1. Introduction

The mainstream of current research work in artificial array tactile sensors concentrates on using soft compliant membranes as the means of transmitting the effect of variable external stimuli to the discrete sensing elements. These tactile devices are usually made of a thin flexible substrate such as pressure sensitive pads, conductive materials, conductive coatings, piezoelectric polymers or elastomers. A large number of tactile sensor configurations using these types of materials have been investigated by researchers. These include the use of anisotropically conductive silicone rubber (ACS) (Hills, 1982), sponges containing carbon particles (Snyder and St Clair, 1978), felted carbon fibres (Rebman and Tull, 1983), piezoelectric polymers such as polyvinylidene fluoride (PVF2) (Nakamura et al., 1985) and conductive elastomers such as Dynacom materials consisting of silicon rubber mixed with metallic compounds (Purbick, 1981).

The major problem with using soft compliant membranes as touch surfaces devices is that the soft material tends to fatigue after a period of use. When the device is used the soft membrane is pressed against the sensing elements by the object being sensed or object target. This tends to deface the material particularly when the object to be sensed has sharp edges. Small cracks develop in the materials which, as well as leading to fatigue problems, can also cause conductivity to drop to the point where the material is no longer useful as a sensing device. Although careful material selection can minimize hysteresis and long term creep, these effects will always be present to some degree in materials such as silicone rubber, elastomer and polymer materials. These materials are also characterized by non-linearity, low sensitivity and slow response time (Harman, 1982).

Some researchers prefer to avoid these potential pitfalls by basing their design on the more proven technology of strain gauges or hard contact surfaces such as rigid pins (Sato et al., 1987). Some of the problems associated with soft compliant membranes can be overcome by improving solid-state devices, some of which are almost hysteresis free, stable and exhibit small non-linearity (Fraioli, 1967; Wortman and Monteith, 1969; Samaun and Angell, 1973).
miniature single crystal silicone sensing devices can now be machined, giving a robust micro-mechanical structure. This yields certain advantages, including the construction of dense packing arrangements which is necessary for production of high resolution tactile sensor devices. Other advantages of such a matrix formulation are the elimination of hysteresis effect, enhancement of measuring accuracy and repeatability, as well as significant compensation for noise, temperature and non-linearity (Fraiolli, 1967; Wortman and Monteith, 1969; Samaun and Angell, 1973).

In this paper a hard compliant pneumatic proximity to tactile sensing device design and performance are described and presented. The reason for opting for a hard compliant device is that it enables repetitive use without having to make contact between the sensing plane and objects of interest, thereby eliminating problems such as wear and damage that might be caused to the sensing plane. In choosing a hard compliant device, an active medium must be used to transmit the effect of the external stimulus to the sensing element. A fluid or light are the obvious choices since they are cheap, wear resistant and easy to obtain. Dry air in particular is available in most industrial plants and laboratories; it has no corrosive or contaminating action as other fluids may have, and requires very little control as is usually required when light is used as a transmitting medium. Therefore, it was specified that the design would be centred around the use of air as a transmitting medium.

2. Tactile imaging device design considerations

In designing tactile sensing arrays, a number of important factors must be considered. The most important factor is to ensure that an adequate sensing resolution for a given application is planned for. The sensing resolution is further subdivided into spatial resolution (i.e. positioning) of sensing elements in the array (on the surface of the sensing plane), and the measurement sensitivity of the sensing elements at each locality. Tactile sensing is a relatively new technology, and has been mainly applied within the field of robotics. In this field, tactile sensors have been developed and used to emulate the human sense of touch. Therefore, the sensing resolution is often planned to closely approximate human mechanoreceptive capabilities. Complex configurations of tactile sensing devices to emulate those of humans are beyond the scope of the current state of the art. Most tactile sensing devices are devised to respond to the changes relating to a specific parameter of interest such as pressure or displacement.

