A Piezoresistive Tactile Sensor

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***Abstract*—A piezoresistive strain-gauge sensor, mounted in an array configuration, for the measurement of distributed pressures during robotic grasp applications is investigated. The prototype presented consists of a 16-element test cell connected to an electronic acquisition unit that also provides temperature compensation. The structure of the tactile sensor and its principle of operation are described.**

***Index Terms*—Noise, piezoresistors, robotics, sensors, temperature compensation.**

I. INTRODUCTION

VARIOUS kinds of pressure array sensors have been developed, based on different techniques of mechanical-to-electrical energy conversion. However, in many cases they lack linearity or sensitivity and, especially, robustness and cost-effectiveness [1]. In this paper, a discrete pressure sensor that consists of an array of metal strain gauges is described which is robust, reliable, and cost-effective. In the present version only 16 (4 × 4) sensing elements are considered, since the primary aim of the work is that of investigating the possibility of increasing the sensitivity of similar devices by reducing the noise. The noise is generated by the piezoresistors, especially by temperature fluctuations.

Particular attention has been paid to the design of the geometrical structure of the device and the design of the electronic acquisition unit, to obtain a small and compact device [2]. This feature is of primary importance for pressure sensors capable of being incorporated in a grasp-effector also equipped with proximity sensors [3] for robotic application in unstructured environments. Each sensing element consists of two strain gauges inserted, respectively, in two independent Wheatstone half bridges (sometimes denoted quarter bridges). The output of each bridge is connected to a current–voltage converter, then to a multiplexer followed by a differential amplifier.

II. SENSOR DESCRIPTION

The sensor is obtained by cutting, from a thin steel sheet (type 28NG62), sixteen cantilevers that deflect under pressure (Fig. 1). Two metal strain gauges (HBM type LY11, Darmstadt, Germany), having a resistance of 120 Ω and a gauge factor $F = 2$, are bonded onto the upper and lower faces, respectively, of each cantilever that induces in them opposite deformations during deflection. The upper one, R_U, is operated in tension while the lower one, R_L, is operated in compression. The maximum deflection is limited by a metallic tooth (not shown in the figure) to protect the sensing elements from overloads.

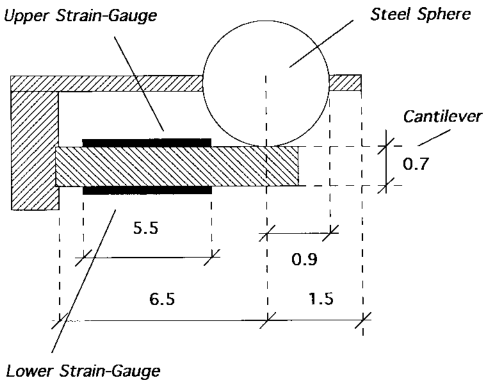

Fig. 1. Structure of the single sensing element in which the upper and lower strain gauges are also shown. The steel sphere transmits to the cantilever (not drown to scale) only the normal force component. The original size of the polymeric carrier of the strain-gauge has been reduced to obtain a more compact array. Dimensions are in millimeters.

By using a technique already developed for the implementation of a ferroelectric polymer tactile sensor [4], a second metallic sheet, with an equal number of circular holes each one corresponding to a single sensing element, is positioned over the first sheet. In each hole, a steel sphere is directly in contact with the front side of the underlying cantilever, but sufficiently far from the strain-gauge to avoid damage. Furthermore, it is constrained at the boundary. In this way, the sphere transmits only the normal component of an external force acting on the upper face to the sensing element.

The sensitivity of the sensor can be changed over a wide range of values from 10^{-1}N to 10 by properly changing the thickness of the metallic support. The actual thickness is equal to 0.7 mm to reach a full scale value of 10 N. In the present version, the planar dimensions of each cantilever are 8 mm × 5 mm; obviously the low spatial resolution of the sensor can be easily increased by using smaller strain gauges and by reducing the size of the cantilevers. The performance of the tactile sensor is summarized in Table I. The calibration procedure has been performed at 24 °C by applying sinusoidal and triangular-wave stress pulses generated by a miniature load cell (Type 9201, Kistler Instrumente AG, Winterthur, Switzerland) driven by an electromechanical shaker and electrically connected to a charge amplifier (Type5007, Kistler Instrumente AG, Winterthur, Switzerland).

