Integrated Circuit Interface for Artificial Skins

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ABSTRACT

Artificial sensitive skins are intended to emulate the human skin to improve the skills of robots and machinery in complex unstructured environments. They are basically smart arrays of pressure sensors. As in the case of artificial retinas, one problem to solve is the management of the huge amount of information that such arrays provide, especially if this information should be used by a central processing unit to implement some control algorithms. An approach to manage such information is to increment the signal processing performed close to the sensor in order to extract the useful information and reduce the errors caused by long wires. This paper proposes the use of voltage to frequency converters to implement a quite straightforward analog to digital conversion as front end interface to digital circuitry in a smart tactile sensor. The circuitry commonly implemented to read out the information from a piezoresistive tactile sensor can be modified to turn it into an array of voltage to frequency converters. This is carried out in this paper, where the feasibility of the idea is shown through simulations and its performance is discussed.

Keywords: tactile sensors, voltage-to-frequency converters, bioinspired chips

1. INTRODUCTION

Although the work on tactile sensors or artificial skins is not new, it is frequently said the most interesting results are still to come [1][2][3]. The interest and research in this field have increased a lot in the last years. This is because more advanced technologies are able to provide complex and smart sensors that can face applications in unpredictable or unstructured environments wich cannot be coped with simpler sensors. There are several very interesting applications that fit this scenario, for instance in medicine, robotics of food processing industry, virtual reality and telepresence, or security [4][1].

Despite the previous works, there is still a gap in the sense of achieving a tactile sensor that is easy to use and robust, but also provides a large amount of useful information that can be exploited in applications [5][3]. The design of tactile sensory-processing systems requires, first the design of sensing capabilities that can be useful, their evaluation on manipulative tasks, and finally the design of the whole system [6][7].

Moreover, the sensor must have the minimum number of integrated circuits and I/O connections in order to reduce the number of cables mounted on the joints of robots and machinery. It must be small and light to be integrated in hands and grippers while not interfering their normal operation. It must also be able to cover large surfaces as a kind of artificial skin. It must be robust, reliable, easy to use, cheap and it should be possible to fabricate in a batch manufacturing process. Finally, it must be able to process a large amount of data in a short time to cope with real time demands of tasks like early slip detection [1][6][8][5][3].

There are not many reported works on sensors that implement not only signal conditioning but also pre-processing on the same sensor substrate [9] presents a prototype of smart nMOS chip. This chip consists of an array of electrodes that is

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covered with a piezoresistive material and circuitry to make convolutions and serial communication. Another work that also involves pre-processing is reported in [10], where a sensor to detect spacial patterns like different textures is implemented. There have been other works that implement circuitry on the same sensor substrate and are based on modified MOS technologies or on coating the sensor surface with some material [11][12][13]. Another approach implements blocks with signal conditioning and communication capabilities to be placed between conductive rubbers in order to obtain smart tactile sensor [14]. It is clear that if a tactile sensor needs to cover a large area, it must be flexible in some degree. However, commercially available MEMS or integrated circuit technologies are not based on flexible substrates. Thus, until more advanced technologies are developed to make smart skins [2][15], it is a better approach the use of the tactile sensor plus some embedded circuitry. For instance, [16] reports a set of tactile sensors with some circuitry for signal conditioning and communication. It is based on discrete components and a microcontroller, a similar work is reported in [5]. The design of a tactile co-processor on an mixed-signal ASIC is also the goal in [8].

With respect to the sensor, although there are implementations of tactile sensors based on piezoelectric materials, capacitive transduction [17], or on optical principles [18], most reported implementations are based on piezoresistive materials [19][20], (Tekscan-[21]),(FSR, Interlink [22]). Their popularity is due to the possibility of making large and flexible sensors in a simple and reliable way, by covering an array of electrodes with the material, which provides an array of pressure sensitive resistors. However, the circuitry which is employed to read out data from these sensors needs to be designed very carefully in order to avoid interferences caused by currents through lateral resistors, i.e. resistors between nodes.

One of the reported techniques which provides better results on this aspect consists of grounding both sides of the resistors that should not contribute to the output current [23]. This paper proposes a simple solution to implement an analog to digital conversion as front end interface of digital circuitry in a smart tactile sensor. This circuitry implements the grounding strategy and employs Voltage-to-Frequency Converters (VFCs) [24] to carry out the analog to digital conversion. The converters are simple to implement and low-cost in terms of area and power requirements. Their main drawback is their relatively mid to long conversion times which is inherent to their principle of operation. On the other hand, this feature results in very small nonlinearity errors and impossible output codes losings. Besides, it makes these converters less error-prone that those which rely on matching a whole ladder of resistor for quantization like Successive Approximation or Flash converters [25]. Moreover, their conversion time can be short enough to cope with the dynamic requirements of medium size tactile sensors. Compared with other techniques which require that the input is “frozen” with a sample-and-hold, the VFCs will give repeatable results in the presence of high frequency noise (relative to the measurement period).

