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An Intelligent Anthropomorphic Hand, with Automatic Grasp

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SUMMARY

The current designs of commercial artificial hands have a low level of innovation. As feedback to the user is difficult to achieve reliably, most devices are simple in design and operation, and limited in functional range. If information on the state of the hand, the forces and any slippage that is occurring is fed back to a microcontroller then more than one degree of freedom can be controlled and a greater and more natural functional range is possible. This paper describes the development of such a device. It outlines the design requirements, the methods of detection of the signals and the training required to operate the hand.

KEYWORDS: Exo-Prosthetics; Artificial arms; Hierarchical control; Microcontroller applications.

1. INTRODUCTION

The human hand has evolved to be a complex and adaptable manipulator. It is able to quickly reconfigure itself into different shapes to enable the owner of the hand both to delicately manoeuvre tiny items and also to forcibly propel heavy objects. It achieves this by a combination of a large number of degrees of freedom and a complex hierarchical control aided by a large number of internal and external sensors. For example, in the motor cortex of the brain, the amount of processing power given to control an area of the body is proportional to the area of brain used to control it: The hands require as much as the legs and trunk combined. Despite this complexity, the usual effort required by the owner of the hand is very small, the hand being more like the extension of the person's will than a tool or device.[1] It is the control hierarchy that allows the person to feel this way.

In performing a natural grasping action the hand is automatically shaped in response to the object and desired task. The grip is based on previous experience and modified by sensory information from the skin of the hand.[2,3]

When a hand is lost through disease or trauma (or the person is born without a hand) the pathways and sensors are lost, non-existent or inaccessible to the person. Little or no feedback is possible without a greal deal of training or concentration. The effort required is likely to be more than is practical. Thus to make controlling an artificial substitute easy the usual compromise taken is to limit the number of degrees of motion (usually to one in the hand itself).

2. CONVENTIONAL SOLUTIONS

As a result, conventional artificial hands fall into two categories:

- Functional: Where the terminal device is a mechanical device such as a hook that can provide both the basic forms of grip: *precision* and *power*.[4–6]
- Cosmetic: Here the hand is in an anthropomorphic format, but is fixed in a precision grip and is non-compliant.

Compliance is one of the most important features of the natural hand. It is able to wrap around an object and spread the contact force over a wide contact area. Therefore the individual forces can be kept low (below 10N for most manipulations). By contrast, one of the most powerful commercial prostheses has a maximum force of 120N, but a minimum detectable force of 12N.[7] The human system can keep the energy expenditure in handling an object at the lowest for stable grip. Artificial manipulation usually must impart a larger force to maintain a stable hold.

Purely mechanical hands, hooks and terminal devices are activated by the harnessing of relative motions of other bodily parts, for example: scapula adduction pulling on a harness that pulls straps that in turn are linked to the terminal device, which opens. The mechanisms themselves are simple and generally designed for single tasks.

Electrically powered hands are commonly controlled using signals derived from muscles on the forearm. When muscles contract they generate small voltages that can be detected, amplified and used as the instructions. These are known as Electromyograms or EMGs. The amplitude of the derived signal is roughly proportional to the tension in the muscle. Conventional systems use a simple ON/OFF control. When the tension exceeds a threshold an ON command is achieved.[8] The hand's motor then turns in one direction. A second muscle is then used to control the movement of the hand in the other direction. There is no feedback within the hand and little except visual outside, so the user has to judge by sight when to stop moving the hand. Thus an operator must concentrate on the control of the device. More recently manufacturers have introduced proportional control of the digits' velocity. Although this allows the operator to undertake more precise positioning than before, it does not address the problem of control without visual feedback. In addition it runs counter to the natural manner in which joints are controlled, which is generally positional.[9]

The appearance of the prosthesis is important to users. Some prefer a fully anthropomorphic device in form, action being less of a concern. Others favour very non-anthropomorphic devices.[10] Devices in the former category are covered and protected by gloves that are generally made of PVC. The gloves can be colour matched to the person's skin tone and are sufficiently natural in appearance that the wearer can mix socially and the appearance rarely brings attention to their device from the casual observer. However the glove may fold or ruck in unnatural ways, and the PVC

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may be stained by all manner of domestic fluids.

