A Magnetic Field Based Compliance Matching Sensor for High Resolution, High Compliance Tactile Sensing *

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Abstract

This paper describes a general approach for producing high resolution tactile sensors that are highly compliant. This approach is based on the idea of compliance matching, wherein the high compliance of the contacting element is matched to the low compliance of the sensing element. A prototype tactile sensor is proposed which uses magnetic fields as the matching medium. We detail the design of an important component of this device, a 64X64 element array of magnetic field sensors.

Introduction

Attempts at producing tactile sensors that have both high compliance and high resolution are frustrated by the conflicting requirements of compliance and spatial resolution. For example, tactile sensors that have a very high spatial resolution such as ones based on integrated circuit technology [13,14] or on fiber optic technology [1], are very non-compliant. They cannot be deformed significantly without breaking. Conversely, highly compliant tactile sensors such as those based on conductive rubber [15], or on ferroelectric polymers [6], have low spatial resolution due, in part, to the difficulty in patterning and fabricating dense sensing arrays in flexible materials.

In this paper we present a general methodology, which we call Compliance Matching, for the production of high resolution, high compliance tactile sensors. In the compliance matching tactile sensor the active sensing surface is highly compliant, such as an elastic membrane. Instead of placing sensors in this compliant surface we use a compliance transforming, or matching medium, to transfer the tactile information from the tactile surface to a high resolution, non-compliant sensing array. That is, the non-compliant, high resolution sensing array senses the perturbation of the compliant membrane, indirectly, instead of sensing the actual tactile forces.

The design of a practical compliance matching device is illustrated which uses magnetic fields as the compliance matching medium. We detail the design of an integral part of this device, a 64X64 element magnetic field sensor array. This compliance matched tactile sensor is designed for implementation in highly compliant grasping elements, such as the fingertips designed for the Harvard three finger hand [3].

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Compliance Matching

The basic idea behind compliance matching is that an intermediate transforming or matching medium acts between a highly compliant surface which is acted upon by a set of applied forces and a non-compliant (rigid) sensor array. The matching process is such that the rigid sensor array indirectly senses the shape of the compliant membrane and is also shielded from the applied forces. Since the sensor array can be very rigid, integrated circuit technology can be used to attain high sensing element density. Furthermore, the shape of the surface is being measured, rather than a stress or strain pattern at some distance into the membrane. Therefore one avoids the problems due to blurring caused by the diffusion of the stress/strain profiles. It is true, however, that obtaining the force profile from displacement measurements is much for difficult than obtaining the force profile from stress or strain patterns [11]. For tactile pattern recognition purposes, however, displacement profiles may be more useful than stress/strain patterns as they have a closer relation to the shape of the object being contacted.

The general compliance matching process is depicted in figure 1. A set of applied forces and torques F is applied to the compliant membrane **M**. This results in the membrane taking on the shape S_M. The matching or transforming process converts the membrane shape to a quantity f which can be measured by the sensing array. The sensor samples this quantity at the resolution of the array to produce $\hat{f}$. From this sample set an inversion process is performed to obtain an estimate of S_M. From this estimate another inversion process may be done to obtain the set of applied forces and torques, F. Depending on the nature of the membrane mechanics, and on the matching process, one or both of the inversion tasks may not be possible. Thus the applied forces and torques may not be available. However, in such a case, qualitative information, such as contact centroids, contact shape and so on, may still be available.

One can classify compliance matching devices into two general classes, based on the way in which the compliance matching process is performed. These classes are *contact*, and *field*, or *action-at-a-distance* . In contact devices the compliance matching is done mechanically, through an intermediate springy material. The primary disadvantage of the contact method is that the intermediate material diffuses the contact forces (or membrane shape), reducing the possible resolution. As an extreme example, consider the intermediate material to be an incompressible fluid, and the sensor to be an array of pressure sensors. The pressure in the fluid at the sensor plane will be constant due to hydrostatic equilibrium. Hence all of the resolution of the sensor array will be wasted since only the average pressure in the fluid is measured. In order to decrease the amount of diffusion, a non-homogeneous intermediate material must be used. For example a foam with narrow, vertically oriented cells, or a set of narrow vertical springs, such as shown in figure 2 would increase lateral resolution. Homogeneous, non fluid, materials such as rubber will also reduce diffusion, but to a lesser degree as there is more lateral interaction than for non-homogenous materials. The compliance of a device that used non-homogenous material would be non-uniform, as the matching material would be stiffer in the horizontal direction than in the vertical direction. Furthermore, to obtain very higher lateral resolutions one would need a very fine foam, and one in which the ratio of horizontal to vertical stiffness was very high. Such materials may be very difficult to manufacture.

