Interface Electronics Design for POSFET Devices Based Tactile Sensing Systems

Leonardo Barboni, Ravinder S. Dahiya, Giorigio Metta and Maurizio Valle

Abstract— **This work presents the development of novel POSFET (Piezoelectric Oxide Semiconductor Field Effect Transistor) devices based tactile sensing system. The tactile sensing system, primarily developed for the robotic applications, consists of 5×5 POSFET touch sensing array and the associated read out and data acquisition system. The POSFET touch sensing devices are obtained by spin coating piezoelectric polymer P(VDF-TrFE), poly(vinylidene fluoride – trifluoroethylene), film on the gate area of MOS (Metal Oxide Semiconductor) devices and polarizing the film in situ. To detect contact events, the taxels utilize the contact forces induced change in the polarization level (and hence change in the induced channel current) of piezoelectric polymer. Both, individual taxels and the array are designed to match spatio-temporal performance of the human fingertips. The data acquisition system is implemented with off-the-shelf electronic components and its design takes into account both the application related requirements as well as the constraints posed by existing hardware on the humanoid robot 'iCub'. The biasing scheme for using POSFET devices and the problems thereof are also been discussed.**

I. INTRODUCTION

Future robots will be expected to work closely and interact safely with humans as well as real-world objects. Among various sensing modalities needed for this purpose, the sense of touch is particularly important. Unlike other senses (e.g. vision, audio), it involves complex physical interaction, and plays a fundamental role in estimating properties such as shape, texture, hardness, material type and many more. Such properties can be better estimated by touching or physically interacting with the objects - as humans do. The sense of touch provides action related information, such as slip, and helps in carrying out actions, such as rolling an object between fingers without dropping it. All these, highlight the importance of sense of touch and call for equipping various joints for robot's body with intrinsic force sensors and for covering the robot's body with extrinsic sensors or tactile sensors. The work presented here pertains to the extrinsic or tactile sensing.

While it is desirable to have tactile sensors over whole body, the robotic hands, especially the fingertips, are accorded higher priority due to their involvement in majority of daily tasks (such as exploration, manipulation and interaction). Further, the desire to impart human like touch sensing capability to robots, makes it necessary to place a large number of tactile sensors on body parts such as fingertips of a robot. Over the years, tactile sensing technology has improved and many force/pressure sensors and sensing arrays, using different materials and transduction methods, have been developed [1]. Most of these sensors are big in size and slow enough to detect static and quasi-static contact events. However, real world contact events are generally dynamic in nature. The bigger size too makes many sensors unsuitable for body sites like robot's fingertips. For fingertips, large numbers (high density) of conformable and fast responding touch sensors are needed. For these reasons, miniaturized touch sensors using MEMS (Micro-Electro-Mechanical-System) approach [2] and mechanically flexible sensors using organic FETs (Field Effect Transistors) have been developed [3]. Yet, the effective utility of tactile sensing in robotics is largely missing. Perhaps, the solution lies in going beyond developing the sensing technology. In other words, there is need to develop a tactile sensing system that includes not only sensors but also the electronics to acquire, condition and transfer the tactile data to higher perceptual levels. To this aim, the work presented here extends the previous works on POSFET touch sensing devices [4] and tactile sensing chips [5].

This work extends our previous works, on novel POSFET touch sensing devices [4] and tactile sensing chips [5], to obtain the tactile sensing system for the fingertips of humanoid robot 'iCub' [6]. The key features of the tactile sensing system are: the 5×5 POSFET tactile sensing array, the readout and the data acquisition system. With center to center distance of 1.5 *mm* between adjacent taxels, the tactile arrays have human fingertip like spatial resolution. Further, the taxel size of $1mm \times 1mm$ ensures human like spatial acuity. This paper is organized as follows: The concept and working of POSFET touch sensing devices are explained in section II. The design of tactile sensing arrays is also presented in section II. The development of the data acquisition for acquiring POSFET output and the results therefrom are presented in section III. The data acquisition system presented in section III is implemented with off-the-shelf electronic components. The data acquisition system presented in section III is implemented with off-the-shelf electronic components because it is an intermediate step towards system on chip integration. The design takes into account the application related requirements as well as the constraints posed by existing hardware on the humanoid robot 'iCub'. The biasing scheme for using POSFET devices

