An Integrated Tactile-Thermal Robot Sensor With Capacitive Tactile Array

Franco Castelli

***Abstract*—A capacitive tactile sensor and a thermal sensor that can be combined into one compact device with both modalities are illustrated. The tactile sensing portion is composed of an 8 $\times$ 8 array of capacitive cells. By using as thermoresistors the rows' traces of the matrix of the capacitive tactile array sensor thermal sensing is obtained. This allows the detection of the gradient of the temperature. A prototype of the new sensor, which has been developed, is briefly illustrated and the so-obtained results are shortly discussed. On account of the simplicity and cheapness of the integrated sensor as well as its high linearity and sensitivity, it appears to be useful for the robots of future generations.**

***Index Terms*—Calorimetric test, capacitive tactile array, dielectric layer, integrated sensors, robot sensor, strain-buckling characteristic, tactile shape discrimination.**

I. Introduction

FOR THE operating of actual robots, many types of vision machines and proximity sensors have already been developed. Contrary to vision tactile recognition is an active process in which it is the sensor moving on the object that identifies superficial characteristics such as roughness, temperature, and thermal resistance.

A wide variety of tactile sensors has been reported, based on both digital and analog readout schemes. Among various transduction technologies, the most successful designs are [1] the capacitive technology [2] and the ultrasonic technology [3], which are based on sensing strain, and the piezoresistive technology [4], which is based on sensing stress. Universal design methods of ferropiezoelectric tactile array [5] appear impossible. The majority of the more recent development efforts are based on the use of piezoelectric polymeric films. These structures are still relatively simple; however, they lack dc response, are difficult to scale to different force ranges, and are not noted for high stability.

Both piezoresistive and capacitive structure are being used. Piezoresistive devices offer higher linearity and somewhat simpler packaging than capacitive devices; however, capacitive pressure sensors are about one order of magnitude more sensitive for a given device size and more than an order of magnitude less sensitive to temperature. All existing tactile sensors [1] are of relatively high cost, on the order of \$550–\$1000/in^2.

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A cheap tactile capacitive sensor integrated with a resistive thermal sensor, having a higher linearity, and somewhat simpler packaging than current sensors is illustrated. Moreover, the thermal sensor, with spatial resolution, allows uncommon temperature gradient detection.

II. Design Issue

A robotic tactile-sensing system for object recognition and manipulation, in essence, emulates the mechanism of human tactile perception [6]. This is a complex process with two distinct modes. The first is *passive touch*, produced by the "cutaneous" sensory network that provides contact force, contact geometric profile, and temperature information. The second is *active tactile sensing*, which integrates cutaneous sensory data and "kinesthetic" information (i.e., limb/joint positions and the state of the muscle). Desired specifications of a tactile sensitive structure are as follows:

- composed of a sensible tactile matrix able to ensure a spatial resolution of 1 or 2 mm;
- sensitive to axial forces of about 0.01 N with a superior limit above 15 N;
- dynamic range between 0–100 Hz.

Tactile sensing technology currently is being developed to enhance the robots' sensors integration, especially the passive touch to emulate the integrated human tactile–thermal perception.

The most common technologies employed by tactile sensors [7] are based on optics, resistance, magnetics, and capacitance. All sensors, regardless of their underlying transduction principle, must convert an applied force into a measurable electrical signal. The approach selected for our tactile sensor is based on measuring the capacitance between two surfaces of traces separated by a dielectric compressible material.

Two parallel electrically conductive plates generate a capacitance that is a function of their separation. If a compressible dielectric is placed between them, a force applied to the top surface of the capacitor will reduce the plate separation distance. The resulting change in capacitance can be used to infer the applied force. This principle is the basis of the force transduction of the capacitive tactile sensor.

Contact geometric profile information can be attained by an array of capacitive cells formed by sandwiching a dielectric layer between two sets of parallel conducting traces, with the top etches perpendicular to the bottom ones. A capacitor is formed each time an upper trace intersects a lower trace. To make an array of 64 force sensing capacitors, 8 upper traces and 8 lower traces are used.