The field compliance matching mechanisms attempt to retain spatial resolution by eliminating the diffusion due to mechanical contact. This is done by in one of two ways; active or passive field compliance matching. In active field compliance matching, which is equivalent to the field emitter-detector structure proposed by Jacobsen [9], the inner surface of the compliant membrane is patterned with a distribution of sources of a field, such as electric, magnetic, electromagnetic, acoustic, chemical, and so on. This field radiates to the sensor plane, where it is sensed. The sensed field distribution can be then related to the positions of the sources and hence to the shape of the membrane. However, if the radiation of the field is spherically symmetric, as most are, one has a problem with defocussing of the image of the source points. A given sensor element may receive radiation from more than one source at the same time, resulting in a smearing and a loss of resolution. Thus some sort of focussing will be required in order to obtain high spatial resolution when many sources are used. For example, if light was used as the matching medium, a lens would be required between the membrane and the sensor array, as shown in figure 3a. Embedding this lens into the structure of the tactile sensor may be very difficult to accomplish due to the limited space that may be available. If focussing can not be done one must use only a small number of sources so that they do not interfere with each other. The resolution possible with reduced source density will be less than that attainable with a higher source density. However, the nature of most compliant surfaces is to diffuse the effect of applied forces over a larger area than the area of contact. This means that the source density may not need be so high as to cause excessive smearing.

The passive field compliance matching process is similar to the active compliance matching process in that a rigid sensor array senses a field quantity that depends on the shape of the contact membrane. However, instead of having the field sources be fixed to the membrane surface, in the passive technique one has the field sources fixed and the membrane modulates this fixed field. For example in the case of a light based device, one could have a number of light emitters located around the sensor array, while the inner surface of the membrane is painted with a textured pattern of some sort. The sensor array would then, (if there was a focussing mechanism) sense the light reflected from the membrane modulated by the pattern painted on the membrane. If the membrane is deformed by applied forces or torques, the sensed pattern would change. This is illustrated in figure 3b. A tactile sensor based on the same principle as the device shown in figure 3b is described in [5]. The same considerations about resolution that applied to the active case also apply to the passive case, save that instead of the distribution of sources, we must consider the spatial structure of the modulation of the field by the membrane.

Some issues of importance to the performance of field based compliance matched tactile sensors are:

- The mechanics of embedding the illumination (field sources) into the structure of the tactile sensor.
- The blurring of detail due to defocussing.
- Noise level and sensitivity of the sensor arrays to displacements of the membrane.
- Response times of the sensor array. With integrated circuit technology one should be able to acheive very fast response times compared with techniques such as conductive rubber tactile sensing.
- Spatial resolution. The resolution attainable by the compliance matched tactile sensor is a function of the field sensor resolution, the source density, the amount of focussing, and the diffusion of the contact membrane.
- The ability of the system to handle occlusions (where the sensing elements are blocked from the field sources).
- Shielding of the sensor from fields unrelated to the fields associated with the tactile sensor.
- Power consumption, size, and number of connections needed by the sensor array.

The nature of the compliance matching process is dictated by the modality of the sensor array. If one uses integrated circuit technology for producing the sensor array one is limited to the types of sensors that can be implemented in this technology. The types of modalities that have been implemented in standard IC technologies include temperature, pressure, magnetic field, electric field, and various chemical properties [2]. In the following section we detail the design of a field based compliance matched tactile sensor which uses magnetic fields as the matching medium.