A specification for a better prosthesis is possible. A survey of users of artificial hands in Oxford and Italy was able to add other details that were felt necessary by these users of the existing technology.[11]

The conclusions were:

(i) The hand should operate without straps or a harness.
(ii) Any new form of prosthesis must be light, power is a lesser concern.
(iii) An externally powered hand must be capable of operating for over twelve hours, either on a single charge or by simple repowering. Electric power sources are the only practical solution, so their batteries must be able to be easily charged.
(iv) With any new device the user must be able to drive a car easily, preferably without any modification to the vehicle.
(v) New materials for the external gloves should be easily cleaned, hard-wearing, cosmetic and able to flex in more than one direction without deformation.
(vi) The hand must be easy to use, adding greater functionality without needing greater concentration.
(vii) The hand must be as compact as possible, with all the drives within the envelope of the hand itself.
(viii) Appearance is an important part of the device. When it is anthropomorphic, the fingers must curl during closure and it must be able to form both precision and power grips. When overtly mechanical, the aesthetics must be taken into account.
(ix) The mechanism must be reversible or symmetrically neutral, allowing both left and right hands to be created from the same parts.
(x) For safety considerations it must be possible to open the hand even when the power is turned off or the controller has failed.

2.1 *Southampton Adaptive Manipulation Scheme*

The control system utilized the Southampton Adaptive Manipulation Scheme (SAMS), which was originally developed in the Control Engineering Group in Southampton University.[12,13] The control derives its outlook from the premise that it is too difficult to feed information about the hand's environment to the operator, so a computer controller must perform the coordination and detailed control of the hand autonomously. The control format is hierarchical and while it is similar to that performed by the human Central Nervous System, it was not designed to slavishly copy that solution.

The prosthesis control is in three levels, (see Figure 1). The top level is the supervisory control, issuing simple commands to open, close, hold, squeeze and release any target object. At the lowest level are the reflexes that control individual digit or joint motion. Between these two is a coordination layer. The task is to minimise the grip force between the target and the hand. This is achieved by maximising the area of contact between the hand and the object. Thus there are force control and position control loops. The two functions exchange information to undertake the task, using information from the shape of the object as well as the commands from the operator and feedback from the low level reflexes. Thus if the person wishes to hold an object they instruct the hand to open wide enough to admit the object, then close around it. The first point of contact between the hand and object indicates the sort of grip required. If the tips of the fingers touch first, the hand adopts a precision grip (the tips of the fingers meet), if the contact is on the palm then the fingers and thumb adjust their relative positions and the hand adopts a power grip (the hand forms a fist); thus the hand can adopt the two generic forms of prehension. Conventional prostheses cannot achieve the latter form as the digits' motion is fixed.

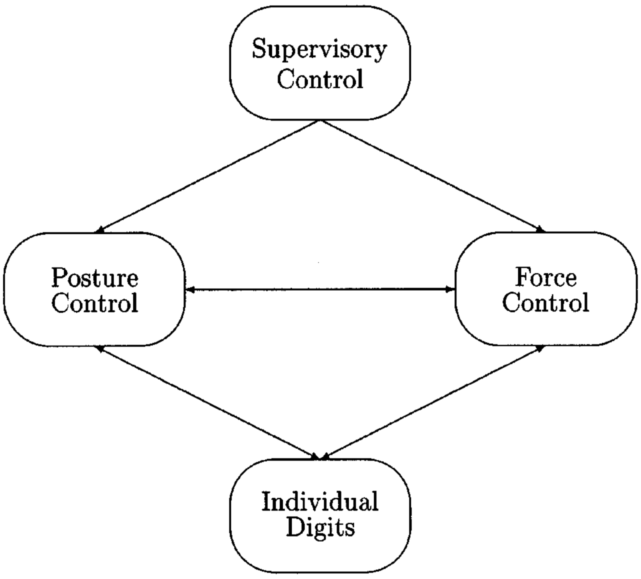

Fig. 1. The Southampton Adaptive Manipulation Scheme, (SAMS). It is arranged in a hierarchical form analogous to the human Central Nervous System.

As the hand is microprocessor controlled, instructions can be given to the hand in a number of ways, but the method most generally employed is electromyography. While similar to that used by conventional hands, here the signals are used in different ways to obtain more useful information. If possible, the EMGs are derived from opposing muscles on the forearm. The command structure of two muscles is closer to that found in the natural arm. An extensor muscle is used in the proportional position control of the digit flexion; the greater the tension the wider the hand opens. When the muscle relaxes the hand closes progressively and the motion stops when the hand is closed or when it is touching an object. It is then flexor tension that switches the hand on to the hold, reflex or squeeze override. Although these two muscles have been instanced, any two muscles (preferably opposing) can be used.

