Improving the functionality of a prosthetic hand through the use of thick film force sensors

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Summary: *A prosthetic hand has been instrumented with a range of sensors to measure grip force with the primary objectives of detecting touch and the onset of slippage of an item grasped by the hand. Two types of sensor have been used for this purpose: piezoresistive sensors to measure and monitor static forces and piezoelectric sensors to measure and monitor dynamic forces. All sensors have been fabricated using thick film printing techniques and their location and placement upon the prosthetic hand has been chosen for optimal performance.*

Keywords: *artificial hand, piezoelectric, piezoresistance, prosthesis, thick film*
Subject category: *10 (Applications)*

1 Introduction

An obvious problem with the majority of prosthetic devices is a lack of feedback control. In the case of a prosthetic hand, for example, the operator is unable to feel an item within the grasp of the hand – the operator has no sense of what it is that they are holding beyond that which can be visually assessed. In certain situations, this could prove to be detrimental (e.g. the user would be unaware if they were holding a very hot or very cold item, possibly resulting in damage to the prosthesis or operator). More generally, the inability to monitor the grip force imposed on a grasped item means that the user can not be totally sure of the security of the grip and could be unaware (or have too little time to respond) should the object begin to slip from their grasp.

An apparent solution to this problem is to include some form of sensing system within the prosthetic device. For the prosthetic hand, such a system might comprise a number of force sensors to monitor grip strength and thermal sensors to measure the temperature of a grasped object. Such a system would be able to alert the operator to take some form of action should an object begin to slip from grasp or was too hot to handle. Better still would be an autonomous system that is capable of taking the appropriate action itself with the minimum amount of operator intervention, thereby removing the burden of responsibility from the user. This has been the direction taken by a number of research groups operating in this field and is also the philosophy adopted by the authors.

It is clear that to monitor grip strength and compensate for slip will require a sensor system that comprises both static and dynamic force sensitive elements. What is not so evident is the choice of enabling technology to produce such sensors. Indeed, a brief examination of the literature shows that a large, disparate range of sensor technologies has been evaluated for their suitability in such systems, spanning optical [1], capacitive [2], hall effect [3] and piezoresistive [4].

In identifying a suitable sensor fabrication technology for use in a prosthetic hand, the standard electrical features of low temperature drift, good accuracy and good repeatability are required. In addition, the specifications listed in Table 1 are also highly desirable. Many sensor enabling technologies meet some of these requirements but few, if any, meet them all. Previous work has identified thick film as a suitable fabrication technique for the design of low cost accurate force sensors [5-7]. The simplicity of this technology also means that production times are relatively short, enabling the quick prototyping and evaluation of candidate sensor structures.

2 Description of the prosthetic hand

The prosthetic hand used in this project (see Figure 1) is a prototype myoelectrically driven device designed at the University of Southampton and described elsewhere [8]. In use, the hand is controlled by the electrical signals produced by any convenient flexor-extensor muscle pair. Signals from these muscles form the inputs to an intelligent, state driven controller which interprets this information before moving the digits of the hand into one of several prehensile positions including hold, squeeze, grip and release, as well as some of the more common hand postures. To perform this function, each finger on the hand is individually controlled by its own dedicated motor, allowing independent flexion and extension of each mechanical digit.

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

Table 1: Specifications for a prosthetic hand force sensor.

The fingers are constructed from a number of interconnecting links, which when driven by the motors cause the fingers to open or close in a natural curl pattern. The finger links are fabricated from a carbon fibre epoxy composite to reduce the overall mass.

