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Thick-film force and slip sensors for a prosthetic hand

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Abstract

In an attempt to improve the functionality of a prosthetic hand device, a new fingertip has been developed that incorporates sensors to measure temperature and grip force and to detect the onset of object slip from the hand. The sensors have been implemented using thick-film printing technology and exploit the piezoresistive characteristics of commercially available screen printing resistor pastes and the piezoelectric properties of proprietary lead-zirconate-titanate (PZT) formulated pastes. The force sensor exhibits a highly linear response to forces up to 50 N with a maximum hysteresis of less than 1.4% of full scale. When configured as a pseudo half-bridge measurement circuit, the force sensor demonstrates superior insensitivity to the position of the force on the fingertip than when configured as a classic half-bridge circuit. The force sensor response is also extremely stable with temperature, typically showing variation in the output response of less than ±0.04% over the temperature range −10 °C to +35 °C when loaded with forces up to 10.8 N. The ability of the piezoelectric PZT vibration sensor to detect small vibrations of the cantilever, indicative of object slip, has also been demonstrated.

Keywords: Piezoelectric; Piezoresistance; Prosthesis; Pseudo half-bridge; Thick-film

1. Introduction

A problem with many prosthetic hands is the limited functionality that they offer. Generally a prosthetic hand is restricted in the number of degrees of freedom in the movement of its digits permitting only a narrow range of grip postures. Typically only the thumb and one finger (or a group of fingers acting together) can be actively moved. For example, one of the most technologically advanced commercial prosthetic hands, the Otto Bock SensorHand™, is limited to movement of just the thumb and two other fingers [1]. Furthermore, many prosthetic devices lack any form of feedback control system meaning that the operator has no sense of what they are holding beyond that which can be determined visually. This has the disadvantage that the prosthetic device could be damaged if, for example, an object that is too hot or too cold were to be grasped. Similarly, a lack of knowledge of the forces imparted by the hand during a grip posture may also result in damage to the grasped object, or at the very least, to the establishment of an insecure grip with the possible consequence of slip occurring.

To address these problems, new designs of prosthesis are required with independent control in the movement of all of the digits to assist in adaptive grasping. Sensors should also be incorporated within each digit to help determine their relative position when forming a particular grip pattern and to record the levels of force exerted by each digit. Localised intelligence in the form of a simple microcontroller could be used to monitor and adjust the levels of force as necessary, permitting the dynamic adjustment of the grip pattern. All of this could be performed independently of the user, thereby removing the burden of responsibility.

This paper describes the design of a new force sensitive fingertip that supports a number of thick-film force sensors and a temperature sensor. Two different types of force sensor have been included: a static force sensor to measure and monitor forces exerted by the fingers during a grip posture and a dynamic force sensor, operating as a vibration sensor,

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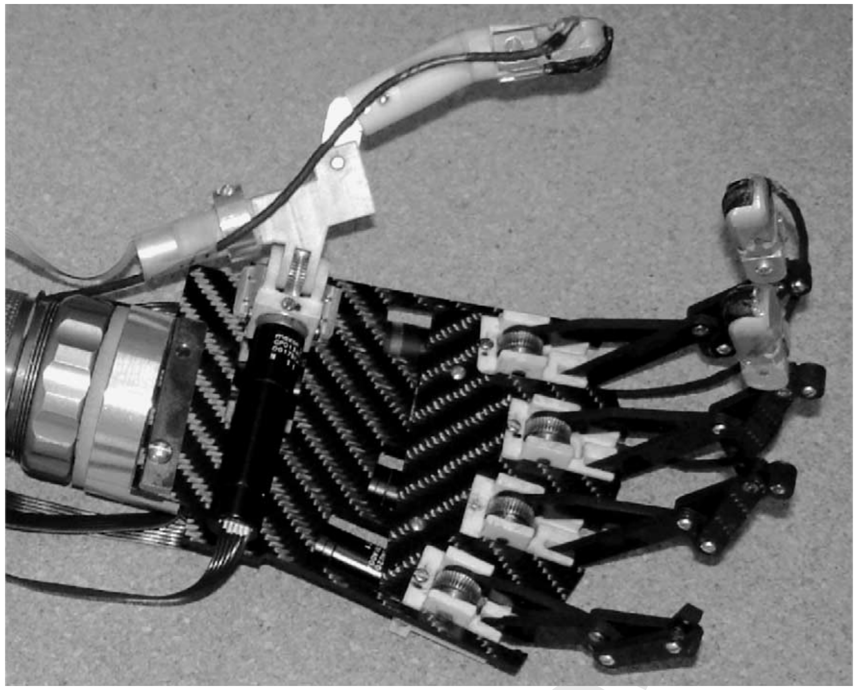

Fig. 1. Skeletal structure of the Southampton myoelectric prosthetic hand showing some early examples of photo-acoustic proximity/slip sensors on two of the fingertips and thumb [2].

to detect the onset of slip. The fingertips act as simple mechanical cantilevers when attached to the distal ends of the fingers of a prototype myoelectrically controlled prosthetic hand (shown in Fig. 1 [2]). 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 [3,4]. To perform these functions, each finger is individually controlled by its own dedicated motor allowing independent flexion (closing) and extension (opening) of each mechanical digit in a natural anthropomorphic curl pattern. The extent of finger closure can be ascertained at any time from the signals derived from rotational position encoders included on the motor drive shafts.