The control states are shown, Figure 2. The transitions between states are made based on the muscular inputs or from sensors on the hand.

Once the digits are touching the object they apply a light force (less than 4N). The touch is compliant so that any change in force on the digits will result in the hand backing off or closing further to maintain the grip while the user is positioning their hand for the best orientation for the task. Once the orientation is correct they can instruct the hand to

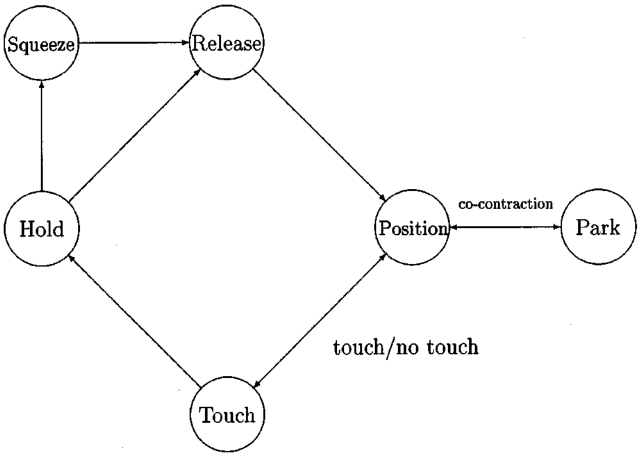

Fig. 2. The hand control state diagram. Transitions between states are based on the muscular command or sensory input.

hold the object, using the second muscle channel. This muscle is concerned with holding the object and so is a flexor muscle. At this point sensors in the finger will detect if the object is slipping within the hand's grip and the controller can increase the grip until the sliding has ceased. If they wish to disable the slip reflex then re-application of the second muscle signal switches the hand into a squeeze mode where the grip force can be made proportional to the peak command signal. If at any time the person wishes to let the object go then they can use the original muscle to open the hand once more.

In this way the opening hand is associated with the same muscle at all times and the operation is progressive and logical. The microprocessor controller also overcomes another problem that besets conventional control: the threshold that is set for the muscle tension to open the hand has generally to be a compromise between making it easy to open an empty hand and deliberately to open one that is carrying an object. With an intelligent controller these two thresholds can be made distinct and so the release of an object is a robust and deliberate act.

The Park state exists to allow the user to switch the electronics into a battery saving, power-down mode. When the controller is initially powered up it starts in this state and co-contraction of both muscles switches into the position control mode.

2.2 Mechanism

The mechanism (Figure 3) had to fulfill the above requirements. It was based round two parallel plates that retain the permanent magnet DC motors and reduction gear trains for independent driving of the fingers and thumb. The digits are driven according to the principles of synergetic prehension;[14] the speed of flexion of the fingers was made higher than the thumb. The thumb was more highly geared which allowed it to provide the grip force. This division of the digit motion allows for a hand with a faster grip speed, while providing a higher grip force. In addition, studies of human prehension show that the digits *are* moved in this form; the thumb is held closer to the target flexing slowly as the fingers close more rapidly upon it. When prostheses have equal angular speed of fingers and thumb (as most conventional prostheses do) the user has to make unnatural compensatory motions with the joints higher up the arm (if they are intact), so that the approach of the fingers and thumb approximates the relative tracks that the natural digits follow.[15,16]

Fig. 3. The Oxford Intelligent Hand prosthesis in power grip. This grip form is not possible with conventional devices.

The fingers are braked by a lever pressing on a wheel on the high speed shaft of the motor. This allows a small force to prevent the fingers being backdriven by a large force. However the lever can be operated by the wearer of the hand so that if the power fails they can release the grip.

As the hand's construction is otherwise symmetrical, reversal of the side plates creates a left or right hand using the same components. This reduces the number of components and the cost of the device.

The first two digits have interphalangeal joints that allow the digits to flex in to the palm as well as to open wide enough to admit large objects. The tips are also driven by a whiffle tree mechanism (similar to a car hand brake) so that if one digit is stopped the other will tend to close further, spreading the load more widely across the surface of the hand than a rigid mechanism would allow.[17] The central mechanism is covered by a shell and a cosmetic glove covers the entire hand. The other two fingers are dummies within the glove so that a realistic, natural-looking form is created.