A Magnetic Compliance Matched Tactile Sensor

In this section we describe a prototype design for a compliance matched tactile sensor which uses magnetic fields as the matching medium. This tactile sensor is intended for use with the compliant membrane finger developed at Harvard. This finger is shown in figure 6, along with the magnetic sensor array which is described in more detail below.

The idea behind the magnetic tactile sensor is simple and is depicted in figure 4. If we cover the surface of the contact membrane with a pattern of magnetized material (such as dipole magnets) then the magnetic field pattern at the plane of the integrated circuit magnetic sensor array will be a (complicated) function of the membrane shape. Thus by measuring the magnetic field with the integrated circuit sensor array one can obtain information as to the shape of the membrane and hence to the distribution of the forces applied to the membrane. Alternatively one could use the arrangement of figure 4b, which is a passive implementation. In this method a fixed, large source of magnetic field is modulated by a ferro-magnetic film (for example the Metglas material described in [10]) that is affixed to the contact membrane. The film alters the reluctance of the magnetic circuit between the source and the sensor, resulting in changes in the magnetic field at the sensor as the film is displaced. A somewhat similar device to this was described by Hackwood et al [8]. Their device was not as compliant as the one that we are proposing, as they used rubber between the magnetic field source and the magnetic field sensors. They used an array of magnetoresistive sensors, while we use the split drain Magfets described below to sense magnetic field in our implementation. These have the advantage of being implementable in standard CMOS technology and can acheive a high spatial resolution (our sensors lie on a 100 micron grid, but could easily be reduced to a 25 micron spacing).

Theory of Operation of the Magnetic Sensor

A key component of the magnetic compliance matched tactile sensor is the magnetic field sensing array. There are currently no high resolution magnetic sensor arrays available commercially, so this application requires the design of such an array. We have developed an array based on the *split drain* MOSFET, or MAGFET, [7]. This device is a MOSFET, having two drains, as shown in figure 5, that is biased on so that current flows strongly through the transistor. In the absence of a magnetic field the currents flowing through the two drains of the MOSFET are equal. However, when there is a magnetic field with a non zero component, B_z, perpendicular to the plane of the sensor, the carriers (electrons or holes) flowing in the transistor are deflected, due to the Lorentz force. As the carriers are deflected by this force, an electric field is built up due to the separation of charge. The force on the carriers due to this field will counteract the force due to the magnetic field. Hence an equilibrium will be attained at a certain displacement of the charge carriers. This charge carrier deflection results in an imbalance in the current flowing through the two drains of the MAGFET. This imbalance is a function of both B_z and the geometry of the split drain. If the split drain consists of two equally sized sections, the currents through the two sections are of the form $I_1 = \frac{I}{2} + \Delta I$ and $I_2 = \frac{I}{2} - \Delta I$, where ΔI is a function of B_z [7]. This current differential can be converted to a voltage and amplified by a current mirror.

The combination of the split drain MOSFET and the current mirror is equivalent to the input stage of an operational amplifier. The sensitivity of this arrangement can be much higher than a circuit utilizing the Hall voltage. A device similar to this has been built and tested by Popovic and Baltes [12]. They claim sensitivities on the order of 1 Volt per Tesla. Their circuit uses complementary split drain MAGFETS, whereas our design uses only a single MAGFET in conjunction with a current mirror. The reason we use the single ended design is to make the sensor as compact as possible. Having complementary FETS in a sensing cell requires that both well and substrate contacts be present, and extra space is required between the P and N channels FETS to minimize the probability of latchup, which can cause the chip to malfunction or be damaged.

We have designed and laid out a 64 by 64 element array of such split drain transistors in an integrated circuit for fabrication in a 3 micron CMOS process. This circuit has fabricated through MOSIS, which is a service run by the Information Sciences Institute of the University of Southern California for DARPA, that acts as an interface between university IC designers and industrial fabrication facilities. Each of the split drain transistor sensing element on the chip is 100 microns square. The size of the entire array is 7.9 by 9.2 mm. The chip is shown in figure 6 alongside the compliant membrane fingertip it is to be installed in.