A. Design of the Dielectric Layer

As previously mentioned, the basic operating principle for the capacitive tactile sensors is the measurement of an applied pressure by detecting the variation in the gap of two parallel capacitive plates. Hence, the material between the two plates is a crucial component of the device; it forms both the elastic layer that compresses in response to pressure, and the dielectric layer that provides the capacitance between the two plates.

Ideally, this material should compress linearly as force on it increases, with a spring-like behavior, and be impervious to hysteresis. Having a material that closely approximates these characteristics makes it easy to translate the output of the sensor back to the applied force, since the detected capacitance will then vary in correspondence to the force. Thus, the material selected should have linear compression over the range of pressures to be applied. Moreover, it should have a high dielectric constant imperious to thermal influence in the temperature range of use. A general outline for designing the dielectric layer is proposed before illustrating the sensor.

On the basis of a survey performed of the available elastomeric dielectric layers, the selected one is composed of a fluoroelastomer denoted "Tecnoflon FLOR 421" (TFOR), currently used as a gasket, kindly offered by Montefluos s.p.a. The TFOR characteristics have been quantified by the following preliminary tests.

- *Permanent Buckling Test*—The dielectric sheet has been compressed at a speed-compression 2 mm/min up to 15% of its thickness. The deformation 60 s after having zeroed the pressure has been within 1.67%; the speed of relaxation has been ≅1.33 μm/s.
- *Strain-Buckling Characteristic*—The test has been performed in the force range 0–100 kN corresponding to the pressure range 0–124.4 N/mm^2; the characteristic has a high linearity in the ranges 1.23–3.69 N/mm^2 and 57.89–124.4 N/mm^2. Nevertheless, this second pressure range is not apt for tactile object recognition and manipulation.
- *Differential Calorimetric Test*—The difference of temperature between the tested sample and the surrounding atmosphere of azote, $N2$, has carried on. It has been possible to detect every structural change in the sample material in the tested range of temperature. The TFOR has been tested in the temperature range from -150 °C to $+300$ °C. This test has underlined a vitreous transition at about -13.6 °C. This transition has to be further tested. Nevertheless, the temperature range 0 °C –150 °C may be assigned as the sensor temperature rated range.
- *Dielectric Constant and Thickness*—The dielectric constant has been measured at 100 kHz, with an automatic PM6304 Philips bridge, to be about 17.6. The current layers' dielectric constant is about 4 [2]. A high dielectric constant increases the overall performance of the device by increasing each cell's effective capacitance. For the same reason, in our prototype, the dielectric layer thickness has been lowered to 0.5 mm and, to double the cells' effective capacitance, the capacitive array has been designed in a sandwich configuration.

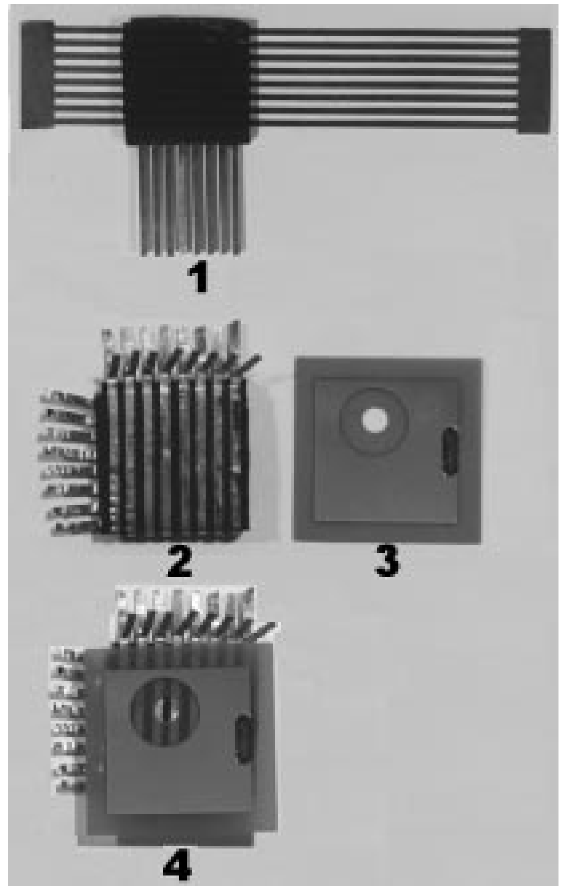

Fig. 1. Photograph of the component parts of the sensor prototype during its construction and the contact test station. *1:* Column traces; see their vertical terminals, fastened between the dielectric layers and the row traces (horizontal) before being enveloped and fastened on the external surfaces of the dielectric layers. *2:* Composed sensor, with its terminals unconnected and the upper shield removed to illustrate the rows' traces (see the white horizontal rows) covering the surface of the upper dielectric layer. *3:* Removed upper shield. *4:* Whole sensor with the terminals unconnected.

