A fist full of sensors

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Abstract. Loss of a natural hand means that the neural connections between the brain and the palm, fingers and thumb are also lost, including any feedback paths e.g. sensing temperature. Equipping an artificial hand with sensors allows for the inclusion of automatic control loops, freeing the user from the cognitive burden of object holding which is similar to the natural low level spinal loops that automatically compensate for object movement. Force, object slip and finger positions are variables that need to be measured in a hand designed for the physically impaired person. A high specification is required for any sensor design.

1. Introduction

1.1 Historical context.
One of the earliest artificial hands was made in the sixteenth century by a French military surgeon called Ambroise Paré (1509-1590) [1]. It had an anthropomorphic shape using spur gears and levers for the movement of individual fingers and was designed for wounded soldiers. Ambroise Paré is regarded as the founder of prosthetics as a science [2]. Thus much of the impetus for the development of artificial limbs came from helping the casualties of war and in more recent times the two world wars. The nineteen fifties and sixties saw an increase in the application of technology in seeking solutions to the problems of artificial prehension. This was also the time of an increase in congenital loss of limbs brought about by the sedative drug thalidomide. Taking this historical background into account, both current and future conflicts will fuel the need for further research and development. Recently, between $25 and $30 million has been initially allocated to prosthetics research in the United States [3].

1.2 Control
Figure 1 shows a basic control loop where the input is the desired output response and the actual output for an artificial hand is finger position or finger-tip force. To implement this system requires a sensor to measure the output variable. In the human, grasping and maneuvering of everyday objects, such as the unconscious holding of a cup of coffee, is brought about by automatic spinal reflex loops. A person is not continuously adjusting the forces produced by ones fingers and thumb to achieve a stable grip on an object. In a similar way the low level control loops in an artificial hand can be dedicated to an electronic controller as shown diagrammatically in figure 2.
1.3 Sensor specification
As well as the normally expected requirements of a sensor, Table 1 shows the more stringent needs of a force sensor for an artificial hand.

**Table 1** Force sensor specification

| Requirement                                      |
|-------------------------------------------------|
| Resolve forces up to 100 N                       |
| High sensitivity to small forces                 |
| Integral power supply                            |
| Lightweight                                      |
| Low cost                                         |
| Little hysteresis                                |
| Low power consumption                            |
| Not susceptible to EM interference               |
| Not easily damaged by large impact forces        |
| Robust                                           |
| Service period of six months                     |
| Simplicity in construction and mounting         |
| Small size with an area less than 100 mm²        |
| Thin in depth for mounting on fingers and palm   |
2. Sensor technology

2.1 Force
An ideal characteristic is shown in Figure 3 where it can be seen that there is more sensitivity at lower forces to allow for the detection of lightweight objects and its slope is monotonically decreasing. This approach is in contrast to the usual desire to make a linear characteristic.

![Figure 3 Ideal force characteristic](image)

Force can be measured in several ways. One simple and successful method has been to use an infra-red LED at one end of an elastic tube with a photo-transistor or diode at the other end to detect the light [4]. If the tube is deformed by the application of a force tangential to the tube the light will be reduced at the receiving end.

Alternatively, placing a magnet near a Hall effect device will produce a output voltage that is proportional to the movement of the magnet [5]. A limitation of this idea is that the current drain is high and hence a sensor will need to be put into sleep mode in order to conserve power requiring an extra signal wire. Also the polarity of the temperature coefficient is not guaranteed, making compensation difficult to achieve in practice.