The use of conventional lightweight materials for the device produces a weight of 560g in the prototype. The digits have three actuating joints linked to curl continuously from fully extended to fully flexed, unlike a conventional prosthesis where the digits are set in a slightly flexed position and only actuated at the proximal interphalangeal joint. The additional joints allow a wider range of objects to be grasped. The fingers open wider than those in fixed flexion and also close more tightly onto smaller objects when in the power grip. For example, the cylinder shown in

Figure 3 could only be held in a precision grip in a conventional hand. This would afford only three points of contact with the hand. A single digit of the Oxford hand would have more points of contact. The maximum size of object that could be held in the hand is only limited by the hand's size (medium adult's size).

The thumb can impart 45N pinch force. This is sufficient for most tasks because the load is spread across the surface of the hand.

2.3 Electronic Controller

The controller (see schematic, Figure 4) is based round the Intel 80C196KC/D microcontroller. This contains the analogue to digital conversion, digital input and output, memory and processing for the control of the hand. In addition to the analogue signals from the EMG amplifiers, the signals from the force sensors on the digit tips and the measure of the digit flexion for the position servo are also input to the analogue input. The slip signal is a stream of pulses that is detected by the high speed input capture facility on the chip (see below). The motors are driven via the PWM outputs from the microcontroller.

In addition the 80C196 has a serial output that can drive an RS232 link. This is used for diagnostics, but more importantly, allows the operator to be trained on the use of the hand using a palmtop PC and appropriate software. Finally, the controller can drive a buzzer to generate signals during operation and in error conditions.

The current generation of electronics uses surface mount components (where possible). The entire controller can be realised in a pair of discs 5cm in diameter. A third disc contains the external EPROM, which is used for development purposes. The microprocessor has at least 4K of internal one time programmable memory for the use of the hand in the field.

The criterion that the hand should operate for at least 12 hours on a single charge is an important one. Without confidence in the endurance of the hand the user population will rapidly become disillusioned by the device and reject it. Thus the design of the electronics and software to minimise the current drain was the over-riding concern. The electronics will draw 50mA during normal operation or 25mA when the microprocessor is switched into sleep mode (PARK). This consumption can be reduced further by lowering the microprocessor oscillator frequency from 12MHz to 6MHz. Endurance trials on the mechanism show that it can complete in excess of 2,500 cycles (including full force closure) on a single charge of a 1Ahr battery.

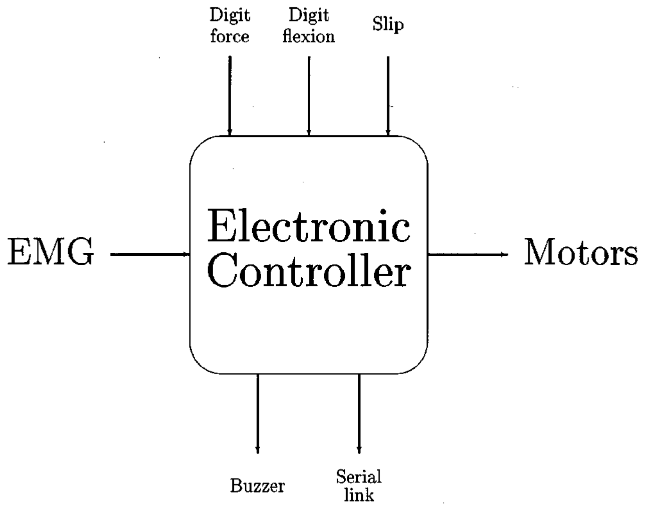

Fig. 4. The electronic controller combines a range of sensory inputs to control the two degrees of freedom within the hand, without the user needing to concentrate on the control.

2.3.1 Slip input. The slip is detected as an acoustic signal.[18] As two surfaces slide past each other some of the energy generated results in a low frequency vibration that can be detected by a conventional microphone. Other methods of detection are possible (for example the detection of the change in normal or tangential forces between the object and the hand).[19,20] The sensor and signal processor's small size and low power consumption contributed to the adoption of the acoustic method.