B. Capacitive Array

As outlined, to double the cells' effective capacitance, the capacitive array has been designed in a sandwich configuration. The array is indeed formed by two dielectric layers of square shape. The column traces of the matrix array are formed (see *1* in Fig. 1) by a set of parallel conducting traces fastened by the two dielectric layers. The rows' traces are obtained by enveloping and fastening the outer surfaces of the dielectric layers by a set of parallel conducting traces with the direction perpendicular to the columns (see *1* in Fig. 1).

The traces have been fastened to the dielectric by a cianoacrilic glue used only at the edge of the dielectric layers without interfering with the cells' dielectric. With the elements arranged on about 3 cm^2 (0.5 tetragon inch), the lengths of the traces forming the columns and rows, respectively, are about 2 and 4 cm in length. The sensor has the top and bottom surfaces formed by the rows' parallel traces (see *2* in Fig. 1) fastened on the two dielectric surfaces, series connected forming the matrix rows. Two parallel-connected capacitors are formed each time, a column trace intercepts a row trace, distributed on the two outside surfaces of the sensor. These two surfaces of the sensor

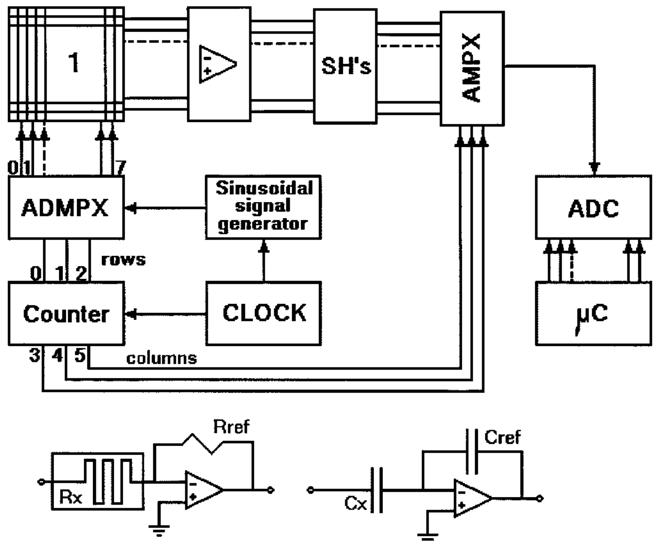

Fig. 2. Block diagram of the readout system. *1* is the actile capacitive array. *ADMPX* is the analog demultiplexer. *AMPX* is the analog multiplexer. On the bottom, on the left side, is the readout thermal unit, and on the right side is the readout capacitive tactile unit.

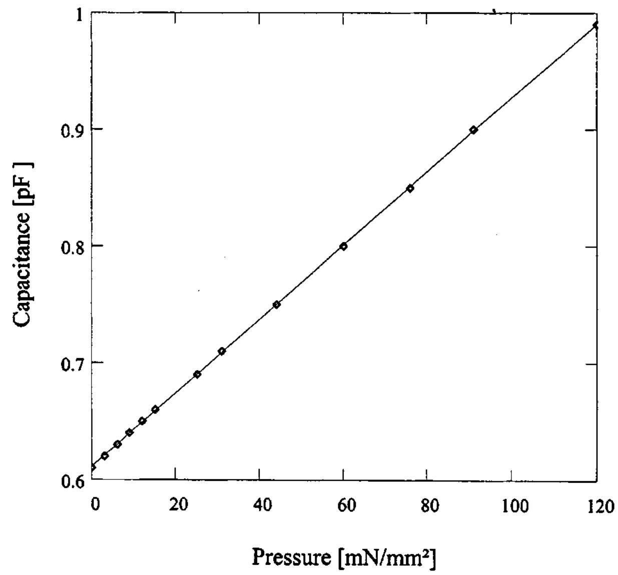

Fig. 3. Tactile sensor output to applied pressure.