2. RAW PIEZORESISTIVE TACTILE SENSOR

Fig.1(a) shows a possible implementation of the piezoresistive tactile sensor, where a sheet of piezoresistive material (not shown in the figure) covers the electrodes. This device can be modeled by an array of resistors that correspond to those between the inner and outer electrodes in Fig.1(a). However, other lateral resistors are also present in the real sensor and can be modeled as resistors between the inner electrodes of different nodes in the array of Fig.1(a). In order to reduce the undesired contribution from these lateral resistors, the circuitry commonly implemented is shown in Fig.1(b)[23]. The array is read sequentially and only one row is driven at a time. Note that the output amplifier forces all output nodes to be connected to the same voltage level in order to avoid the parasitic currents due to lateral resistors (among nodes in the row), and that rows that are not driven are also grounded, thus lateral resistors are virtually shortcircuited and do not contribute to the output.

3. SYNCHRONIZED VOLTAGE TO FREQUENCY CONVERTER

Fig. 2 shows a symbolic schematic (including waveforms) of a synchronized voltage to frequency converter, whose operation can be simply described as follows. If the integrator output crosses the threshold vref, the comparator places a high value at the bistable input (suppose that Q is high). However, the output does not follow it immediately, but it is synchronized with the clock by the flip-flop and changes at the next rising edge of the clock. At the same time, the inverted output (low value) is fed-back to the flip-flop input , thus the output will go back down at the next rising edge of the clock

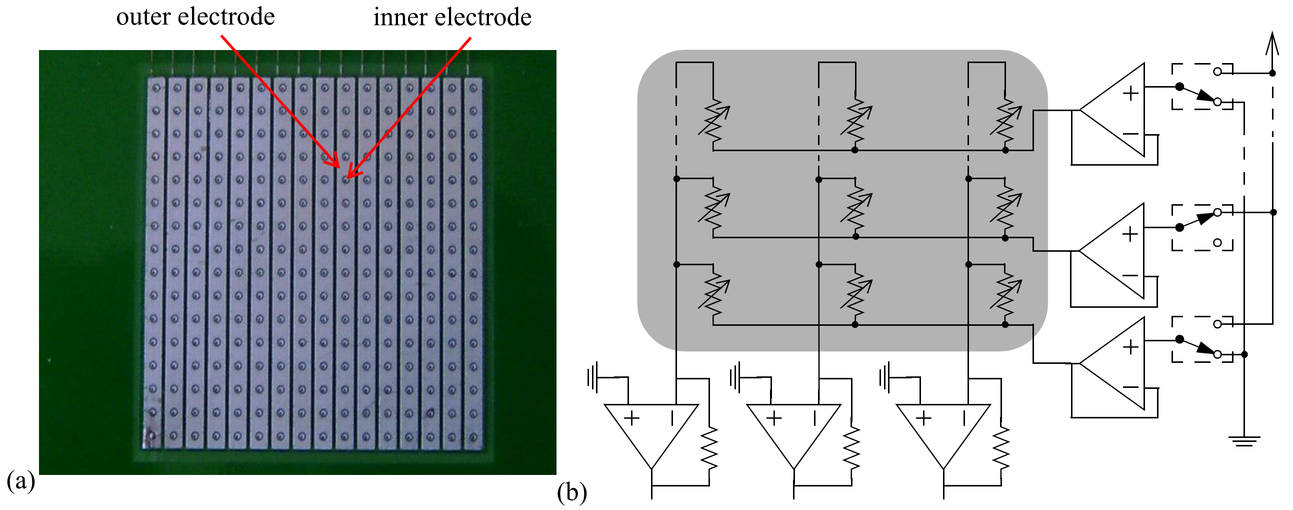


Fig.1. Tactile sensor based on piezoresistive materials (the sheet of sensitive material has been removed) (a) and simple model with common signal conditioning circuitry.

and the duration of the output pulse is just one clock cycle. Note that the circuit operates in the charging phase as long as the output is high, thus

$$\Delta v_C = T_{CLK}\frac{dv_C}{dt} = T_{CLK}\frac{(i_0 - i_D)}{C} \tag{1}$$

Once the capacitor is charged for a clock cycle, it is discharged again until v_C reaches v_{ref} and the rising edge of the clock updates the flip-flop output. $i_D = v_{in}/R$ is the constant current that discharges *C*, thus the time t_D is given by

$$t_D = \frac{|\Delta v_C|}{\left|\frac{dv_C}{dt}\right|} = \frac{T_{CLK}((i_0 - i_D)/C)}{\frac{i_D}{C}} = T_{CLK}\left(i_S\left(\frac{i_0 R}{v_{in}} - 1\right)\right) \tag{2}$$