Other factors include the choice of the sensing element and the substrate or matrix that contains the sensing elements. With the transducer (i.e. sensing element), one important consideration is to ensure that a continuously variable output is achieved. This refers to the sensor’s capability to respond to changes in the value of applied stimulus in a continuous fashion. The measurement characteristics of the sensing elements should ideally be linear, hysteresis free and have a fast response time. In reality, however, all sensing elements exhibit non-linear characteristics somewhere in their working range. An important consideration is therefore the extent of the operating range for which linear response to an external stimulus can be expected. The same consideration is also true of the effect of hysteresis.

Other considerations that might affect the performance of tactile sensors are fatigue of the membrane or substrate, drift in conductivity or saturation, noise and environmental conditions. Miniaturisation of sensing elements has two main advantages. First, it enhances the sensing resolution as denser arrays of these can be constructed. Secondly, with smaller devices problems due to non-linearity diminish. Miniature single crystal silicon sensing devices can now be machined, giving a robust micro-mechanical structure.

The tactile sensing device design must also utilise the air jets in a such a fashion that the tactile sensor should have an acceptable spatial resolution (air jets spacing) and also a good sensitivity response. The other major consideration is the ease and cost to produce. Furthermore, the positions of the air jets must be selected in such a way so as to ensure that the air supply jets do not impinge on the sides of the column and cause turbulent conditions to occur.
3. Tactile sensing design principle

The pneumatic proximity-to-tactile sensing device as shown in Figure 1 is based on a line array of 16 back pressure air jets which monitor any change in the pressure of an air cushion. The air cushion pressure is generated by a duplex inlet air supply to feed a volumetric air chamber. The air escapes from the air chamber through the 16 nozzles and strikes the target of interest. Each back pressure air jet is designed so that it is completely isolated from the air flow in the volumetric air chamber in order to avoid any interference between the air flow in the air chamber and the back pressure air jet. The design of the high resolution proximity-to-tactile sensing device was developed via a number of iterative designs to meet the demands of a flexible, robust and cheap to manufacture sensing device (Benhadj and Dawson, 1987, 1995).

The devised pneumatic proximity-to-tactile device (see Figure 1) can be used in three modes. First, the sensing device can be employed as a proximity device to obtain a qualitative image of an object when positioned 2-3mm away from it. In this mode of operation the device sensitivity is low. Secondly, it can be utilised as a “near tactile” device when positioned at a distance less than 2mm away from the target. In this mode of operation the tactile device is very sensitive and results in a high resolution image of the object surface, providing details such as small holes, grooves, slots, and other surface discontinuities. The resolving power of the sensor with an approximate fine motion of the sensing block is 0.5mm tangential to a sensing plane and 10-50m normal to it. Thirdly, when the device is in a contact mode, a maximum back pressure signal corresponds to a footprint shape of the contacting domain which can be utilised to ascertain the highest area of the object surface.

Air is used as a transmitting medium between the effect of the external stimulus to the sensing element. With air, two different approaches to measurements can be adopted. First, pressure can be utilised as a parameter which responds to the changes caused by the external stimulus. Secondly, flow rate or flow velocity may be used. The former was selected as it would correspond more directly to pressure receptance in cutaneous tactile sensing. In order to ensure sufficient sensing resolution, air flow should be concentrated as jets and the pressure would normally be monitored from individual corresponding sensing elements. The configuration chosen was to measure the back pressure to an air jet, striking a target. Each jet is then considered as a source of excitation (stimulus) that is monitored by a corresponding back pressure jet that leads to a sensing element. In this way one may control the source of stimulation (air jet pressure), monitor the feedback (back pressure jet) and ascertain information about the target which affects the feedback pressure. An array of such supply air jets and corresponding back pressure feedback jets can provide quantitative information about the profile of target surfaces.

The devised proximity-to-tactile device does not suffer from problems associated with most sensing devices such as wear, fatigue, hysteresis and drift in conductivity because of its data acquisition from a “near-tactile” mode. A 2.5mm centre to centre spatial resolution is achieved in this device configuration. The size of the individual sensing element (IC pressure sensors) for each sensing site limits the ultimate spatial resolution. The measurement resolution (i.e. sensitivity) is found to be 1mV/m, and the device thus falls into the required category of skin-like sensing devices. This device also has a very acceptable repeatability.