Each finger is constructed from a number of interconnecting links, the pivot points of which are coincident with the positions of the human finger joints. The finger links and palm of the hand are fabricated from a carbon fibre epoxy composite to reduce the overall mass of the hand (approximately 550 g including wrist connector). The thumb is manufactured from Hilube Vesconite™ and is controlled by two orthogonal motors giving 2 degrees of freedom in movement, simulating the abduction, adduction, flexion and extension movements of the natural thumb. In conjunction with the four independently controllable fingers, the hand therefore has a total of 6 degrees of freedom in movement allowing a range of natural grip postures to be adopted.

As the hand closes around an object during operation the fingertip cantilevers are bent against their supports creating a change in the surface strain of the fingertip. Since the strain produced is directly proportional to the magnitude of the force bending the fingertip, the force may be determined with a suitably positioned strain sensor. If an object is not held securely within the hand and begins to work itself free, the slip sensors will detect any movement of the object in the form of a vibration signal and initiate closure of the relevant finger (or fingers) to tighten the grip. The magnitude of these grip forces will be continuously monitored by the static force sensors in each fingertip and their information used to decide when the new grip is tight enough and to stop closing the fingers. Similarly, if the measured temperature of an object being gripped is determined to be potentially damaging to the prosthesis, the hand is commanded to cease closing the fingers around that object.

In use, the skeletal structure of the prosthetic hand shown in Fig. 1 will eventually be entirely enclosed within a rubberised glove to give the hand a more aesthetic look.

2. Sensor array design

The fingertip cantilever supports independent force, slip and temperature sensors on a common stainless steel platform. Each of these sensors have been produced using thick-film technology, exploiting respectively the piezoresistive, piezoelectric and thermo-resistive effects of both commercial and proprietary thick-film materials. A single fingertip can-

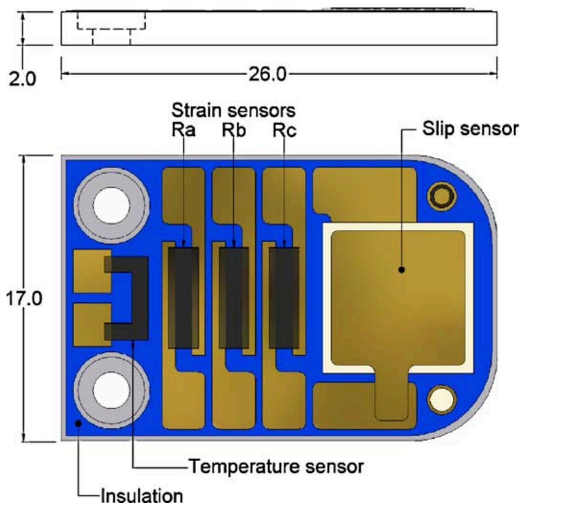

Fig. 2. Dimensions of fingertip cantilever (mm) showing the locations of the various sensors.

tilever sensor array is shown in Fig. 2. The dimensions of the cantilever have been chosen to mimic the size of an average human adult male fingertip and also to allow the measurement of fingertip forces up to 100 N without exceeding the maximum working strains of the materials used. The figure shows that the cantilever design includes two recessed holes to allow it to be secured to the distal end of each finger using metric M2 size bolts. The beam root axis is located approximately 6 mm from the flat end of the cantilever (left hand side as viewed in the figure), giving an effective cantilever length of 20 mm.

2.1. Static force sensor

It has been well documented that thick-film resistors exhibit proportional resistance changes with applied strain (the piezoresistive effect) with a strain sensitivity higher than that of conventional metal foil strain gauges [5–8]. This, when coupled with the ability to print the thick-film resistors to any size and at any location upon the surface of the cantilever make this technology an ideal candidate for strain sensing in this application.

Conventionally, strain sensors are usually arranged in Wheatstone bridge circuits with up to four individual sensor components located at the root of the cantilever and on both sides, thereby exploiting strains of compression and tension to maximise measurement sensitivity. However in this application only the top surface of the cantilever is used (to reduce costs and processing time) and therefore only tensioning strains are measured as the fingertip is bent by a force. This still allows the arrangement of the thick-film resistors into a classic half-bridge circuit, although this would prove to be unsuitable for this application. The reason for this is that the strains experienced at the root of the beam are the same when a force of arbitrary magnitude is located at the tip of the beam and when a force of twice that magnitude is located half-way along the beam (assuming ideal beam behaviour). Such an arrangement would therefore be unable to distinguish between these two situations.