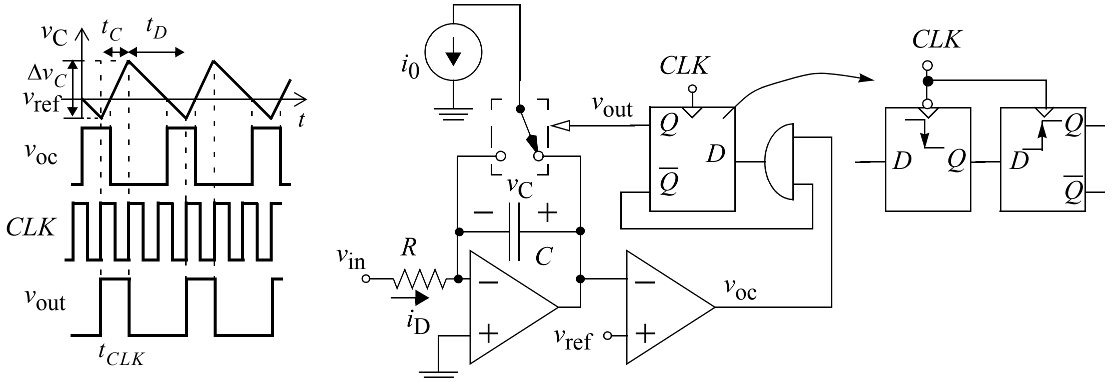


Fig.2. Synchronized charge balancing converter. The charging phase length is fixed by the clock period, which is supposed very accurate.

where i_S in (2) corresponds to the next superior integer function.The cycle is repeated and the output of the flip-flop results in a periodic signal whose frequency is

$$f = \frac{1}{T_{CLK} + t_D} = \frac{1}{T_{CLK}\left[1 + i_S\left(\frac{i_0 R}{v_{in}} - 1\right)\right]} \tag{3}$$

The circuit in Fig. 2 has a problem to solve due to the lack of synchronism between the input voltage and the clock. This problem can be solved by building the D flip-flop with two flip-flops in cascade or with a flip-flop and a latch in cascade, like the right part of Fig. 2 shows, where the clock edge for both flops is delayed.

4. INTEGRATED INTERFACE

Fig. 3 shows a straightforward interface with the sensor where the amplifiers in Fig. 3 have been replaced by voltage to frequency converters. First, note that the input node is grounded due to the negative feedback loop in the integrator. Thus, the strategy to reduce the errors caused by lateral resistors is implemented. Second, note that the voltage input of the converters is set to a constant value $V_{bsensor}$. In our circuit, the sensed variable is not the voltage input but R in (3). Actually, we are interested in measuring the force, whose relationship with resistance in piezoresistive materials is approximately,

$$Force = \frac{K}{R} \tag{4}$$

where K is a constant. Hence, from (3) and (4) we can write,

$$Force = \frac{T_{CLK} i_0 K f}{V_{bsensor}} \tag{5}$$

Thus, the force exerted on a single node of the tactile array is proportional to the frequency of the VFC output signal. The output frequency signal from a VFC can be easily translated into a digital code in order to be processed, stored or displayed by conventional digital circuits and systems. Fig. 4 shows the simplest way to carry out this conversion. There, a counter, which is only enabled for a given interval T_G (named gate time), counts the transitions of the input signal. Thus, the counter

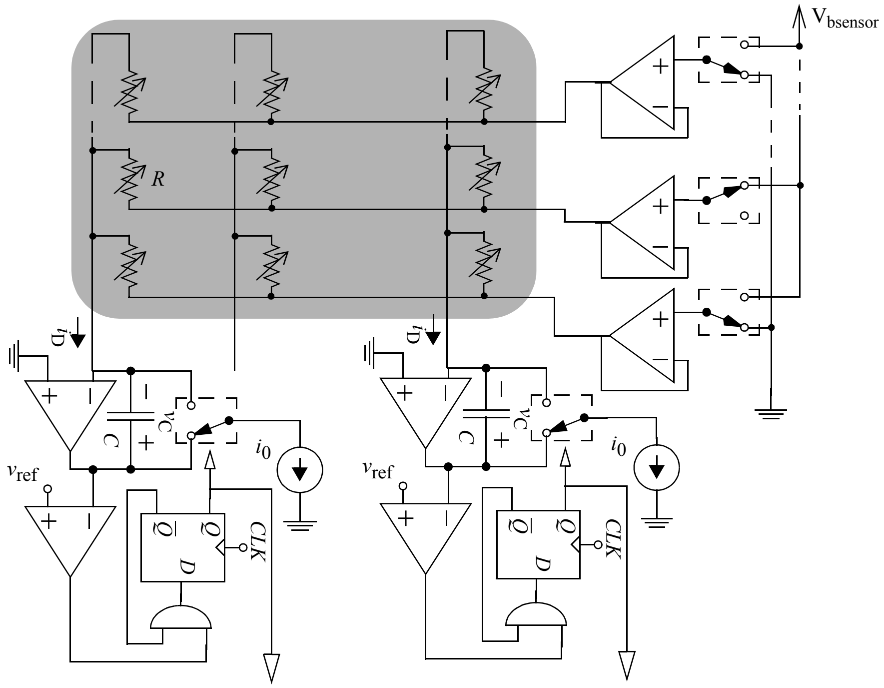


Fig.3. Direct interface with VFCs in the front end.