have to be shielded by a thermally conductive, both mechanical and electric shield. Our prototype used a shield made of polyamide with a 35-μm copper intermediate layer (see *3* in Fig. 1), kindly offered by Kunze Folien GmbH. This thermally conductive shielding foil has a high electrical isolation and an overall thickness of 140 μm. The foil is extremely flexible and very tough.

C. Readout System Design

The block diagram of the tactile sensor matrix and its interface circuitry along with signal conditioning is shown in Fig. 2. For our prototype system with 8 rows and 8 columns, a 6-bit counter generates rows and columns addresses. The three LSBs are fed to the analog *DMPX* and are used for the row addresses. The three MSBs are fed to the analog *MPX* and are used for the column addresses.

The sinusoidal signal generator supplies the selected row; the voltage drops on each of the eight rows' cells are amplified and sampled in a holding system. Then, through an A/D converter, they are processed by a microprocessor.

D. Thermal Sensor

The thermal sensor has been obtained by the rows' traces of the capacitive array. The spatial thermal resolution is obtained by the resistance of each of the 8 rows' traces (2-mm spaced) detected by a multiplexing system similar to the one in Section II-C.

A thermal sensor with spatial thermal resolution appears uncommon in the sensor's current literature and seems to respond to the actual trend to improving the ability of recognition of the object by identifying the superficial characteristics such as temperature and thermal resistance.

E. Prototype Rated Characteristics

A prototype of the illustrated sensor has been designed and constructed. A photograph of its component parts is shown in Fig. 1. This photograph illustrates the rows' traces during the construction and before their assembling. More precisely, we have only to detail the construction of the traces. They have been constructed by the technique of photochemical- etching of a copper sheet 0.1-mm thick. The rated characteristics of the prototype are as follows:

- 8-by-8 matrix of force-sensing *capacitive cells*;
- overall dimensions, 18 mm $\times$ 18 mm;
- thickness of the dielectric sheet of Tecnofon FOR 421, 0.5 mm;
- cells' capacitance ≅0.62 pF;
- cells' interax 2 mm;
- overall pressure and force rang, respectively, 0–0.25 N/mm^2 and 0–81 N with buckling from 0% to 66%;
- resistance of each row's trace thermoresistor ≅100 mΩ;
- copper thermoresistors interax 2 mm;
- temperature range 0 °C–150 °C.

III. Test Results

The illustrated prototype and material have been used in carrying on a series of tests intended to detect the sensor performance and operativeness. For test results, the tactile sensor and the thermal sensor have been tested separately. Nevertheless, it could be possible to merge the two devices together. Test results on the dielectric layer have been illustrated in Section II-A.

A. Tactile Force Sensitivity

To performing the tactile force test, a contact sensor test section has been used. The station allows applying precise force to the selected location. A preliminary test has been carried out, to detect the characteristic of the *capacitance to a uniform pressure* on the whole sensor's surface in the pressure range 0–120 mN/mm^2 (see Fig. 3). The characteristic of the mean

TABLE I
CELLS' CAPACITANCES, IN PICOFARADS, AT ZERO PRESSURE

0.76	0.61	0.66	0.57	0.51	0.48	0.56	0.70
0.74	0.65	0.60	0.54	0.58	0.57	0.61	0.71
0.71	0.65	0.62	0.54	0.56	0.64	0.54	0.58
0.70	0.66	0.66	0.53	0.61	0.61	0.57	0.62
0.64	0.70	0.68	0.56	0.69	0.49	0.52	0.50
0.63	0.61	0.58	0.53	0.51	0.52	0.51	0.64
0.61	0.57	0.65	0.58	0.64	0.61	0.59	0.61
0.61	0.64	0.67	0.60	0.67	0.62	0.59	0.64