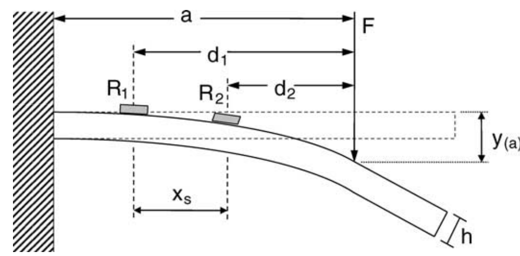

Fig. 3. Location of two strain sensing elements R_1 and R_2 upon the surface of a cantilever beam deflected by an amount $y_{(a)}$ when subjected to a force F at a distance a from the beam root.

To overcome this problem, a position-independent force sensor has been designed that uses two independent strain sensor elements located upon the fingertip cantilever at different distances along its length. When a force deflects the cantilever each of these sensors experiences a different strain level with resultant changes to their resistances. It can be shown that the ratio of the normalised changes in resistance of the two sensors indicate the position of the force on the fingertip whilst the magnitude of the normalised change in resistance gives a position-dependant measure of the force level. Hence by measuring the normalised changes in resistance of both sensors, a position-independent value for the force can be derived. The principle is illustrated with reference to Fig. 3 and described below.

Fig. 3 shows two resistive strain sensors R_1 and R_2 located upon the top surface of a cantilever beam of thickness h, each a different distance from the beam root and separated by a distance x_s. When a force F acts upon the beam at a distance a from the beam root, the beam is deflected by an amount $y_{(a)}$. Under these conditions the respective strains ε_1 and ε_2 experienced by the two sensors are given by:

$$\varepsilon_1 = \frac{3d_1h}{2a^3}y_{(a)} \quad (1)$$

$$\varepsilon_2 = \frac{3d_2h}{2a^3}y_{(a)} \quad (2)$$

Here, d_1 and d_2 are the distances of the two sensors from the position of the force. The size of the deflection at the point where the force makes contact with the cantilever, $y_{(a)}$, is given by:

$$y_{(a)} = \frac{Fa^3}{3EI} \quad (3)$$

where I is the second moment of area of the beam and E is Young's modulus for the beam material. For a rectangular beam of width b and thickness h, I is given by:

$$I = \frac{bh^3}{12} \quad (4)$$

and so Eq. (3) may be rewritten as:

$$y_{(a)} = \frac{4Fa^3}{Ebh^3} \quad (5)$$

Substituting Eq. (5) into Eq. (1) gives a force-dependant value for the strain in sensor R_1, thus:

$$\varepsilon_1 = \frac{6d_1F}{Ebh^2} \quad (6)$$

From Eqs. (1) and (2) it can be seen that the ratio of the strains in the two sensors is directly proportional to the ratio of their distances from the force, i.e.

$$\frac{\varepsilon_1}{\varepsilon_2} = \frac{d_1}{d_2} \quad (7)$$

Fig. 3 also shows that the distance d_2 can be expressed in terms of the sensor separation distance x_s through the relationship $d_2 = d_1 - x_s$. Substituting this expression for d_2 into Eq. (7) and re-arranging yields:

$$d_1 = \frac{\varepsilon_1 x_s}{\varepsilon_1 - \varepsilon_2} \quad (8)$$

Substituting for d_1 into Eq. (6) gives:

$$\varepsilon_1 = \frac{6F}{Ebh^2}\frac{\varepsilon_1 x_s}{\varepsilon_1 - \varepsilon_2} \quad (9)$$

From which an expression for the force may be derived:

$$F = (\varepsilon_1 - \varepsilon_2)\frac{Ebh^2}{6x_s} \quad (10)$$

The strains experienced by the two sensors can be found through the direct measurement of the normalised changes in resistance of the sensors using the definition for gauge factor, G, namely:

$$G = \frac{\delta R/R}{\varepsilon} \quad (11)$$

Here, δR is the change in resistance due to a strain ε, from a previously unstrained value of R. Assuming that the gauge factors for both sensors are identical, which is not unreasonable considering that both thick-film resistors are processed at the same time with the same paste, Eq. (10) may be re-written in terms of the measured changes in resistance of the two sensors:

$$F = \frac{Ebh^2}{6Gx_s}\left(\frac{\delta R_1}{R_1} - \frac{\delta R_2}{R_2}\right) \quad (12)$$

Hence, a position-independent measurement of the force on the fingertip can be determined simply by measuring the difference in the normalised changes in resistance of the two sensors.

Closer inspection of Eq. (12) reveals that a trade-off exists between the force sensitivity and the separation distance between the two sensors. If the separation distance x_s is minimised, the un-bracketed term of Eq. (12) is maximised. However, as x_s is reduced the difference in the strains experienced by the two sensors is reduced and the bracketed term of Eq. (12) is lowered. Since the latter term is the actual property that is measured it would be prudent to arrange for this term to be as large as possible to achieve good measurement resolution. Moreover, as x_s is increased the portion of the fingertip upon which a practical measurement of force can be made is reduced. The force must always act on that portion of the cantilever beam between the set of sensors and the beam tip to ensure that both sensors experience a force-dependant strain (i.e. d_1 and d_2 in Fig. 3 must both be positive). The length of beam between the position where the force acts and the beam tip experiences no force induced change in the surface strain.