The array is scanned in a raster scan fashion by the circuit shown in schematic form in figure 7. Shift registers along the left hand side of the circuit shift a single "turn-on" bit which allows current to flow through all of the split drain devices in a single row. As the scan proceeds, successive rows are turned on. Only one row at a time is one. Shift registers along the bottom shift a single "select" bit which selects the output of one column at a time. All the split drain devices in a given column share a single current mirror located at the bottom of the column. Since only one row is on at a time, these current mirrors have current flowing through them from one split drain device only. The row shift register is shifted only when a complete column scan has been finished. The column shift register is shifted by an external clock signal. The output of the selected current mirror is amplified and buffered before it is sent to an analog output pad. The shift registers are initialized by a reset pulse. The amount of current that passes through the split drain devices is controlled by a bias voltage which is switched in when a row is selected. This bias is used to adjust the offset voltage of the current mirror to be roughly half of the supply voltage, in order that the buffer amplifier operates in its linear, high gain region. The sensitivity of the split drain devices are also affected by the bias voltage.

Experimental Properties of the Array

We have measured a number of properties of the 4096 element sensor array chip that we have fabricated. The power dissipation of the chip is around 10 milliwatts. The sensitivity of the magnetic sensors to changes in magnetic fields (as well as a demonstration of their use as membrane displacement detectors) is shown in figures 8, 9 and 10. Figure 8 plots the output a a single sensor element as a function of the distance from the sensing element to the center of a bar magnet having dimensions 15mm X 9mm X 4mm. The bar magnet is aligned so that its north-south axis is perpendicular to the sensor plane. The magnetic field measured by a Gauss meter at the same distance is also plotted for comparison. This graph show the sensitivity of the array to vertical membrane displacements (assuming a source of the same strength as used in the experiments). The graph in figure 9 shows the relationship between the sensor output and the magnetic field at the sensor. The $B - V_o$ characteristic of the sensor is seen to be quite linear over most of the range. Figure 10 shows the output of a single sensing element as a function of the lateral position of a the bar magnet, when the height of the bar magnet above the sensing plane is kept constant (at 5 mm). This graph shows the sensitivity of the sensing array to horizontal displacements of the membrane. In this case however the bar magnet is aligned so that the north-south axis is parallel to the sensor plane. The lateral resolution of the sensing array is hidden somewhat in the above graph since the bar magnet has a thickness of about 4mm and acts as a distributed source. However, one can see that one can still obtain lateral resolutions of less than 4mm.

The maximum practical clock speed of the fabricated arrays has been found to be about 500Khz. This works out to a frame rate of about 125 frames/sec (500,000 pixels/sec / 4096 pixels/frame). We are looking at ways in which faster scan rates can be obtained in future array designs. The current mirrors which amplify the current differential of the split drain MAGFETS have been found to be quite sensitive to process induced variations in their dimensions. As a result we observed some nonuniformity in response (offset voltage and gain) between columns of the array. This non-uniformity can be compensated for to some extent once the array output has been digitized, however we are investigating an improved design that eliminates this problem all together.

Summary

We have introduced a general scheme for implementing high resolution high compliance tactile sensors. This method relies on an intermediary transforming process that matches the high compliance of a compliant contacting membrane to the very low compliance of a sensor array. In this way one can obtain a highly compliant tactile sensor whose resolution is limited only by the diffusive properties of the membrane, which can be made quite thin, and not of the sensor. The oversampling provided by the sensor can be used to reliably deconvolve the diffusion of the membrane. The separation of the sensor from the contacting surface eases the problems of wiring to then sensor that arise when the sensor is embedded in the contacting membrane [5].

The compliance matching process seems most readily accomplished through the use of fields, or action-a-distance methods. In these methods the contact membrane and the sensor are mechanically isolated and are linked only through the intermediating field quantity. We proposed a compliance matched sensor based on magnetic fields, where the shape of the contact membrane is inferred from the magnetic field pattern sensed at the sensor plane due to sources of magnetic field (dipoles) located on the membrane surface. Other field quantities could also be used, such as light, sound, etc., and each would have their attendant technical difficulties. The magnetic field approach has itself a number of technical challenges, including the integration of strong field surfaces into an elastic surface without affecting the elasticity of the surface, and the design of a high resolution magnetic field sensor array. We presented a design for such an array and presented some of the properties of an early prototype of the array. These results indicate that the devices will be useful as sensors of membrane deformation.