Figure 1 The pneumatic proximity-to-tactile prototype imaging device
4. Tactile sensing air slow configuration

In this section the air flows’ behaviour in the proximity-to-tactile sensor device configuration is presented. The development is processed in three stages in order to satisfy the understanding of the air flow mechanics created in the sensing device before relating it to the design of the proximity-to-tactile sensor configuration. The three stages are shown in Figure 2 and represented as Air flow A, Air flow B and Air flow C.

- Air flow A concerns the air flow leaving the air chamber of the sensing block through a nozzle; this air flow is developed between the air chamber and the sensing plane. A large volume air chamber is constructed in order to maintain a constant pressure supply. The length of the back pressure air jet is kept to a minimum in order to reduce the pressure losses along the air jet length and also to increase the volumetric flow accordingly. This also ensures a sufficient pressure gradient between the jet’s inlet and the atmosphere to sustain a high flowrate through the air chamber and the back pressure air jet.

The velocity distribution of the air which flows steadily parallel to the axis in the annular space between two coaxial cylinders is given by the following equation:

\[ V_s = \frac{dp}{4\mu dx} \left( r^2 + Abr + B \right) \]  \hspace{1cm} (1)

where \( \mu \) is the air viscosity, \( dp \) is the pressure drop between inlet and the outlet pressure.

The boundary conditions are determined as follows:

\[ V_s = 0 \quad \text{at} \quad r = R \quad \text{and} \quad r = r_1 \]

\( R \) and \( r_1 \) are the outer and inner radius respectively.

From which the two constants of integration \( A \) and \( B \) are determined as follows:

\[ A = -\frac{(n^2 - 1) r_1^2}{ln n} \]

\[ B = \frac{(n^2 - 1) r_1^2}{ln n} (ln r_1 - r_1^2) \] \hspace{1cm} (2/3)

where \( n = (R / r_1) \).

And the rate of volumetric flow is derived by double integrating the velocity:

\[ Q_x = \int_0^{2\pi} \int_0^R V_x r \, dr \, d\theta \] \hspace{1cm} (4)

From equation (1) the pressure drop (\( dp \)) can be calculated and therefore the pressure (\( P_2 \)) of the air flow leaving the air chamber through the nozzle can be evaluated. The flow rate through the air chamber (\( Q_x \)) and the pressure entering the air chamber (\( P_1 \)) are set by a flowmeter and pressure regulator respectively. The velocity can also be determined in the same manner by using equation (1).

- Air flow B is the air flow between the sensing plane and the target. When an air flow strikes a solid surface (i.e. a target of interest), it does not rebound from the surface as a rubber ball would rebound as shown in Figure 3. Instead, some of the air flow escapes on all sides of the target...
and an air cushion is formed in between the sensing plane and the target. The air flow leaves the air chamber with a velocity and pressure as defined in equation (1) and equation (2). This creates a pressure at the surface of the target as an air cushion and this is assumed to be as follows

\[ P_{\text{cushion}} = (\text{Pressure leaving the air chamber}) - (\text{Pressure loss}) \]  \hspace{1cm} (5)

The pressure loss between the sensing plane and the target surface is related to the gap size \((dx)\). Therefore, as the gap \((dx)\) between the sensing plane (or the end of the air chamber) and the target surface reduces, the pressure loss respectively decreases. It can therefore be inferred that as the gap \((dx)\) reduces, the air cushion pressure tends to equal the pressure leaving the air chamber and therefore the pressure at the entrance of the back pressure air jet.

Another important factor is the force of the air flow that strikes the target surface. The striking force should not exceed the force necessary to hold the target in position. The force normal to the target surface is determined as follows:

\[ F_X = \rho V_X Q_X \]  \hspace{1cm} (6)

where: \(\rho\) is the density of air.