In order to determine a practical value for x_s the force sensor design shown in Fig. 2 includes three identical thick-film strain sensitive resistors located at different distances from the cantilever beam root. This arrangement permits the investigation of three combinations of resistor pairs. For the purposes of this paper, these three strain sensing resistors are referred to as R_a, R_b and R_c with R_a being the closest to the beam root and R_c the closest to the tip (free end). Each resistor measures 6 mm in width and 1 mm in length (between electrodes) and are positioned 3 mm apart along the cantilever beam length with the first of these resistors located 1.3 mm from the beam root axis.

In use it may prove impractical to perform two independent measurements of resistance change. For example, the alternating measurement of independent resistors means that a truly continuous measurement of fingertip force cannot be achieved; the time difference between measurements can result in dramatic differences in the cantilever strain distribution when the finger is closing quickly around an object. In addition, the time required to perform a complete measurement will limit how quickly a decision can be made by a local intelligent controlling system to open, close or stop the finger. The shorter this time interval can be made, the better.

A resistance-measuring circuit based on the classic Wheatstone bridge is therefore proposed as being suitable to provide a continuous force signal in accordance with Eq. (12). The circuit, shown in Fig. 4, is a pseudo version of the half-bridge arrangement. In this version, both of the strain

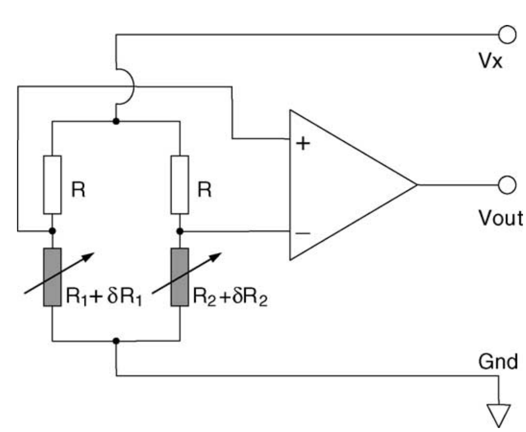

Fig. 4. Pseudo half-bridge measurement circuit for static force sensor.

sensitive resistors are located in the bottom half of each arm of the circuit (shown shaded). The output of this circuit normalised with respect to the excitation voltage, V_x, is approximated by:

$$\frac{V_{out}}{V_x} = k\left(\frac{\delta R_1}{R_1} - \frac{\delta R_2}{R_2}\right) \quad (13)$$

With reference to Eq. (12) it can be seen that the normalised output voltage of the pseudo half-bridge circuit is directly proportional to the position-independent force with the constant of proportionality, k, given by certain physical properties of the beam, the gauge factor of the sensor and the sensor separation distance.

2.2. Slip sensor

The slip sensor utilizes the piezoelectric properties of lead-zirconate-titanate (PZT) which has been rendered into a suitable format in our laboratories for thick-film screen printing [9]. The piezoelectric effect describes how electrical charge is liberated within certain polycrystalline materials due to mechanical deformation of the material. The PZT layer is printed as a square pattern of side 9 mm and approximate thickness of 100 μm between two gold electrodes (with effective common area of 8 mm × 8 mm) in a sandwich structure as shown in Fig. 2. After printing and firing, the PZT layer must be poled in an electric field to initiate the piezoelectric properties.

The slip sensor operates as a simple vibration sensor producing a charge that is proportional to the level of vibration on the surface of the fingertip. When an object is gripped by the prosthetic hand, any movement by the object that indicates the beginning of slip will produce a vibration in the cantilever and is promptly detected by the sensor and readily converted to a measurable voltage through the use of a charge amplifier.

2.3. Temperature sensor

The temperature sensor consists of a simple reverse-‘C’ pattern (width 1 mm and effective length of 6.5 mm) of a positive temperature coefficient thermistor paste printed between the two mounting holes on the fingertip surface. The thermistor paste chosen demonstrates a highly linear relationship between resistance and temperature with a quoted temperature coefficient of resistance (TCR) of the order of 4100 ± 500 ppm/°C over the temperature range −55 °C to +125 °C. The temperature sensor is used to indicate if an object being gripped is either too hot or too cold for the prosthesis as well as providing temperature compensation for the force and slip sensors should this prove necessary.

3. Sensor array production

Apart from the PZT thick-film paste used in the construction of the slip sensor, all other thick-film pastes were supplied by Electro Science Laboratories (ESL) through their United Kingdom distributor Agmet (UK). The grade of stainless steel used for the substrate was bright annealed AISI 430S17 and was cut and machined to the required dimensions by wire erosion. Before printing the various thick-film materials upon the stainless steel cantilevers, their surfaces were thoroughly degreased using acetone followed by rinsing in de-ionised water. No other pre-processing surface treatment was required.

The proprietary PZT paste was formulated by mixing ball-milled and attritor-milled PZT-5H powders supplied by Morgan Electro-Ceramics Ltd. in a 4:1 ratio by weight with a Ferro 7575 lead borosilicate glass (10 wt.%) [9]. The resultant powder was then blended with a standard thick-film organic vehicle (ESL 400) to produce a thixotropic paste with a viscosity of approximately 59 ± 2 Pa s (measured with a Brookfield CAP 1000+ viscometer, spindle #3, 10 rpm at a temperature of 25 °C).