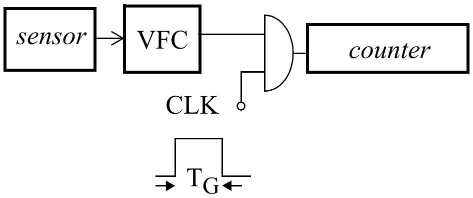


Fig.4. Digital processing of the output frequency signal of a VFC. The transitions in a fixed time interval T_G are counted and the average frequency is computed.

stores the decimal value $N = f \times T_G$, which encodes the input voltage in a binary number. If $FS = f_{max} - f_{min}$ is the full scale frequency range, the resolution of the A/D converter will be

$$n = \log_2(FS \times T_G) \tag{6}$$

where *n* is the number of bits of the output digital word. Hence, the larger the gate time, the larger the resolution, which is also limited by the resolution of the VFC. Note that the input frequency must remain constant during the gate time for proper conversion, otherwise an average of the input frequency is computed.

Let us now design the interface for a specific case of a sensor with 16 x 16 taxels (nodes in Fig. 1) [Melch00] whose content should be read in 2ms (in order to detect features like slip, the throughput limit is around 250Hz, meaning that the array has to be read in 4ms at most [26]) with 8-bits of resolution [8]. Note that just the nodes of a row in Fig. 1 are read out by the set of VFCs, thus the conversion time should be 2/16 ms for the whole array. This means that $T_G = 1/8\ ms$, hence $FS = 2,048MHz$ from (6) and taking into account that $n = 8bits$. Equation (3) and the description of the way the circuit in Fig. 2 works give the following expression for the frequency of the clock,

$$f_{CLK} = max\left(f\left[1 + i_S\left(\frac{i_0 R}{v_{in}} - 1\right)\right]\right) \tag{7}$$

Since $i_D = v_{in}/R$ must be smaller than i_0 for the charge of the capacitor to be possible, $i_S\left(\frac{i_0 R}{v_{in}} - 1\right) \geq 1$ and (7) results in $f_{CLK} = 2f$. Thus, the frequency of the clock should be at least $f_{CLK} = 4,096MHz$. Taking into account additional setup times (like delays in the processing of data and multiplexing the circuitry), a clock of 5MHz in Fig. 2 is considered as a good and feasible choice (we have to calculate again T_G for a maximum output frequency of 2.5MHz). We can also conclude that,

$$2T_{CLK} \leq T_{CLK} i_S\left(\frac{i_0 R}{v_{in}}\right) \leq 257 T_{CLK} \tag{8}$$

If we consider $\frac{i_0 R}{v_{in}}$ as an integer to ease the calculations, we can write,

$$\frac{2V_{bsensor}}{i_0} \leq R \leq \frac{257 V_{bsensor}}{i_0} \tag{9}$$

we can also write from (1),

$$C \approx \frac{T_{CLK} i_0}{(\Delta v_C)_{max}} \tag{10}$$

Note that (9) limits the range in resistance of the sensor. For low resistive sensors, the ratio $\frac{V_{bsensor}}{i_0}$ should be low, while it should be high for high resistive sensors. A maximum value of i_0 is imposed by the technology and the goal of low power consumption that is required for embedded sensors. If we take $i_0 = 2mA$ to cope with sensors in the range of Kohms, equation (10) provides a value of 400pF for the capacitance of the integrator for $(\Delta v_C)_{max} = 1V$. This capacitance is too large to be implemented on chip, thus an external capacitor would be the best choice. Another alternative consists of adding a current scaling stage before the VFC. This is illustrated in Fig.5., where a current conveyor is used to keep the input at a constant voltage as required to ground the lateral resistors in the sensor. The current scaling is made in the simplest way with an asymmetrical current mirror, as Fig.5(a) shows in a direct implementation. A slight modification results in the simpler implementation shown at Fig.5(b), where the input current to the frequency converter has opposite sign to that in