We are currently involved with the integration of the magnetic sensing array into the Harvard Compliant Fingers (shown in figure 6). These fingers are compliant fluid filled membranes which allow compliant gripping [3,4]. These fingers currently contain a pressure transducer, which provides a measure of the hydrostatic pressure of the fluid inside the finger. We will investigate the optimal placement of field sources on the membrane surface with respect to spatial resolution and sensitivity.

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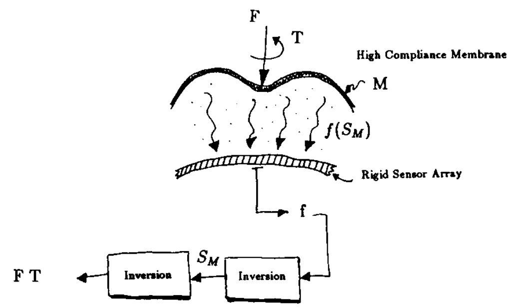

Figure 1. Compliance matching tactile sensor.

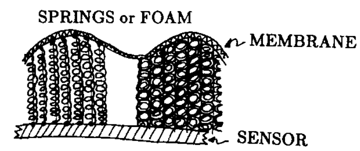

Figure 2. Contact compliance matching. Springs or foam provide compliance matching between the membrane and the sensor.

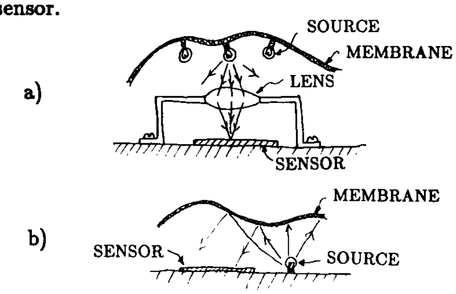

Figure 3.a) An active sensor showing focussing.

b) A passive compliance matched sensor.

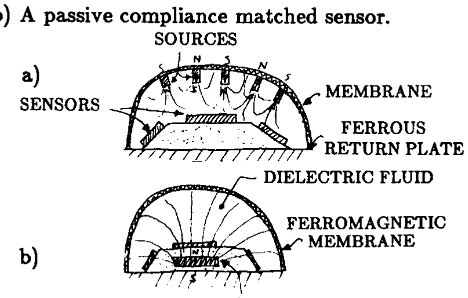

Figure 4.a) An active magnetic field based compliance matching scheme.

b) A passive magnetic field based compliance matcher.

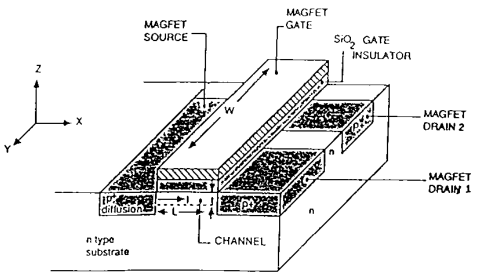

Figure 5. A split drain MOSFET magnetic field sensor.

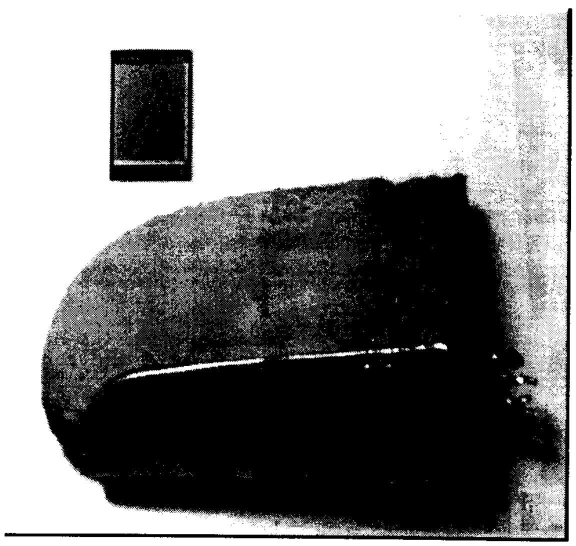

Figure 6. The magnetic field sensor array chip alongside the Harvard compliant robotic fingertip. The sensor chip size is 1.0 by 0.8 cm.