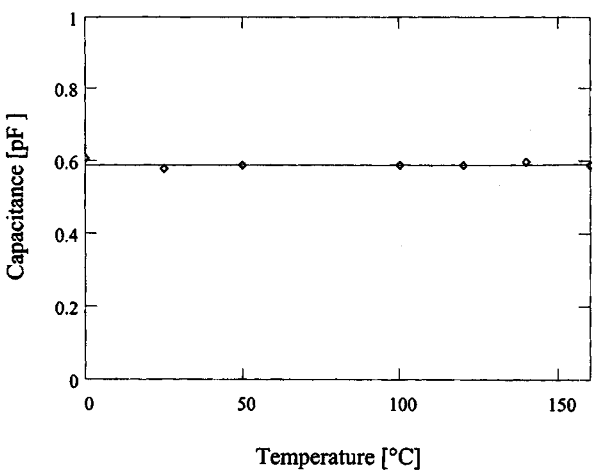

Fig. 4. Cells capacitance to temperature.

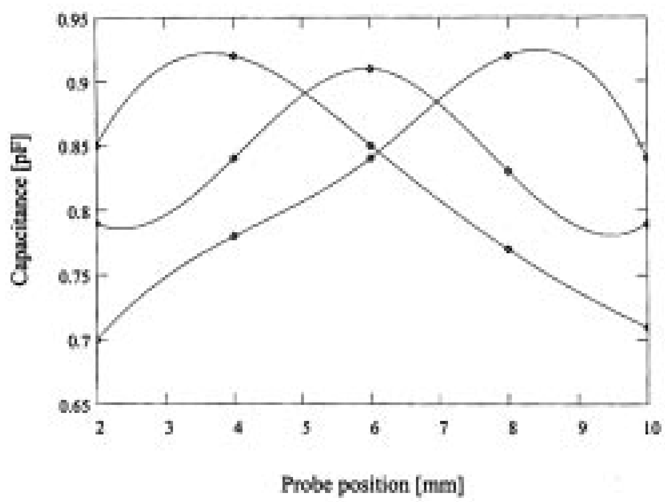

Fig. 5. Tactile spatial selectivity.

capacitance of the parallel-connected cells related to the pressure can be approximated with a linear regression characteristic with $1 - r \cong 310^{-5}$, *linearity* ≅0.3%, and *sensitivity* ≅0.05 pF per N/mm^2. The cells' capacitances have been detected within ±0.01 pF. The same test in the same pressure range has been repeated on single cells, e.g., on the central one. Similar characteristics in a wider pressure range, with an overload of 2.35 mN/mm^2, have been detected on six cells (the central one and the two lateral ones on the same central row and three on the central column consecutive from the column edge). The slopes of the six characteristics are within 0.25%. Moreover, the following have also been detected.

1) The cells capacitance at zero pressure (see Table I) has been detected. The cells capacitance mean value deviates only 2.1% with $\sigma = 0.063$ from the rated value.
2) The tactile sensor *hysteresis,* with tactile force applied over 1 min has been 2% and over 3 min has been 3.5%.
3) *Repeatability* has been better than 5%.
4) The *influence of temperature* on the cells' capacitance at zero pressure has also been detected. From test results (see Fig. 4), the cells' capacitance in the rated 0 °C–150 °C temperature range appears impervious to temperature.

The illustrated capacitive tactile array appears much simpler than previous ones both in construction and use (see, e.g., [8]). It is characterized by a higher sensitivity. For example, experimental results in [9] outline measured capacitive values in femtofarads instead of picofarads found in the proposed design.

B. Tactile Spatial Resolution

The spatial resolution of the sensor is limited by the spacing between the capacitive cells centers and the elastomeric properties of the dielectric and protective covering. For a sensor that records just surface standard force, the one or more cells directly in contact with the stimuli should only detect a point source. Obviously, having a sharp sensor response will give more detail in tactile force outlines of probed objects.

To determine the spatial resolution or selectivity of our device, the contact sensor test section has been used to apply a uniform pressure at different locations along a row. The probe, a rod of 1-mm radius, was advanced at 2-mm intervals applying about 100 mN/mm^2 pressure at each point.