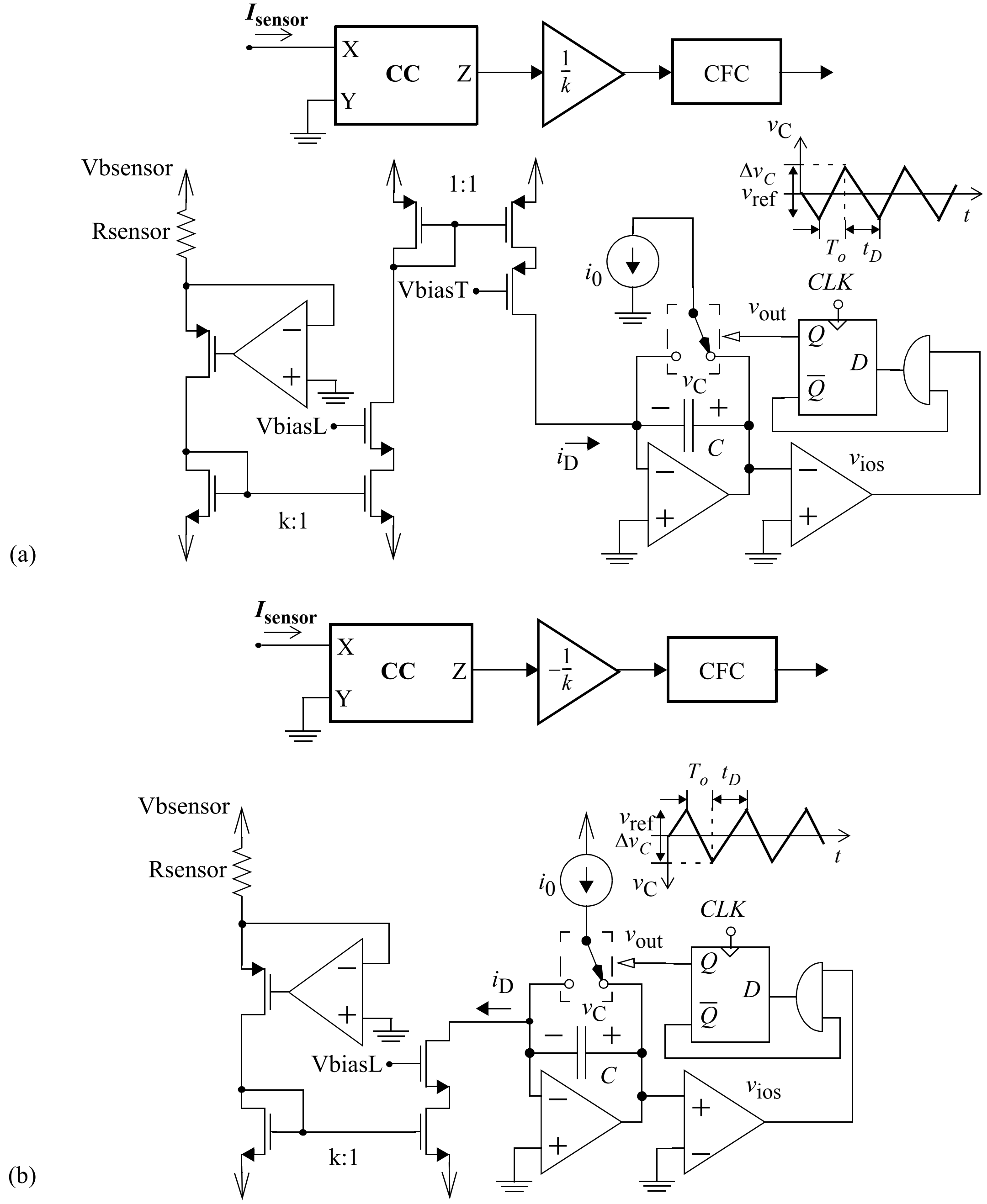


Fig.5. Possible implementations of the interface with current conveyors and current mirrors

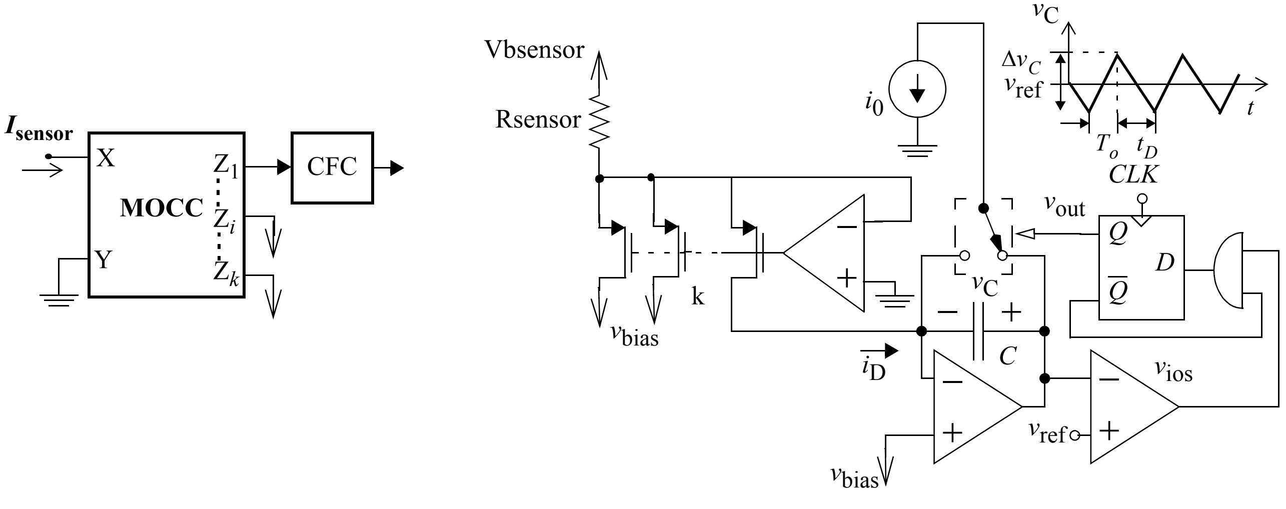


Fig.6. Interface with a multiple output current conveyor

Fig.5(a), thus the converter is modified to cope with this requirement. Finally, a simpler implementation could be achieved with a multiple output current conveyor, as Fig. 6 illustrates. The input current is divided and only the current from one output is converted into a frequency. This is certainly the simplest implementation, although it requires a low impedance reference V_{bias}. Note that current switches can be easily added to the circuitry in Fig. 5 and Fig. 6, specifically to the array of k transistors in the current mirror (Fig. 5) or current divider (Fig. 6) to achieve programmability of the interface and being able to carry out the analog to digital conversion of the signal provided by sensors with different ranges of resistance.