III. ELECTRONIC UNIT

Substantially, the sensor consists of an array of Wheatstone half bridges (Fig. 2) in which the couple "dummy gauge-strain gauge" ($R_D - R_U$ or $R_D - R_L$) is connected to a

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TABLE I
MEASUREMENTS HAVE BEEN PERFORMED ON SIX SETS OF STRAIN GAUGES, MOUNTED ON THE SAME MECHANICAL SUPPORT. ENVIRONMENTAL CONDITIONS WERE THE SAME FOR THE PROXIMITY SENSOR [3]. TEMPERATURE WAS 24 °C AND RELATIVE HUMIDITY 77%

frequency	0.01 ÷ 40 Hz	
nonlinearity	1.2 ÷ 1.3 %	(0.1 N < F <10 N)
force resolution	0.05 N	
hysteresis	2.5 % F.S.O.	
temperature drift	0.6 % F.S.O./ °C	(10 °C < T < 35 °C)

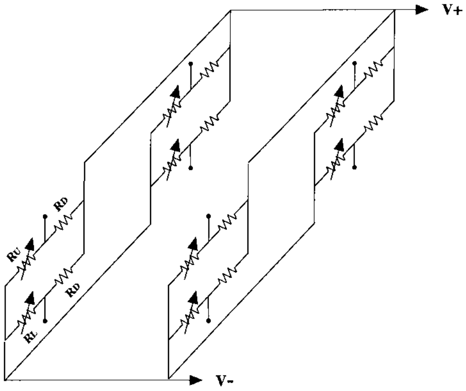

Fig. 2. Tactile sensor configuration that shows the upper and lower piezoresistive arrays (2 × 2 elements). Each couple "dummy gauge-strain gauge" is inserted in a Wheatstone half-bridge circuit and is connected through an analog multiplexer to a differential amplifier (not shown).

current–voltage converter realized with a low noise TL072 operational amplifier (op amp) (see Fig. 3). The outputs of the upper converters, A_1, are connected through an analog differential multiplexer to the inverting input of a single-ended differential amplifier, implemented with a TL071 op amp, A_3. The A_2 lower converter outputs are connected through the same multiplexer to the noninverting input of A_3. The signal related to each sensing element is reconstructed via software after sampling.

The advantage of this circuit topology is twofold. It allows the doubling of the electrical signal generated by the pressure on each cantilever and a drastic reduction in the noise generated by the transducers. Each pair of strain gauges bonded onto the opposite faces of the same cantilever generates pressure signals that have the same amplitude but are opposite in polarity and temperature signals that are equal in amplitude and polarity. In this electrical configuration (see Fig. 3), the push-pull voltages, due to the external pressure, are added in modulus and amplified, if necessary, by the last stage. On the other hand, the voltage generated by temperature gradients of the surrounding environment appears at the same differential inputs as a common mode (CM) signal and is strongly attenuated.

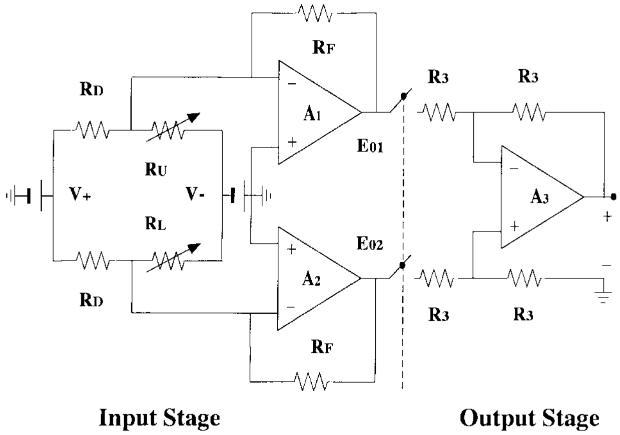

Fig. 3. Electrical connection of the upper and lower strain gauges of a single sensing element to the electronic acquisition unit. Multiplexer channels are not shown. The current signals are converted into voltage signals and amplified by the last stage.

Although the output of a Wheatstone bridge is usually connected to a differential buffer amplifier, also known as instrumentation amplifier [5], in this case two half bridges have been connected to two independent current–voltage converters followed by a single-ended differential amplifier, without loss of sensitivity. In fact, the CM noise signal, which is not rejected by current–voltage converter, is very small. The particular arrangement protects the strain gauges and the electrical connections well against air-flows or temperature gradients. In addition, since the first stage of the electronic unit is very close to the sensor, the loss of sensitivity due to ohmic drop of the lead wires is insignificant and does not need to be compensated.

In the present configuration, the output of the upper or lower channel of the first stage does not depend on the strains induced simultaneously on both the upper and lower piezoresistors, as would happen if a differential buffer amplifier were used. Hence, in the quiescent state, both the channels can be tested and calibrated separately. Furthermore, the gain is selected by using fixed resistors instead of variable resistors, which is preferable when the sensor is integrated in mobile small end-effectors. Finally, the sensitivity can be increased by increasing the bridge supply voltage. Since in this particular topology each op amp of the first stage does not suffer from common-mode voltage limitation, the only limit to the supply voltage is imposed by the piezoresistive strain gauges because of self-heating, as well as the proper limitations of the gauge elements (5 V in our case). A further advantage in using this circuit is the possibility of measuring the temperature separately on each pair of strain gauges in the quiescent state by measuring the voltage at the output of the converters. Both signals also can be added to give a more accurate measurement of the local temperature. In this case, however, very low $1/f$ noise amplifiers must be used, and the preliminary rough results will not be discussed in this work.