To ensure electrical isolation of the various sensor components from the stainless steel fingertip the surface of the latter was electrically insulated by successively printing and firing a number of layers of a thick-film dielectric paste (ESL 4986) to a combined post-fired thickness of approximately 80 μm. This particular dielectric paste has been specifically formulated as an insulation layer for type 430 stainless steels, having a closely matched value for its coefficient of thermal expansion. A gold conductor paste (ESL 8836) was then printed and fired to define the electrodes, interconnect and interface pads of the various sensors (approximate post-fired thickness of 10 μm). This was followed by the printing and firing of a double layer of the proprietary PZT paste over the bottom electrode of the slip sensor to an average post-fired thickness of 100 μm. Next, a gold conductor paste (ESL 8836) was printed and fired over the top surface of the PZT layer to form the top electrode of the slip sensor (approximate post-fired thickness of 15 μm). Finally, a resistor paste with nominal sheet resistivity of 10 kΩ/□ (ESL 3914) and a thermistor paste (ESL PTC2611) with a resistivity of 10 Ω/□ were printed as single layers and co-fired (approximate post-fired thickness of 12 μm). These two resistive materials respectively form the static force sensor and the temperature sensor. All layer firings were performed in a BTU 6-zone belt furnace with a peak firing temperature of 850 °C, temperature ascent and descent rates of approximately 50 °C/min and total cycle time of 60 min except for the PZT layers where the peak temperature was raised to 950 °C.

After fabrication, the PZT slip sensors on individual cantilevers were poled in a dc electric field (field strength of approximately 4 MV m^{-1}) at a temperature of 150 °C for 30 min. The electric field was applied directly to the slip sensors by connecting a high tension voltage source between the sensor electrodes. The devices were then allowed to cool to room temperature whilst the electric field was maintained across the PZT layer. The d_{33} piezoelectric coefficient of a number of samples (a metric for the vibration sensitivity) was then measured using a Take Control PM35 piezometer, yielding an average value of 46 ± 2 pC N^{-1}. This is significantly lower than the bulk value of 593 pC N^{-1} reported by the manufacturer of the PZT powder [10]. This is partly due to the dilution effect of the glass mixed in with the PZT powders and as a result of the different processing conditions affecting the stochiometry. In addition, it has previously been observed that the very act of fabricating a PZT sensor on a stiff substrate material introduces a clamping effect that restricts the movement of the PZT layer and thereby reduces the measured d_{33} coefficient [11].

4. Experimental results

4.1. Static force sensor

To evaluate the performance of the static force sensor, the resistance values of the three thick-film resistors were measured on a number of devices under various fingertip loading conditions. Resistance measurements were made using a $6\frac{1}{2}$ digit resolution multimeter in fixed range with a moving average filter of 20 readings depth (Keithley 2000 DMM). Measurements were performed using 4-wire techniques for improved accuracy and resolution.

From the recorded resistance data simulations of the output response of a pseudo half-bridge circuit were modelled using the various pair combinations of the three resistors. These simulated results are presented through the following sections and where appropriate, offset compensation has been applied so that the simulated output is always equal to zero under zero force conditions. This is accomplished by setting the values of the passive resistors in each arm of the bridge circuit equal to the unstrained values of the sensor resistors in the same arms. In practice, this would be achieved by replacing the passive resistors of the bridge circuit with variable types that can be adjusted under microprocessor control each time the finger is in the fully open position and consequently when the fingertip strain sensors are unstrained.

The decision to model the pseudo half-bridge response rather than physically hard-wire the resistor pairs into a real measurement circuit was taken since it was felt that the direct measurement of individual resistance values may prove more informative in explaining observed responses.

4.1.1. Linearity

The static force sensor was evaluated by securing the fingertip structure to a purpose built test rig and then loading and unloading the fingertip with masses equivalent to a total of 50 N. An example of the changes in resistance observed as forces at the tip of the cantilever were both increased and decreased in 2 N increments is shown in Fig. 5. To a good approximation the changes in resistance of each of the three resistors demonstrates a linear relationship with applied force. The figure also shows that the gradients of the characteristics vary between the three resistors, with sensor R_a showing the greater sensitivity and sensor R_c showing the lowest. This is a consequence of their positioning upon the cantilever, with sensor R_a the closest to the beam root and therefore experiencing the greater level of strain for any particular force.

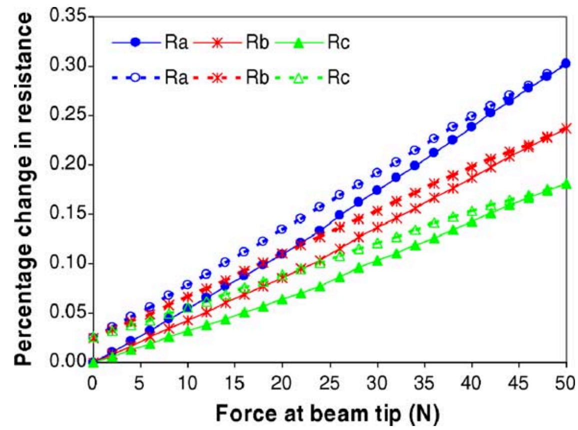

Fig. 5. Percentage change in resistance of the three thick-film resistors as a function of force at the cantilever tip.