5. RESULTS

In this section, simulation results showing the performance of our proposed interface, using a linear tactile sensor with 16 elements, are presented and discussed.

The piezoresistive tactile sensor presented in section 2 has been used to get the stimuli to be applied in our simulations. In this case, we have used a piezoresistive material from Interlink to cover the electrodes. The relation between the applied force and the resistance between the electrodes of each taxel has been estimated experimentally. For a range of applied force from 0 to 15N (1.5 Kg.), this material exhibits a variation of resistance from 60KOhms to a few hundreds of Ohms. This information has been used to tune the interface circuit proposed to accomplish the specificatons related to this specific material. Thus, in order to get a resolution of 8 bits for this range of resistance, we need to be able to measure a minimum variation of the sensor resistance of 250 Ohms.

We have performed simulations using the three different interface circuits in Fig. 5 and Fig. 6, with a current scale constant k of 80. The design parameters have been chosen to get the specifications already described. Taking into account the measured range of resistance, we have designed our interface to be able to measure a minimum resistance of 500 Ohms, and a minimum variation of the sensor resistance of 250 Ohms. Thus, following the equation (9), we have chosen $V_{bsensor} = 0{,}5V$ and $i_0 = 25uA$. The selected clock frequency is 5MHz, due to the reasons explained in section 4. Thus, the value of the capacitance, given by (10), for a $(\Delta v_C)_{max} = 1V$, is C=5pF, which is a suitable value for the integration of the system.

Fig. 7 shows the relationship between the output frequency signal and the sensor resistance.. It can be observed that specifications have been met. As stated in equation (9), the minimum resistance that can be measured is

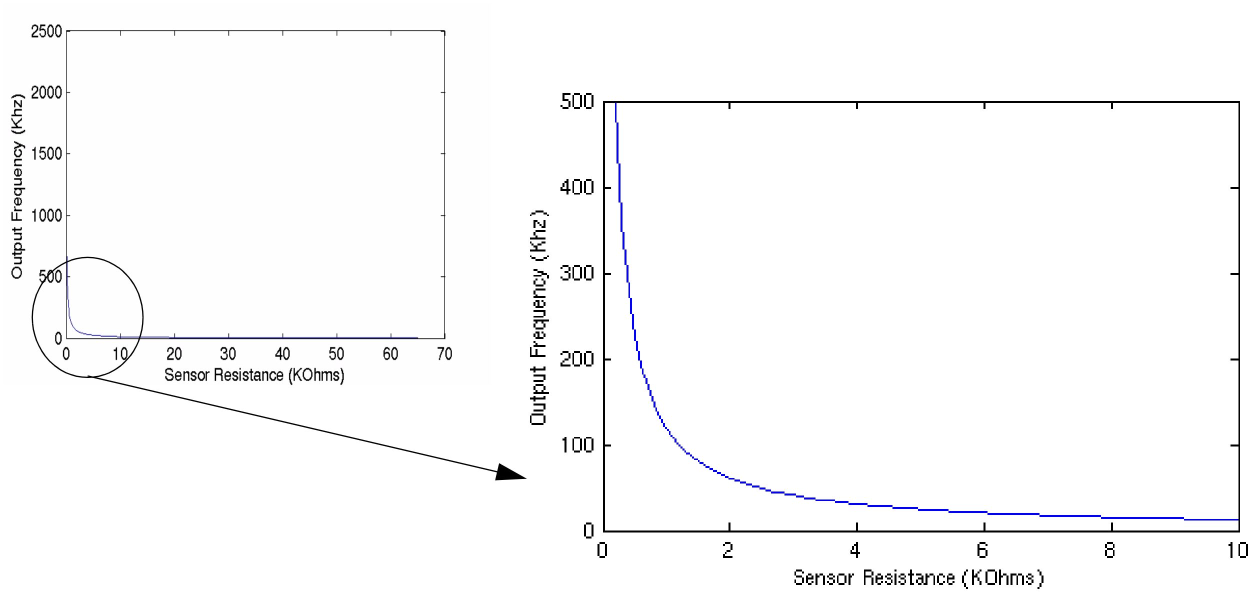


Fig.7. Output frequency of the VFC vs. sensor resistance

$R_{min} = \frac{2V_{bsensor}}{i_0} = 500\text{ Ohms}$, which corresponds to the maximum frequency signal at the output of the VFC, $f_{max} = 1/(2T_{CLK}) = 2.5\text{Mhz}$, as stated in equation (8). Thus, considering a resolution of 8-bits, the maximum resitance that can be measured is $R_{max} = \frac{257V_{bsensor}}{i_0} = 64.25\text{K Ohms}$. The minimum variation of the sensor resistance that means a change at the output frequency is $\Delta R = \frac{V_{bsensor}}{i_0} = 250\text{ Ohms}$. It can also be noticed that the output frequency is not linearly proportional to the sensor resistance. However, as shown in Fig. 8, the output frequency of the VFC is proportional to the