If $\varepsilon_{\mathrm{MU}}$ and $\varepsilon_{\mathrm{TU}}$ are, respectively, the mechanical, M, strain and the undesired thermal, T, expansion on the upper, U, strain-gauge, and $\varepsilon_{\mathrm{ML}}$ and $\varepsilon_{\mathrm{TL}}$ are the mechanical strain and the thermal expansion on the lower, L, strain-gauge, when an external force is applied to a single cantilever the relative variations of resistance of the upper and lower sensing elements are respectively

$$\frac{\Delta R}{R_{\mathrm{U}}} = F(\varepsilon_{\mathrm{MU}} + \varepsilon_{\mathrm{TU}})$$

and

$$\frac{\Delta R}{R_{\mathrm{L}}} = F(-\varepsilon_{\mathrm{ML}} + \varepsilon_{\mathrm{TL}})$$

Let R_{F} be the feedback resistance of the current–voltage converter, R the resistance of the strain-gauge in the quiescent state and V the bridge supply voltage. Since, in general, the converter output

$$V_0 = -V\left(\frac{R_F}{R}\right)\left(\pm\frac{\Delta R}{R}\right)$$

is proportional to the ratio $\pm\Delta R/R = \pm F\varepsilon$ (where ε is the global strain), depending on whether the piezoresistor is operated in tension or compression, the signal at the output of the differential amplifier is proportional to

$$F(\varepsilon_{\mathrm{MU}} + \varepsilon_{\mathrm{TU}}) - F(-\varepsilon_{\mathrm{ML}} + \varepsilon_{\mathrm{TL}}).$$

Hence, since $\varepsilon_{\mathrm{MU}} = \varepsilon_{\mathrm{ML}} = \varepsilon_{\mathrm{M}}$, the global mechanical strain, and $\varepsilon_{\mathrm{TU}} = \varepsilon_{\mathrm{TL}} = \varepsilon_{\mathrm{CM}}$, the strain that generates the CM signal, the output voltage is proportional to $2F\varepsilon_{\mathrm{M}}$ while undesired signals are completely rejected.

By supplying the op amp with a dc voltage of ± 15 V and by choosing $V^{+} = -V^{-} = 4$ V, $\varepsilon = 0.1\%$ and $R = R_{\mathrm{U}} = R_{\mathrm{L}} = 120\ \Omega$, to have an output voltage swing $V_0 = -E_{01} + E_{02} = 16$ V the resistance must be $R_{\mathrm{F}} = 120$ kΩ. In fact the output offset voltage of each converter, is given by the following expression

$$V_{0S} \approx -R_{\mathrm{F}}\left(I_1 + \frac{2V_{i0}}{R}\right)$$

where I_1 is the inverting input bias current and V_{i0} is the input offset voltage, and is approximately equal to -6 V. Since the typical and the maximum value of the op amps output swing are 28 V and 32 V, respectively, it is preferable to limit the signal at both the inverting and noninverting input of the second (differential) stage to 14 V (at most 16 V). On the other hand, the unipolar output voltage $E_{01}(E_{02})$ of the first stage upper (lower) converter cannot exceed this value because of saturation problems. Hence, the maximum output ac voltage $E_{01} = V_{01} - V_{0S} = -8$ V (at most -10 V) in agreement with the chosen value of R_{F}. In any case, the offset, together with the thermal drift signal, is sufficiently canceled by the differential last stage that is kept from saturation when a force of 10 N is applied. An output offset-voltage balancing circuit for each converter could be used but that would complicate the circuit topology. Op amps supplied with a unipolar dc voltage have not been used so that, sometimes, temperature related signals having opposite polarity with respect to pressure related signals could be measured.

IV. CONCLUSION

A simple, efficient and cost-effective tactile sensor has been described, with low spatial resolution, for robotic applications. The version described consists of sixteen pairs of piezoresistive strain gauges mounted on opposite faces of an equal number of metallic cantilevers. The signal generated by each element is sampled through an analog multiplexer, amplified by a fixed-gain differential stage, and reconstructed via software. Although particular care must be used in choosing and assembling the electronic components, the particular structure allows an increase in the sensitivity of the sensor and a drastic reduction in the thermal noise, which is the largest source of error in similar devices. In addition, the sensor does not suffer from loss of sensitivity due to lead wires and the interposed multiplexer channels have a negligible influence on the detected signals. Other causes of loss of sensitivity and the possibility of also measuring the local temperature need a more detailed analysis.

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