The results in Fig. 5 also show that there is an offset in the unstrained resistance value for no applied load and that the level of this offset is common to all three sensing resistors. This is a consequence of hysteresis within the system, which is clearly evident from these results. The source of the hysteresis may be inherent due to the effect of particular mechanical properties of the stainless steel cantilever (e.g. stiffness) and/or it may be characteristic of the thick-film resistors themselves.

Using the experimental data from Fig. 5 the pseudo half-bridge circuit response was modelled as a function of the force at the cantilever tip. Results are displayed in Fig. 6 for each pair combination of resistors acting as the active elements in the bridge circuit. Only the results as the masses were added to the cantilever beam (i.e. increasing force) are shown. The simulated results for when the masses were removed are not shown since these are practically identical. The results show that all three sensor pair combinations exhibit good linearity in their responses with sensor pair R_a and R_c demonstrating twice the measurement sensitivity of the

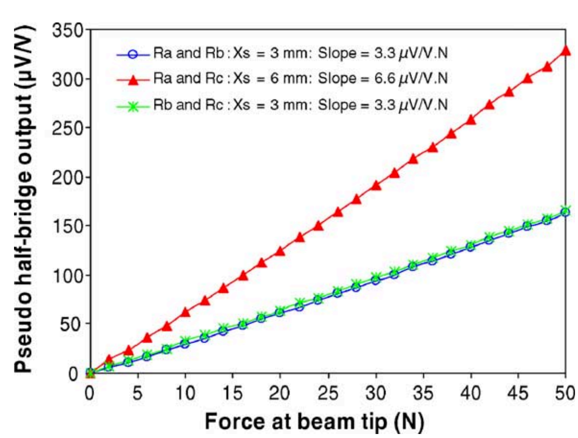

Fig. 6. Simulated pseudo half-bridge output as a function of cantilever tip force for all sensor combinations.

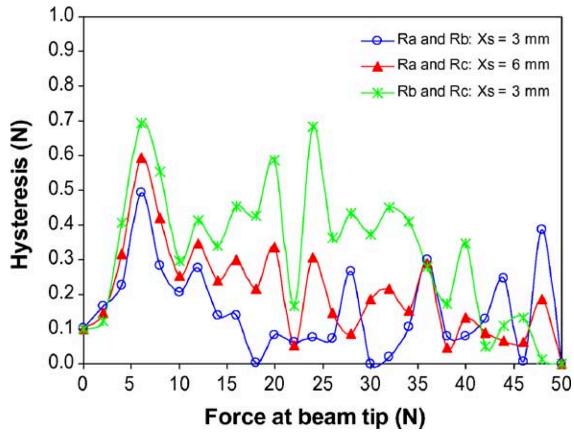

Fig. 7. Hysteresis in simulated bridge output as a function of cantilever tip force for all sensor combinations.

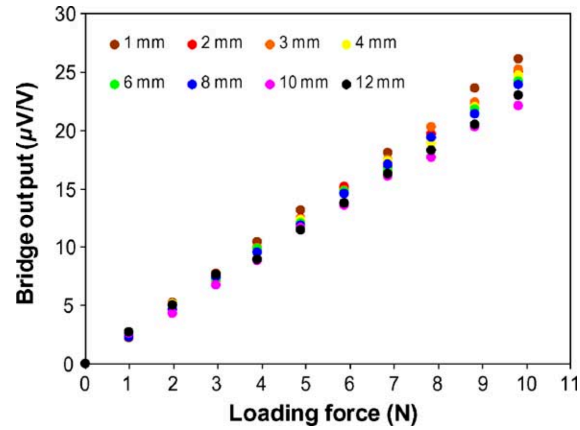

Fig. 8. Simulated bridge circuit response as a function of loading distance from the cantilever tip based on measured resistance changes in sensors R_a and R_b.

other two sensor combinations. This is expected since this sensor pair is separated by the greatest distance and therefore experiences the greatest difference in strain levels between the pair. This is compensated in Eq. (12) by the presence of the sensor separation distance (x_s) in the denominator of the constant of proportionality. Applying this compensation to the measured gradients of the traces in Fig. 6 gives a design value for the force measurement sensitivity of 1.1 μV/V N per millimetre of sensor separation distance.

