary-closing basis; the hand will automatically close when the subject is relaxed with minimal myo-activity. Each digit of the hand will continue to close until encountering an object, whereupon each individual drive is powered down, and the controller has achieved a TOUCH state. This results in the prosthesis exerting the smallest feasible touch force on the object whilst maintaining maximum surface area contact. To initiate a grasp, flexor tension causes the controller to implement a HOLD state. This mode utilises slip sensor feedback to maintain optimum grip force whilst arresting any instability that may occur when the user manipulates the object. This state can be overridden by a further flexor tension that causes a SQUEEZE state whereby current sensor feedback enables proportional force control of the prosthesis by the user.

Multiple-axis hand prostheses possess the capability of initiating various prehensile patterns (although obviously limited by the number of degrees of freedom within the device). The SAMS state control system is designed to maintain optimum grasp rather than to govern the implementation and discrimination of grip scenarios. Consequently, supplementary sensors on the hand have been used previously [6] to effectuate multiple grip configurations; for example, a force sensitive resistor on the side of the index finger would be activated by the user to initiate a lateral (or 'key' grip). This method of explicitly triggering prehensile patterns is inconvenient. However, a direct implementation of grip type from EMG signals would prove extremely difficult, if not impossible, for the user to achieve due to the limited number of degrees of freedom obtainable from the myoelectric signals.

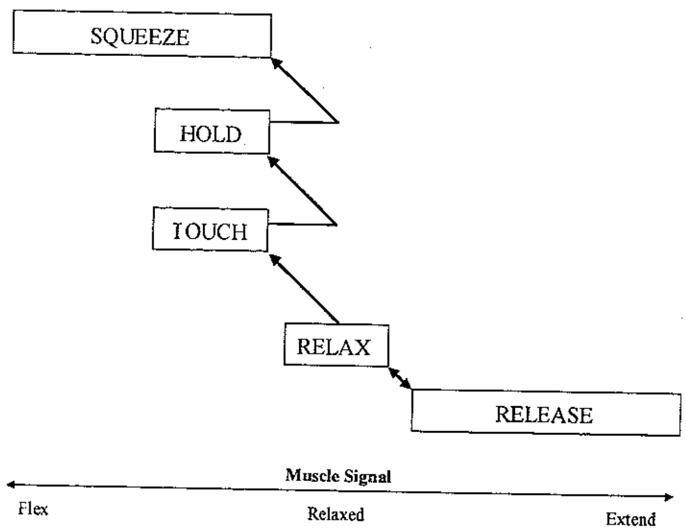

Figure 2 - SAMS Control Structure

Despite this, a unique method of control may be achieved by the combination of the SAMS system and the UNB myoelectric controller [9]. The UNB controller was originally designed for the control of multiple axis upper limb prostheses (such as powered elbow, wrist and hand devices). The controller is capable of determining three independent degrees of freedom from the user's myoelectric signals, and subsequently produces three state outputs and a proportional flexion/extension amplitude signal (see Figure 3).

The proposed control system for the Southampton-Remedi hand is to afford the user maximum versatility. The system essentially consists of two separate controllers implemented on two individual microprocessors. The UNB myoelectric controller is used to determine prehensile pattern (either lateral, power or precision) by the selection of an appropriate degree of freedom, and once initiated, the flex/extend signal is used then to drive the SAMS state control in the conventional manner. The combined control scheme provides the user with ability to directly implement prehensile pattern control with automatic adaptive manipulation (Figure 3).

MICROCONTROLLER, SENSORS AND DRIVE SYSTEMS

In order to keep power consumption to a minimum and maximise motor control, H-bridges are used to drive each motor (see Figure 4). The circuit uses pulse width modulation (PWM) with a frequency of 16kHz, and forward/reverse logic signals to control motor terminal voltage and direction.

Until recently it was not possible to integrate accurate sensing systems within prostheses due to the technological limitations and excessive cost. However the Southampton-Remedi hand has incorporated high-accuracy sensing systems that are capable of providing precise information on position, slip, and motor current (to determine fingertip force and monitor motor performance).