- Air flow \(C\) is the air flow through the back pressure air jet and the volumetric flow rate across the section area is known as Poiseuille’s formula and sometimes as the Hagen-Poiseuille formula. For a length of \(dx\) of the pipe over which the piezometric pressure drops from \(P_2\) to \(P_1\), the equation in terms of radius \(R\) can be expressed as follows:

\[ Q_X dx = -\frac{\pi R^4}{8\mu} dp \]  \hspace{1cm} (7)

The theory outlined above proves useful in understanding the effect of parameters such as the dimensions of the air chamber, the nozzle diameter and the length and diameter of the back pressure air jet. These parameters are very important in the tactile sensor design. The derived equations are also helpful in determining the amount of air supply one needs in order to meet the design requirement. A low pressure supply will limit the tactile sensor sensing sensitivity, and a higher pressure supply on one hand increases the tactile sensor sensitivity but on the other hand higher pressure can destroy the \(IC\) pressure sensor element; it is therefore desirable to supply the device with an optimum pressure supply.

5. Tactile imaging

The spatial resolution of this tactile sensor depends directly on the size of the back pressure air jets; the smaller the diameter of the back pressure air jets the better is the resolution. The ideal tactile sensor as mentioned by Professor Harmon (1982) exhibits a spatial resolution of 1mm and this emulates the human touch sensing. In this configuration, the size and the means of machining the air jet columns do not allow us to perform this ideal spatial resolution. In the final design configuration the back pressure air jet column (i.e air way) has a 1.5mm outside diameter and a 1mm internal diameter and the nozzle is designed with a 2mm outside diameter. This results in a centre to centre back pressure air jets spacing distance of 2.5mm as shown in Figure 4.

The spatial resolution is however a very important feature if the tactile sensor is to identify objects. The more compact the back pressure air jets, the better spatial resolution is
achieved. However consideration also need to be given to the size of the air jets. The objective is to achieve the maximum number of back pressure air jets in an area as small as possible. In order to achieve a reasonable spatial resolution without affecting the sensitivity of the tactile sensor configuration, a method of scanning the same line of the target twice is recommended and can be achieved in the following manner.

Figure 4 illustrates two lines of 16 back pressure sensing elements; the first line corresponds to the first line scanning of 16 output signals of a 2.5 mm centre to centre between each tactile sensing elements and are stored as the following set of line array numbers \{1, 3, 5, 7, 9, 11, 13, 15, 17, 19, 21, 23, 25, 27, 29, 31\}. The device is then shifted by 1.25 mm from the first line scan and another 16 output signals of 2.5mm between each tactile sensing elements are stored in the following set of line array numbers \{2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, 30, 32\}. At the end of the first line scanning our line array will consists of 32 output signals rather than 16 output signals. This will increase our spatial resolution from 2.5 mm to 1.50 mm centre-to-centre and twice the data information is acquired. The binary image obtained from the tactile data information is of a better resolution as shown in Figure 5 and can be used for part identification.

6. Conclusion

The devised pneumatic proximity-to-tactile device presented in this paper can be used in three modes. First, the sensing device can be employed as a proximity device to obtain a qualitative image of an object when positioned 2-3mm away from it. In this mode of operation the device sensitivity is low. Second, it can be utilised as a “near tactile” device when positioned at a distance less than 2mm away from the target. In this mode of operation the tactile device is very sensitive and results in a high resolution tactile image of the object surface, providing details such as small holes, grooves, slots, and other surface discontinuities. The resolving power of the sensor with an approximate fine motion of the sensing block is 0.5 mm tangential to a sensing plane and 10-50 m normal to it. Third, when the device is in a contact mode, a maximum back pressure signal corresponds to a footprint shape of the contacting domain which can be utilised to ascertain the highest area of the object’s surface.

Near-tactile data are obtained at the interface with the object or target and can be used in environments which are inaccessible to vision sensing devices. Because of its data acquisition from a “near-tactile” mode, the devised proximity-to-tactile sensing device does not suffer from problems associated with most tactile sensors such as wear, fatigue, hysteresis and drift in conductivity. The measurement resolution (sensitivity) is found to be 1 mV/m, and the device thus falls into
the required category of skin-like sensing devices. This device also has very acceptable repeatability characteristics.

References