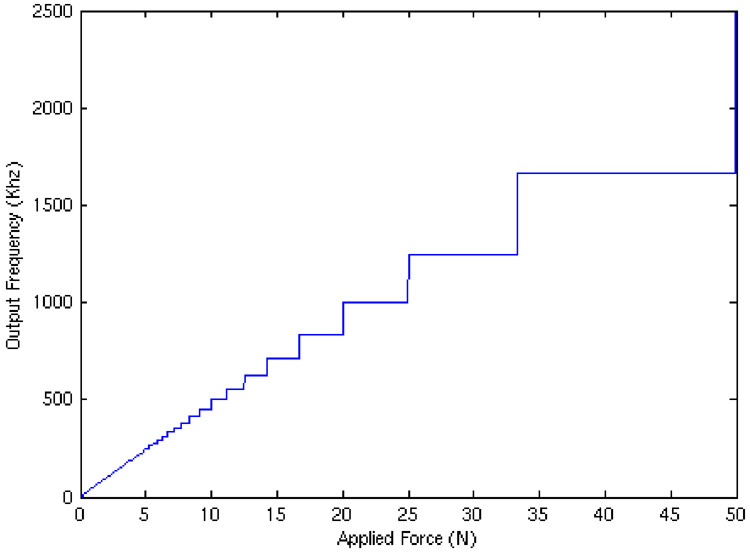


Fig.8. Output frequency of the VFC vs. the applied force

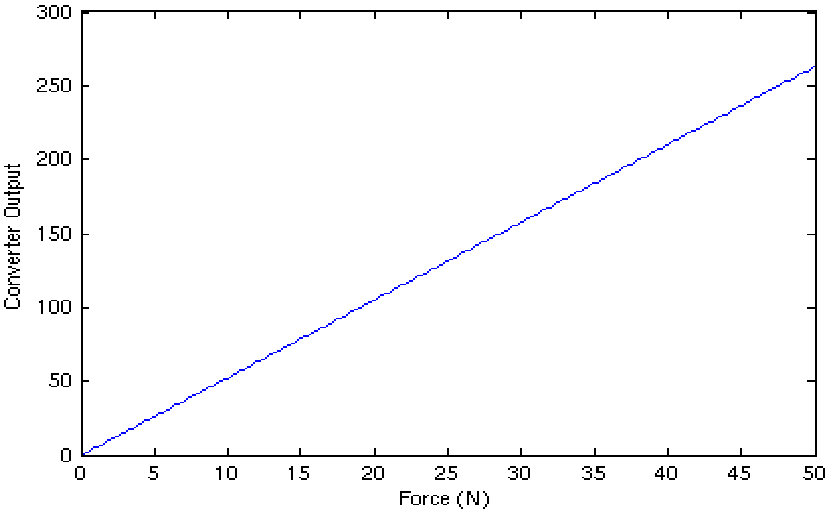
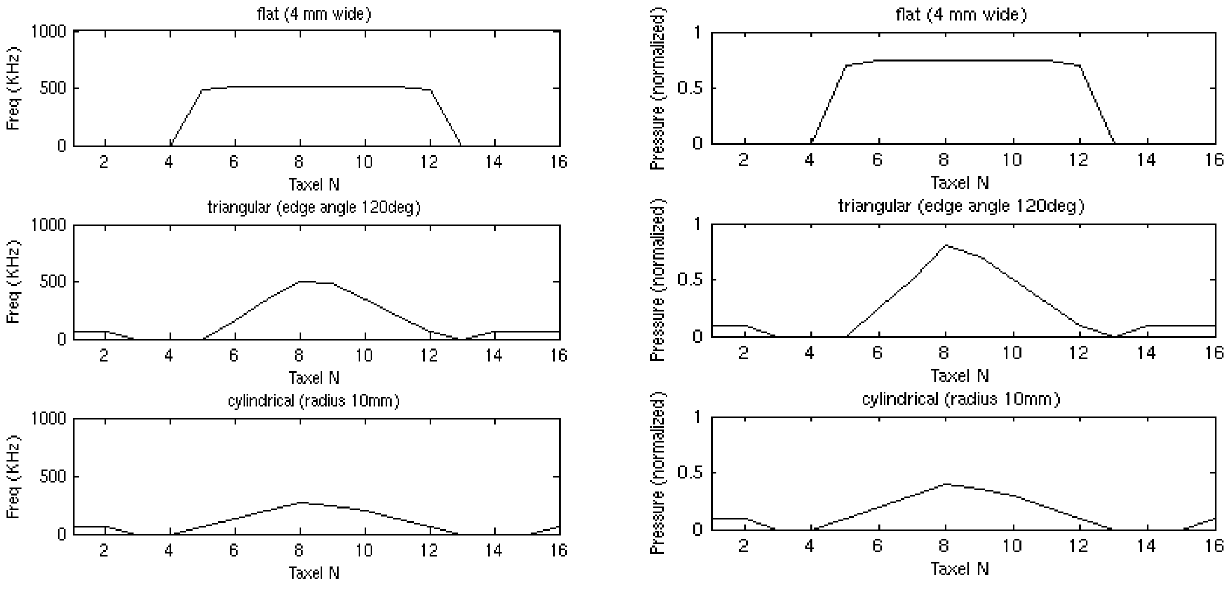