The microphones used have a wide bandwidth, making them sensitive to a wide range of extraneous signals, but the sensor can be designed to exclude all but the frequencies of interest. In this case the sensor is designed around a rubber tube that contacts with the surface of the external glove (schematic Figure 5). Slip signals are thus mechanically connected to the air inside the tube, while the impedance for any external sounds is far less well matched. The slip signals are generally several orders of magntiude larger than external noises.

An important concern for reliable operation is that the hand should respond in a similar manner despite being used in a wide range of conditions (surface texture, slip speed, etc.). It has been shown[18,21] that if the detected bandwidth is kept narrow (less than 1kHz) and low (from 10Hz), the signals remain broadly similar over a wide range of circumstances. The schematic of the slip processor is shown in Figure 6.

The resulting analogue signal is converted into a stream of pulses of 2.2μs in width. The output from several sensors can then be summed and the result is counted. The derived force demand is made proportional to that value. Once the slip signal is no longer being generated the drive demand is halted.

3. USER TRAINING

The manner of operation of the hand is designed to be as simple as possible. The operation of the hand is demon-

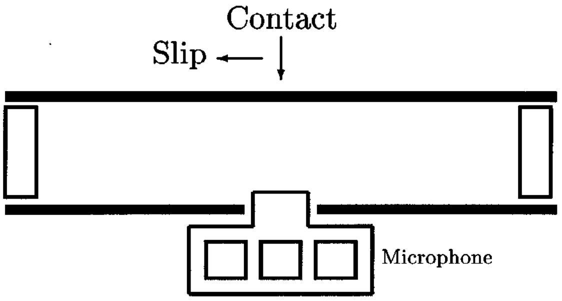

Fig. 5. Schematic of the slip sensor. The vibrations set up as an object slips past the sensor are detected by the microphone in the tube.

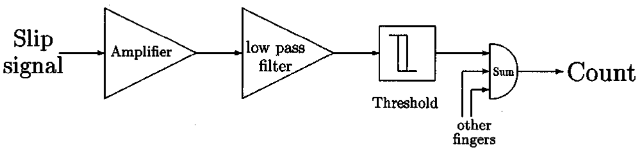

Fig. 6. Schematic of the slip signal processor. The vibration signals are amplified, filtered and converted into a train of pulses that can be counted. The sum is then used as the force demand to the controller.

strated to potential users on a bench mounted hand. A centre biased joystick serves as a mimic for the two myoelectric channels, (which are usually an opposing pair and so only operate singly). Motion of the joystick in one direction simulates one muscle contracting and motion in the other is the second muscle (a button serves as co-contraction). The user is shown the full functionality of the device. Next, electrodes are placed on the skin in a process to find the optimal location of the muscle electrode. They are trained using a screen from a suite of diagnostic software, which runs on a Palmtop PC. The software shows a series of horizontal bars, their length proportional to the EMG input value.[22] The trainee user practices producing clear, deliberate contractions of the msucles.

Once they are able to show control of the two muscles separately and together a second program is run on the PC. This is a simulation of the prosthesis. An animated hand opens and closes in response to the user command. Keyboard input simulates object contact and a generic object is illustrated in the grasp of the hand. Upon release, the object disappears as the hand resets to a precision grip. When confidence in their control is achieved the user can progress to controlling the prosthesis on the bench. Finally, the users are fitted with a conventional prosthesis suspension system, which consists of a closely fitting plastic socket that both supports the device and holds the electrodes in the correct position on the forearm. Additional training in the use of the hand is performed using standard everyday tasks. These tasks use household objects from kettles to hammers. The tasks are designed to encourage the wearer to use the hand in an active role. In addition, abstract objects made of foam strips are used to test the user's ability to control the hand.[13,23] If they apply too much force then the foam strips splay outwards and this is clearly visible to the therapist as well as the user.

4. CONCLUSION

The development of the Intelligent Hand Prosthesis in Oxford has demonstrated that it is possible to construct a practical and functionally sophisticated prosthesis. Tests of the hand in the field are currently underway when assessments of the device's ease of use and longevity will be made.

The technology that is inherent in the hand could be used in other robotic devices. Its small size, weight and cost make it a possible manipulator for teleoperation. In addition, in the rehabilitation setting, a hand could act as a terminal device for a rehabilitation robot. The anthropomorphic nature of the device is particularly appropriate in the domestic setting where most objects the robot is likely to encounter were devised with the human hand in mind.

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