The digital signal processor (DSP) used is optimised for digital motor control and manages all of the input/output (I/O) to the sensors with a minimal requirement for additional hardware. Although designed for governing single brushless dc motors, the prosthesis controller maximises the I/O potential of the DSP by governing the multiple-axis brushed dc motors of the hand.

A small number of hardware interface circuits between raw sensor signals and the main controller are necessary. Digital magnetic encoders mounted to the motors generate digit position information. This quadrature signal is decoded and input to the DSP in the form of a 16bit count, ranging from zero at full extension to 0x2748 at full flexion. This provides a resolution of approximately 120bits per degree of digit rotation (thereby assuring far greater control accuracy than is actually achievable given the non-linearity of the mechanical system).

Supplementary hardware also includes interfacing between the acoustic slip sensors [2], the motor current sensors, and the controller. The analogue current signals are filtered through a low-pass 500Hz Bessel filter to reduce the noise interference generated by the switching of the H-bridge power electronics (Figure 4).

CONCLUSION

The Southampton-Remedi hand is a novel six axis hand prosthesis capable of stable prehension through the use of multiple independent digits. The mechanical design has been based on biomechanical studies of the natural hand.

The control of multiple degree of freedom devices can prove an extreme burden to the user. The Southampton Adaptive Manipulation Scheme has been illustrated to alleviate this burden by transferring low-level grasping control from the wearer to the hand itself. In order to maximise the potential of various grip scenarios, the UNB myoelectric controller is to be used to initiate a lateral, power or precision grip prior to triggering the SAMS control system.

Multiple, accurate sensing systems are an integral and essential component within the hand to achieve autonomous grasping control, by providing information on digit position, motor current and object slip.

Although the Southampton-Remedi hand is not expected to undergo clinical trials at this stage, the functional range of the device is to be assessed using the Southampton Hand Assessment Procedure [10]. The abstract tasks within this evaluation procedure are designed specifically to assess various prehensile patterns, and thereby provide initial assessment criteria for examining the functional range of the device.