Fig.9. Digital Code vs. applied Force

force applied to the tactile sensor. Thus, as can be observed in Fig. 9, when we measure this frequency, the digital code stored in the counter is proportional to the applied force.

We have used the three different interface circuits presented in Fig. 5 and Fig. 6 to perform our simulations, obtaining identical results in all cases. Fig.10(a) shows the output from simulations with the tactile sensor with 16 elements that are under a pressure whose profile is depicted in Fig.10(b). Three different indenters shapes have been considered: Flat, triangular and cylindrical.



(a)

(b)

Fig.10. Simulation results (a) and stimuli model for different indenters (b)

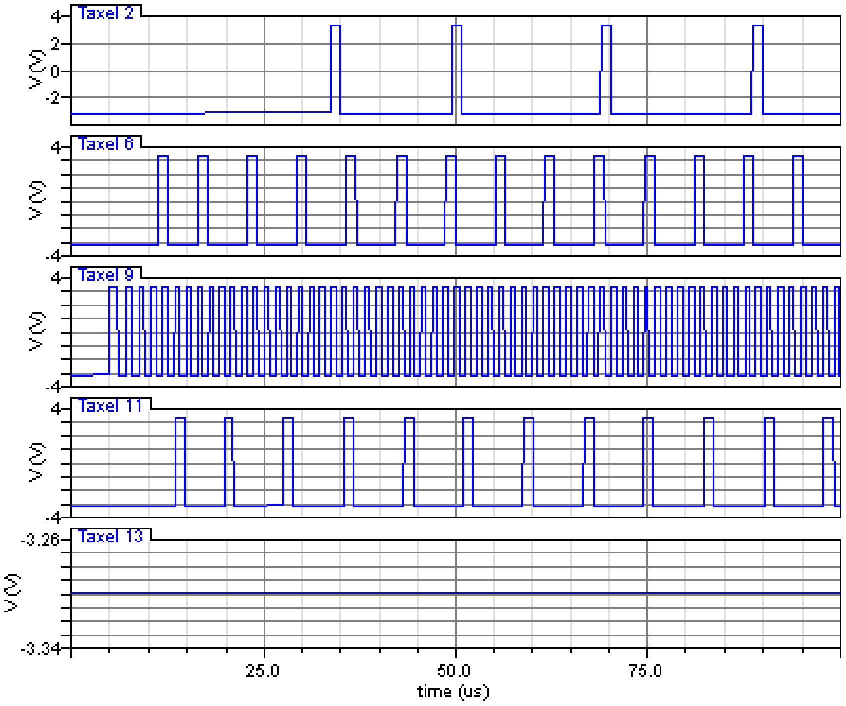


Fig.11. Transient Simulations Results for triangular indenters.

As can be observed from these simulation results, output frequency and applied force are linearly proportional. This effect can be observed in Fig. 11, which shows the transient response for different taxels of the sensors, when pressing a triangular indenter on the array of sensors.

6. CONCLUSIONS

This paper proposes the use of voltage to frequency converters to perform the analog to digital conversion in the front-end interface of tactile sensors based on piezoresistive materials. The need for specific hardware is due to the requirements of signal conditioning of a large amount of sensors in a short time, in order to being able to face real time manipulative tasks. This approach would also allow the implementation of most of the circuitry in just one or two chips to get a smart and compact tactile sensor. The sensors based on piezoresistive materials or conductive rubbers are quite simple, but they must be carefully biased in order to avoid the interference of parasitic lateral resistors. This is carried out by grounding both sides of these resistors, which means the implementation of a low impedance input node. This can be accomplished with a direct connection with a voltage to frequency converter due to the negative feed-back loop in the integrator in the input stage of the converter. This approach is simple and direct, but it only works for high resistive sensors. If the resistivity of the sensors is low, external capacitors are required, or the input current should be scaled down before entering the converter. The latter can be realized with a current conveyor to keep the low input impedance plus an asymmetrical current mirror. It can also be implemented in a simpler way with a multiple output current conveyor that already includes the current division. The resulting implementations are simple and have the advantages of the voltage to frequency converters in terms of low cost, high linearity and robustness to high frequency input noise. However, the quantization of time makes these converters slow when compared to others that employ electrical references in the quantizer. Hence, they can be suitable to interface medium size tactile sensors (for instance 16 x 16 taxels), but might not cope with dynamic requirements associated to very large tactile sensors in real-time demanding tasks.

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