4.1.2. Hysteresis

The hysteresis in the simulated response of the pseudo half-bridge circuit as a function of cantilever tip force is shown for each combination of resistor pairs in Fig. 7. Here, the hysteresis is defined as the difference in the simulated bridge output voltages using resistance data recorded when masses were added to the cantilever tip and as they were removed. The difference value is then converted to an equivalent value of force using the gradients of the traces in Fig. 6. The results show that the general level of hysteresis is quite low. The maximum value of 0.7 N, equivalent to an error of 1.4% of the full scale range of forces investigated, occurs for that pair of resistors that experience the lowest strain levels (sensors R_b and R_c). The lowest level of hysteresis occurs for resistor pair R_a and R_b, which is the closest pair to the beam root and experiences the largest strain levels. These levels of hysteresis are far lower than might at first be suggested from the data shown in Fig. 5. This is a consequence of the fact that despite the obvious difference in the characteristics of individual resistors between loading and unloading masses at the cantilever tip, the differences between the changes in resistance of pairs of resistors track extremely well under these two different conditions.

4.1.3. Effect of load position

The effect of the position of the force on the response of the static sensor was investigated by performing similar mass loading experiments at different positions along the length of the fingertip. Data from resistance measurements were used to model the output response of the pseudo half-bridge circuit. A typical result based on the measured changes in resistance of the pair of resistors closest to the cantilever beam root (i.e. sensor combination R_a and R_b) is shown in Fig. 8. Very similar results are obtained for the other two combinations of strain sensor.

Fig. 8 shows that there is some variation in the bridge circuit response with the position of the force. In general, as the force is moved further from the cantilever tip and toward the strain sensing resistors, the force measurement sensitivity of the circuit decreases. This is demonstrated more clearly in Fig. 9 where the slopes of the traces from Fig. 8, normalised with respect to the slope at the 1 mm distance, are plotted as a function of the distance from the cantilever tip. For comparative purposes, the modelled equivalent response for a classic half-bridge measurement circuit (where the two active resistors are diagonally opposed in the two arms of the bridge circuit and experience the same strain levels) is also shown.

Fig. 9 shows that the static force sensor measurement sensitivity (or resolution) is dependant upon the position that the

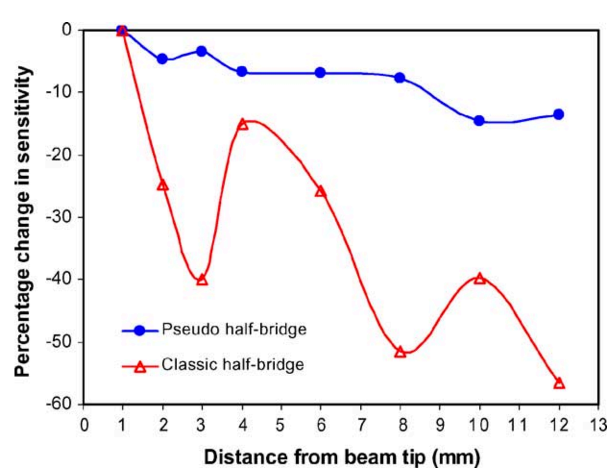

Fig. 9. Comparison of static force sensor measurement sensitivity as a function of loading position for two different half-bridge circuit configurations.

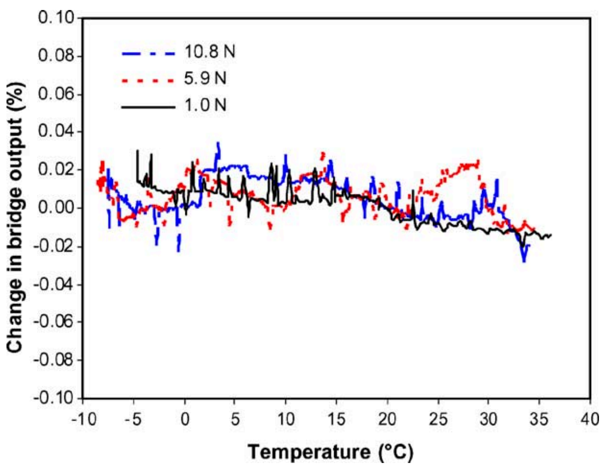

Fig. 10. Percentage change in bridge output as a function of temperature and cantilever tip force.

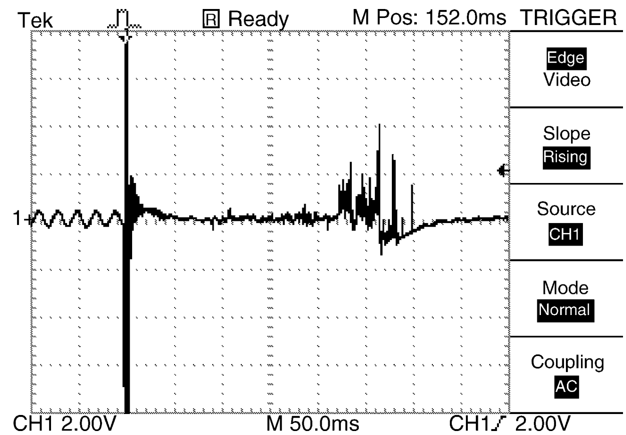

Fig. 11. Oscilloscope trace of output from charge amplifier as 100 g mass is dropped onto the surface of a PZT slip sensor and then allowed to slide over its surface. Horizontal axis: 50 ms per division; vertical axis: 2 V per division.

force acts on the beam for both bridge circuit models. However, the extent of the dependency is lower when the resistors are configured in the pseudo half-bridge arrangement. From results obtained over a number of similar experiments, the measurement resolution of the pseudo half-bridge version of the static force sensor has been observed to decrease from its maximum value at a rate of between 1 and 2% for every millimetre the acting force moves closer to the sensor.