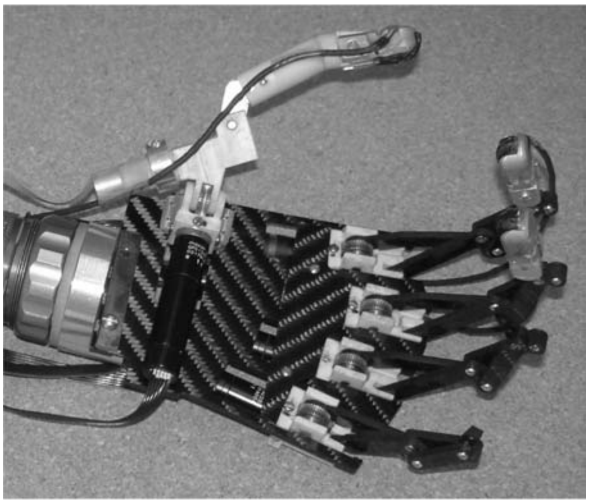

Figure 1. The Southampton-Remedi prosthetic hand [8].

The thumb is a two part assembly controlled by two orthogonal motors giving 2 degrees of freedom in movement. Moving the thumb in combination with any number of the finger units allows a range of natural grip postures to be adopted.

The palm of the prosthetic hand is also made from a carbon fibre epoxy composite to minimise the mass. The palm provides a common base for the location of all the finger motors as well as providing space for the attachment of force sensors and some electronic conditioning circuitry.

3 Sensor design and location

The principal objective of this research program is to detect and correct for the onset of slip in the grip of a prosthetic hand, without the need of user intervention. To achieve this, two types of force sensor will be utilised: static force sensors to realise absolute force measurement and dynamic force sensors used as simple microphones to 'listen' for the possible beginning of slip. The number of sensors required to adequately perform this task and their location upon the hand will be determined throughout the course of the project.

A second objective of this research is to detect and measure the temperature of a grasped object. This will be achieved by monitoring resistance changes in a number of (calibrated) thick film thermistors located over the inner surfaces of the hand.

3.1 System concept

The manner by which the force sensors are to be used in this application is as follows. As the hand initially closes around an object, the moment of first contact between the object and the inner surfaces of the prosthetic hand will be detected by both the dynamic (near instantaneously) and static force sensors located on the palm and on the palmar (inner) surfaces of the fingers. As the hand continues to close, the static force sensors directly measure the forces exerted upon the object. By continuously measuring the grip forces allows the decision as to when the action of closing the hand should cease (and the current grip force be maintained) to be made by some local intelligence.

If the object begins to slip from the grip of the hand, the vibrations produced through friction are detected by the dynamic force sensors that are also located on the finger tip palmar surfaces. This information is then used to re-activate the drive motors of the hand and increase the grip force, with the process being constantly monitored by the static force sensors.

3.2 Modifications to finger link system

In the initial stages of this research program it was decided to locate the sensors on just the finger tips – a single static force sensor, a single dynamic force sensor and a single temperature sensor for each of the four fingers. It was also decided that the best mechanical structure on which to implement these sensor devices would be a cantilever beam. Ideally, this would be mounted at the far end of the finger such that it lay symmetrically about the central long axis of the finger. This would help to reduce force measurement errors due to shear affects caused, for example, by off-axis loading of the cantilever.

Unfortunately, the finger link system of the existing prototype prosthetic hand is not suitable to attach a cantilever such that it is inline with the finger long axis. Hence it has been necessary to redesign the finger link system to accommodate the required placement of the cantilever structure. The modified finger link system is shown in the diagram of Figure 2. This has been modelled to ensure that the trajectory of the finger tip during opening or closing of the hand is not significantly different from that of the original version.

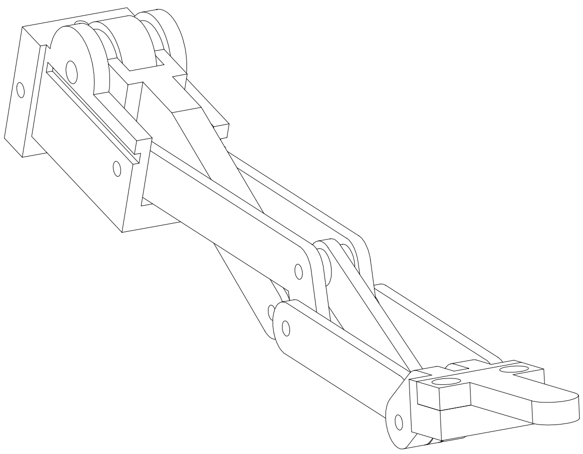

Figure 2: Modified finger link system. The knuckle block containing the drive wheel assembly is shown on the left of the diagram, and the cantilever finger tip is shown to the right.