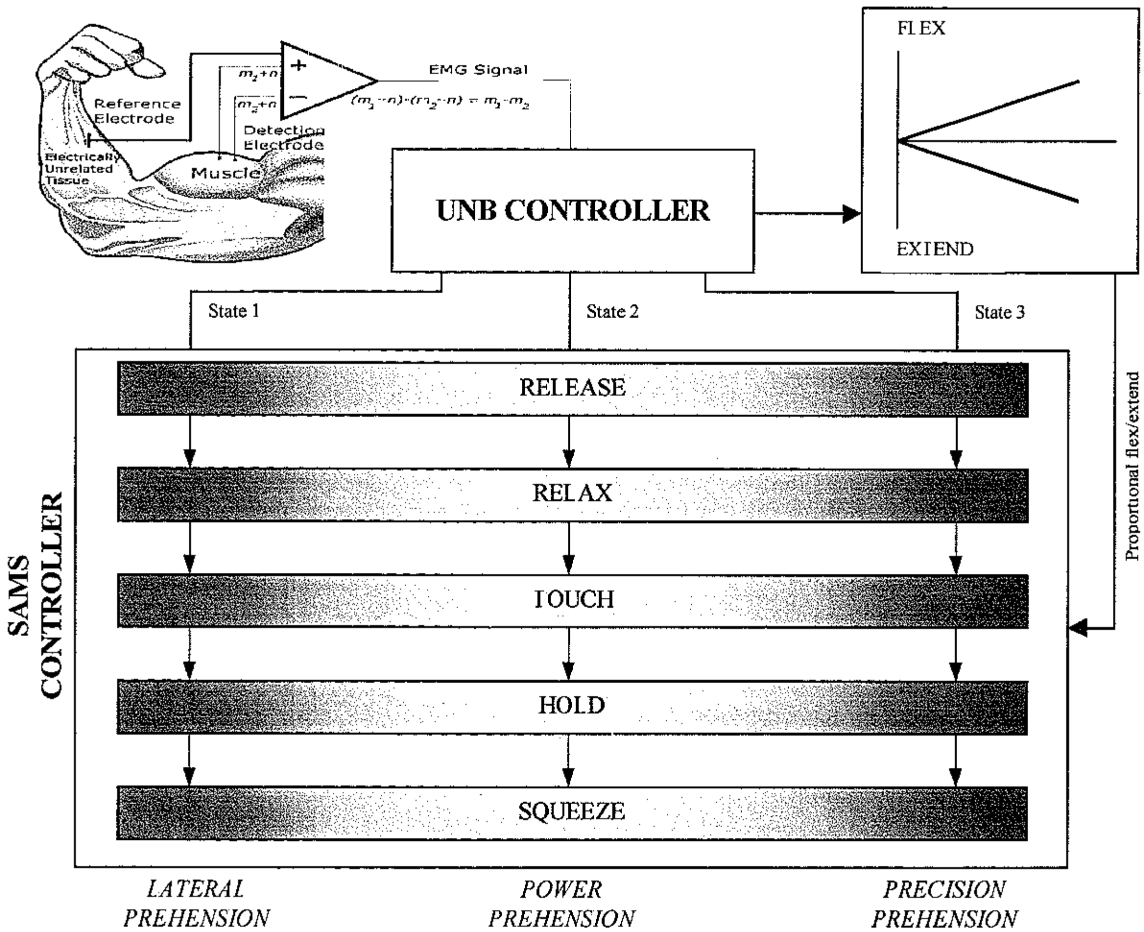

Figure 3 - Direct Prehensile Pattern and Adaptive Manipulation Control with the UNB/SAMS Controllers

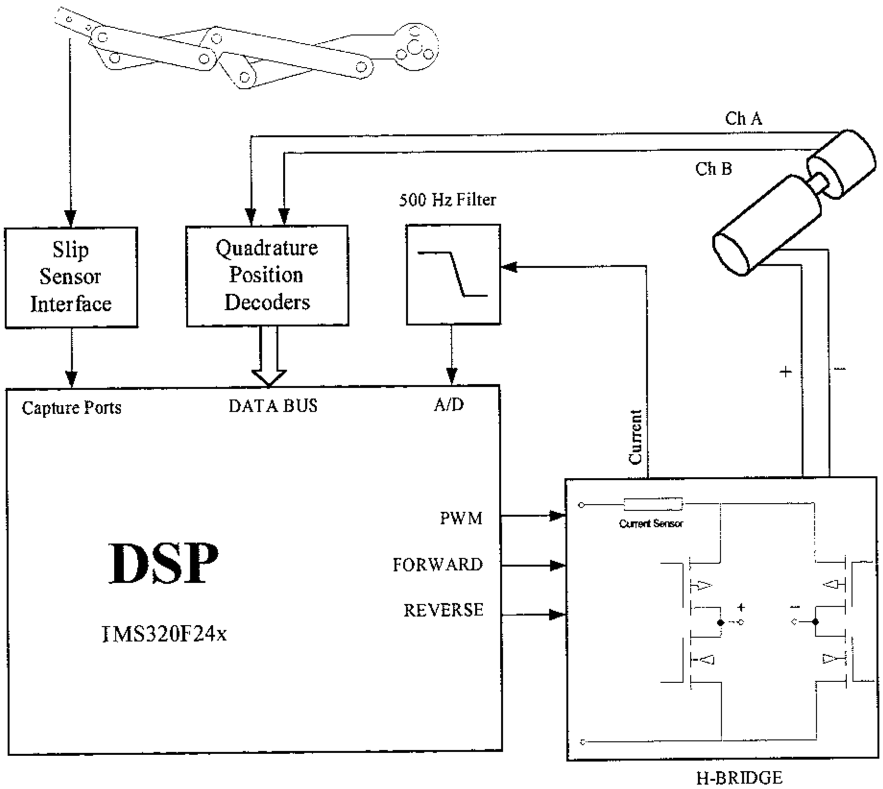

Figure 4 - Overall Input/Output System Control

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