4.1.4. Effect of temperature

The effect of temperature on the static force sensor response was investigated by measuring the sensor resistance values in a Vötsch VT4021 environmental chamber at temperatures between −10 and +40 °C and with different loads applied to the tip of the cantilever. A typical set of results is shown in Fig. 10, revealing an extremely low sensitivity to temperature of less than ±0.04% change in bridge output over the temperature range and loading conditions investigated. This is a result of first order temperature compensation inherent in the bridge circuit architecture, enhanced by the extremely good matching of the resistance–temperature characteristics of neighbouring, co-processed thick-film resistors.

4.2. Slip sensor

To test the functionality of the slip sensor, small masses were dropped onto the surface of an inclined fingertip and allowed to slide over the top electrode of the sensor. Fig. 11 shows a typical response obtained from one of these devices when connected to a simple charge amplifier. The initial moment of impact can be seen on the left of the trace as well as a vibration signal on the right side of the trace as the mass slips over the sensor surface. Both signals are readily detectable above the background noise level and demonstrate the potential of the sensor to detect the moment of first contact that the hand makes as it encloses on an object as well as its ability to detect the onset of slip.

4.3. Temperature sensor

The resistance–temperature characteristics of a number of samples of the fingertip temperature sensor were measured in an environmental chamber over the temperature range −10 °C to +40 °C. The local temperatures experienced by the thermistor sensors were determined by measuring the resistance of a calibrated commercial thin-film Pt100 temperature sensor glued to the surface of one device. The average measured resistance of the thick-film thermistor temperature sensors as a function of temperature was shown to demonstrate a highly linear relationship of the form

$$R_{(T)} = R_{(0)}(1 + \alpha T) \tag{14}$$

with a coefficient of determination (R^2) of 0.9998. In Eq. (13) $R_{(T)}$ is the resistance at a temperature T, $R_{(0)}$ the resistance at 0 °C and α the temperature coefficient of resistance (TCR). From the recorded data, an average value for α of 4230 ± 50 ppm/°C and an average value for $R_{(0)}$ of $35.4 \pm 5.5\,\Omega$ was determined. The large spread in the value for $R_{(0)}$ reflects the large variation in post-processed resistance values for the printed sensors; an artifact of the thick-film printing process. This is not considered a problem since individual temperature sensors may be balanced in a suitable bridge circuit in practice. The small variation in the value for α (approximately 1.2%) means that temperature may be inferred from resistance in a repeatable manner and to a high degree of accuracy. For the values reported here, a resistance measurement resolution of 0.15 Ω is required to resolve the temperature of the fingertip to 1 °C.

5. Conclusions

The static force sensor has been demonstrated to give a linear response over the force range 0–50 N with a maximum hysteresis level of 0.7 N (equivalent to 1.4% of full scale). The force measurement sensitivity (or resolution) is dependant on the separation distance between the two strain sensitive thick-film resistors that comprise the sensor, with a measured value of 1.1 μV/V N mm when configured in a pseudo half-bridge circuit. However, as the sensor separation is increased with one sensor moving closer to the cantilever tip, the available length of the fingertip that can then be actively used to resolve a position-independent measure of the fingertip force is reduced. This is a consequence of the requirement that the force must always act on that portion of the cantilever between the set of strain sensors and the cantilever tip, if the sensors are to experience a change in strain.

The response of the static force sensor shows some degree of variation with the position that the force acts upon the fingertip. This position sensitivity can be potentially eliminated in practice if the acting forces are constrained to the same position on the fingertip. This could be achieved (for example) by raising the profile of the fingertip at that location such that it was the proudest part of the surface and therefore always the first point of contact with a gripped object.

The effect of temperature on the response of the force sensor is virtually negligible due to the close matching of the resistance–temperature characteristics of the individual strain sensitive thick-film resistors and the inherent first order temperature compensation achievable with a bridge measurement circuit.

The proprietary piezoelectric PZT thick-film paste exhibited a good degree of piezoelectric activity with an average post-processed value for the d_{33} coefficient of 46 ± 2 pC N^{-1}. Although research into the functionality of this sensor is at an early stage, its ability to detect fingertip vibration has been demonstrated, making its use as a slip detector viable. To reach this objective, further research will be undertaken involving the analysis of the vibration signals obtained under controlled conditions to determine physical characteristics of the gripped object. For example, it may be possible to determine whether a gripped object is solid or hollow, or whether its surface is smooth or rough. This information could then be used in helping to decide what level of force the fingers need to exert upon an object to maintain a secure grip.

A simple resistive temperature sensor has also been demonstrated. This has been shown to demonstrate an extremely linear relationship between resistance and temperature with a resolution of 0.15 Ω/°C.

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Biographies

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