3.3 Sensors

The force and temperature sensors are printed upon the top (palmar) surface of the cantilever structure, as viewed in Figure 2. The cantilever is machined from grade 304 stainless steel and has a nominal thickness of 3mm, which may be changed (along with the beam width) to adjust the force sensitivity or the force measurement range of the device. The other dimensions for this cantilever structure are shown in Figure 3 along with the individual patterned thick film layers that compose the sensor systems. Prior to printing any of the sensor structures onto the surface of the cantilever, it must first be electrically insulated with a thick layer of a screen printable dielectric material.

The static force sensors exploit the piezoresistive properties of commercially available thick film resistive pastes. When printed and fired with electrically conductive end terminations in a planar configuration, these pastes form electrical resistors that exhibit a proportional change in their resistance with applied strain (gauge factor typically ranging from 8 to 10 [9]). The resistors are arranged on the cantilever in a classic resistance bridge circuit, as shown on the left side of Figure 3. Two of the four resistors that form the bridge circuit are located at the theoretical position of maximum strain (for a given beam deflection) whilst the remaining two are located in a region of zero strain. When a force is exerted upon the inner surface of a finger tip, the mechanical cantilever is deflected and the resultant strain causes a proportional change in the ratios of the sensor resistors that constitute the bridge circuit. This may be easily measured with a simple differential instrumentation amplifier.

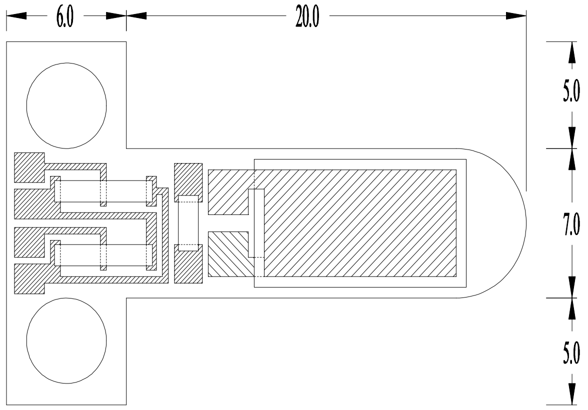

Figure 3: Dimensions of finger tip cantilever (mm) and location of sensors. The patterned areas represent different thick film layers.

The dynamic force sensors are fabricated from PZT (lead zirconate titanate) that has been rendered into a form that is suitable for thick film printing [10, 11]. This material is piezoelectric, i.e. it generates an electric charge when mechanically deformed. Multiple layers of this material are printed and fired upon an underlying electrically conductive pad before a final conductive pad is printed upon the top surface to yield a vertical stack, as shown to the right side of Figure 3. After polarization in an electric field of strength of approximately 4 MVm^{-1} and temperature in the range 150°C to 200°C, these multi-layered devices exhibit a d_{33} piezoelectric coefficient of the order of 130 pCN^{-1}.

Each dynamic force sensor covers a large proportion of the available area of each finger tip cantilever and is used to detect any sudden variations in the force over the finger tip surfaces, which could be indicative of an object slipping from grasp. The change in force over the surface area of a single piezoelectric sensor causes a proportional change in the charge distribution of the PZT layer which is readily measured by an impedance balanced charge amplifier.

An estimation of an object's temperature held within the prosthetic hand can also be ascertained by the use of thick film resistors or thermistors printed upon the surfaces of the mechanical hand at various locations. A single thermistor element is shown located between the force sensors on the finger tip cantilever in Figure 3. By monitoring the resistance of this element, the localised temperature may be inferred. Such devices additionally provide first order temperature compensation for the force sensors.

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