The results of this test are summarized in the plots of Fig. 5. The curves show the response of three adjacent sensor cells when the probe is linearly stepped across them. The top of the plots is spaced with good approximation 2-mm apart as expected, since this is the array center-to-center spacing. Notice that there is some response overlap between adjacent cells. That is, when probing on a cell, the neighboring cell will show some

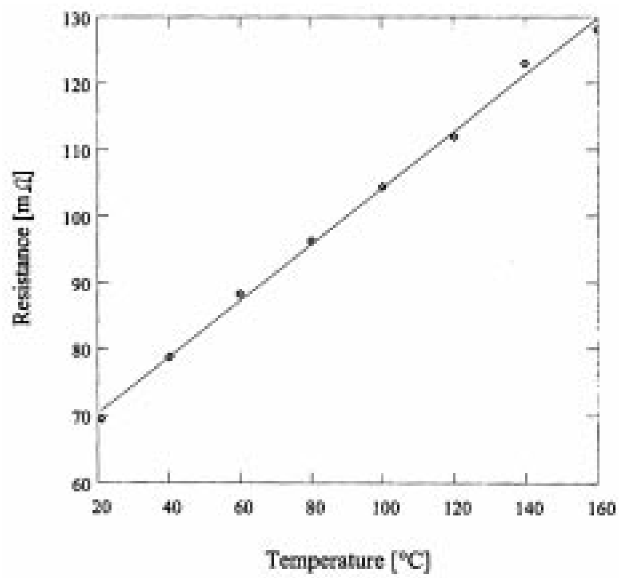

Fig. 6. Thermal sensor's output resistance to the applied temperature.

response as well. This behavior is desirable since it avoids the dead zones between cells that should otherwise result.

By observing the spatial cells' responses, we can conclude that the blurring between adjacent sensor cells is very low. In each of the three cases, the force tops occur directly at the point of contact.

C. Tactile Shape Discrimination

Pressing the tactile sensor against an object and recording the resultant force profile gives the shape of an object. If visual inspection is impossible, such as when a manipulator end-effector obscures the view, this is especially desirable. The spatial resolution of the previous section indicates that the shape discrimination ability of our sensor's prototype is adequate for current manipulation tasks.

D. Thermal Temperature Selectivity

The measured characteristic of one trace of the thermal sensor resistance related to temperature is illustrated in Fig. 6. The characteristic is linear with *linearity* and *temperature coefficient* $\cong$0.4%, sensitivity $\cong$0.4 mΩ/°C on an overall resistance $\cong$100 mΩ.

E. Thermal Material Recognition

One of the primary applications for the thermal sensor is recognition of an unknown material from a library of thermal profiles. We can expect that the temperature at the surface of the sensor, if previously indirectly heated, will drop at an exponential rate when placed in contact with an object. The shape and the final value of this curve are related to both the thermal diffusivity and conductivity of the sensed object, in addition to the characteristics of the sensor itself. Material recognition can be established by matching the sensor's response curves to a library of response curves, where a good match constitutes identification.

Moreover, the thermal sensor with spatial thermal resolution of our prototype appears useful in the actual trend of improving the ability of this sensor to recognize an object. Identifying the superficial characteristics of a composite object using temperature and thermal resistance difference can do this.

IV. Conclusions

Simple construction models were used to design the integrated tactile–thermal sensor. The sensor is formed by an 8×8 array of capacitive cells (tactile sensor). A feature of this sensor is that thermoresistors are integrated into the row armatures of the capacitive tactile sensor matrix. This makes it possible to detect the temperature gradient which seems uncommon and improves the ability to recognize an object. Recognition is accomplished by identifying superficial characteristics of a composite object, both by detection of the differences in temperature and thermal resistance. This allows bettering the robot's characteristic of manipulation and aspect recognition.

A sensor's prototype has been designed and constructed using simple packaging. Test results on this prototype prove a high linearity and sensitivity, adequate for current manipulation tasks. The prototype also shows a high immunity from influence variables. These characteristics overcome some of the disadvantages of previous capacitor sensors that had less linearity and more complex packaging than piezoresistive devices. The sensor is a very cheap device that has a tactile and thermal sensitivity, with unusual spatial resolution for temperature gradient detection.

Acknowledgment

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