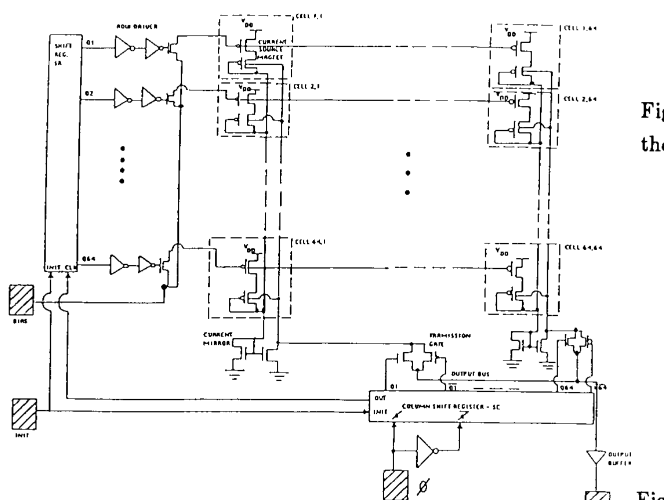

Figure 7. The circuitry of the magnetic field sensor array.

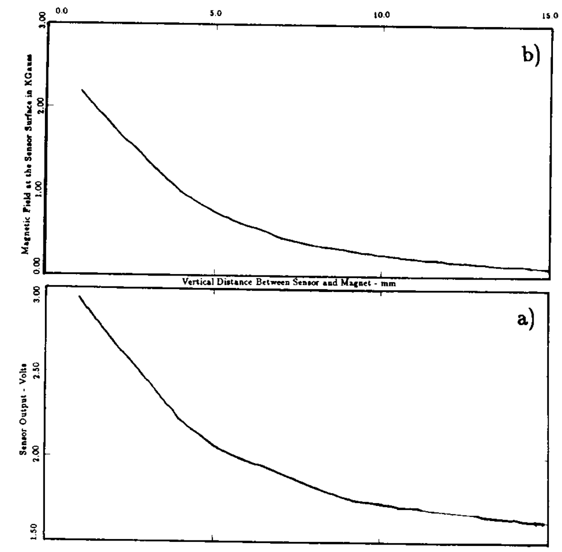

Figure 8.a) The output of a single magnetic field sensor as a function of the vertical distance from the magnet.
b) The field of the magnet at the sensor plane as a function of the vertical distance between the magnet and the sensor plane.

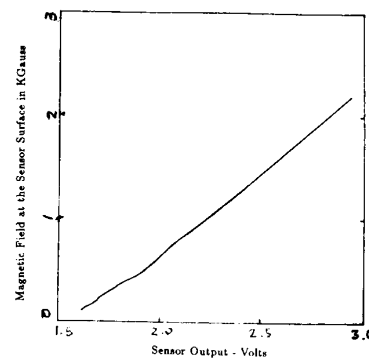

Figure 9. The output of a single sensor as a function of the magnetic field strength at the sensor surface.

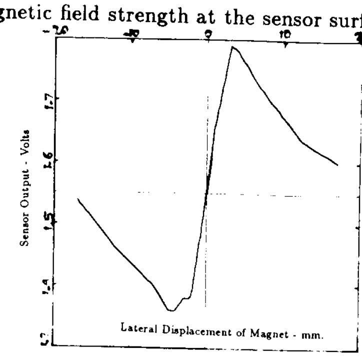

Figure 10. The output of a single sensor as a function of the lateral displacement of the magnet, with the vertical distance to the magnet fixed at 0.5 cm.