2.2 Constraints on the number of sensors
Consider an artificial hand that has a mass of 500g. If the total mass of the sensors is 20g then this represents 4% of the total hand mass (bottom line in figure 4). If each sensor weighs 1g then the number of sensors that can be accommodated is 20 (bottom line in figure 5). In contrast 20g is 20% of the total mass for a 100g hand (top line figure 4). If the sensors can be made with a smaller mass then either more sensors can be accommodated or the percentage of a hand’s mass reduced. For example, with 20% of a 100g hand there could be 200 sensors, each having a mass of 0.1g (top line figure 6). Currently, a reasonable target mass for a touch sensor is 1g, making a total of 10g, for a sensor to be placed at the end of each of the five digits and five on the palm surface. Hence the sensors represent 3% for a reasonable target mass of a hand of 350g. There is a clear requirement from the users of artificial hands that designers should make the mass as small as possible, yet in order to increase functionality requires more intelligence in the system and hence more sensors. For a light hand of 200g then if a sensor has a mass of 0.1g (the mass of a small surface mount integrated circuit), then 100 sensors represents 5% of the hand mass. The plots shown in figures 5 and 6 are scalable and can be used for any combination of hand mass, mass of a sensor and percentage of hand mass, for example changing the range from 0.01 to 0.1g for a single sensor results in the vertical axis changing range from 0 to 1000 in figure 5.
2.3 Slip
The human hand takes clues from a variety of sensor information to determine if an object is slipping. In experiments on the automatic control of precision grip, the human reflex loops adjust the gripping force to match the mass of the object being lifted, providing a small safety margin to prevent slips [6]. For an artificial device, a dedicated slip detector is needed and several different types have been studied. One of the most useful is that of a small hearing aid microphone to pickup the small sounds made as an object moves across the finger surface. A limiting factor of this idea is to reduce the impact
of false signals from environmental noise. A promising newer technology is to use thick-film piezoelectric polymers made from lead zirconate titanate (PZT) [7]. A transient output signal is produced from the associated charge amplifier when an object with a rough surface is moved across the sensor surface (figure 7).

![Oscilloscope trace of the output from a charge amplifier as a 100g weight is dropped onto the surface of a PZT slip sensor and then allowed to roll over its surface.](image)

**Figure 7** Oscilloscope trace of the output from a charge amplifier as a 100g weight is dropped onto the surface of a PZT slip sensor and then allowed to roll over its surface

### 2.4 Position
Opening and closing a hand are the first movements that someone will need to make in order to form a grip on an object. Positioning of the fingers and thumb relative to the palm can be achieved in a standard proportional, derivative and integral closed loop control system. A simple solution to measuring the digit position is made with simple potentiometers located at the main pivot point of the finger mechanism (usually corresponding to the metacarpal-phalangeal joint). This design requires attachment of the potentiometers to bearing-shafts of the finger mechanism and can be bulky. An alternative solution is to include a digital shaft encoder at the back of the motors actuating the fingers. On power-up the hand is opened or closed to its fullest extent in order to reset the incremental encoder.

### 2.5 Temperature
Including temperature sensors in the finger tips would allow for the detection of hot objects and either alert the user with an audible signal or allow for the automatic release of an object. This facility may help to protect the hand from damage caused by hot objects although this idea may require the placing of a sensor close to the glove surface in order to stand a chance of responding quickly enough. Incorporating a temperature sensor also allows for environmental compensation should this be necessary (approximate operating range -10 to 50°C).

### 2.6 Control input signals
Signals from the user are derived form the contraction of residual muscles located in the person’s stump which are typically those used to move the wrist (extensor carpi radialis and flexor carpi ulnaris). Surface electrodes with a good instrumentation amplifier are used on the skin surface to measure the small electromyographic (EMG) voltages (order of one microvolt). The two signals are then rectified and low pass filtered creating a delay of about one tenth of a second. Initially, the extensor signal is used as the input in a finger-position control loop. The two signals can then be further processed by a microcontroller to generate states such as open, close, hold, squeeze or release of an object. These states can be determined by simple thresholds or more sophisticated methods such as artificial neural networks.
3. Conclusions and future developments

The lack of sensors in artificial hands and associated controllers has limited their functionality and technological progress. A recent press release has highlighted the desire to investigate an advanced solution exploiting the results from experiments on monkeys, where small electrodes inserted into their brains, have allowed them to move robotic arms by thought (assuming that this is transferable to humans) [3]. Expensive and invasive procedures are not necessarily the panacea but research opens up new designs and amputees will embrace the solution which fits their individual needs. Technology “push” compared to user “pull” both offer the individual a greater choice of prosthetic solutions.

Integration of more than one sensor modality on a single site provides a controller greater flexibility through combining signals in a single communications channel. With touch sensors placed around the finger and palm surfaces, object movement can be found from the combined signals [8]. More than one actuator also allows for the maneuvering of an object with the fingers and thumb.

An integral power supply (table 1) may in future be replaced by the requirement for one that is self powered as this will not only reduce battery size but also allow for the removal of power cables, leading to increased reliability and reduced mass.

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