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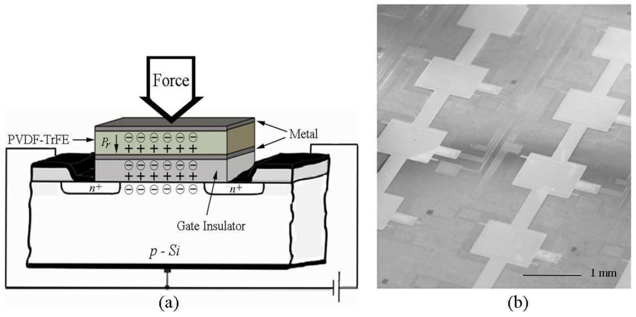


Fig. 1. (a) The Structure and working of a POSFET touch sensing device. (b) A part of 5 × 5 POSFET tactile sensing array, after fabrication [4], [5].

and the problems thereof are also been discussed in section III. Finally, section IV summarizes the results along with a note on future work.

II. POSFET TACTILE SENSING ARRAY

A. *Structure and Working of POSFET Device*

The structure of POSFET taxels, shown in Fig.1, is similar to a metal-ferroelectric-metal-insulator-semiconductor FeRAM (Ferroelectric Random Access Memory). The fixed charges $\pm Q$, shown in Fig.1, appear due to the remanent polarization (P_r) of the piezoelectric polymer film and the charge neutrality condition. The charge carriers thus accumulate at the surface of the semiconductor according to the polarization direction. For piezoelectric polymers working in thickness mode, as in this work, the mechanical stress T_3, electric field E_3 and electric displacement D_3 are related as [7]:

$$D_3 = d_{33}T_3 + \varepsilon_{33}E_3 \tag{1}$$

Where, d_{33} and ε_{33} are the piezoelectric and dielectric constants of piezoelectric polymer respectively. Following (1), the electric displacement and hence the polarization can be controlled by the electric field E_3 and the applied force F or stress T_3. While former is used in FeRAM to switch the polarization state, the latter is used in the POSFET taxels to modulate the charge in induced channel of underlying MOS device [4]. Thus, the force variation is directly reflected into channel current of POSFET devices - which can be further processed by an electronic circuitry that may be present on the same chip. Thus, each taxel is an integral "sensotronic" unit comprising of transducer and the transistor and is capable of 'sensing and partially processing at same site'. In this sense, a POSFET taxel can be compared with the mechanoreceptors in human skin - that not only sense the contact parameters, but also partially process the tactile data at same site [8]. Such a marriage of sensing material and the electronics helps in improving signal to noise ratio and the force sensitivity.

A similar approach, but using extended gates, has been reported in past for ultrasonic [9] and force sensing [10]. The extended gate approach brings the sensor and conditioning electronics closer and hence the overall response is better than the conventional approach - where the sensor and conditioning electronics are placed apart. However, extended gates introduce a large substrate capacitance, which in turn, significantly attenuates the voltage available at gate terminals of MOS transistors. Thus, benefits of closely located sensor and electronics are not fully exploited. Further, the extended gates occupy a large area which otherwise can be used for on-chip electronics. The reliable interconnects between extended gate and MOS transistor is also an issue - more so in case of flexible touch sensing devices. The POSFET touch sensing devices used in this work are relatively free from such problems. They have linear response over wide range of contact forces (0.1-5 N at 20 Hz) and have already been tested for wide dynamic range (forces with constant amplitude and variable frequency) of 2 Hz – 2.13 kHz, which is much wider than previously reported works [4], [5]. The ranges of both amplitude as well as frequency of mechanical stimulus, for which POSFET devices have been tested, are also much wider than that experienced by humans in normal manipulative tasks.

B. *Design of POSFET Tactile Sensing Arrays*

The 5 × 5 element tactile sensing arrays, a part of which is shown in Fig. 1, are designed to have spatial resolution and acuity similar to that of human fingertips. The overall dimension of the tactile sensing chip is 1.5 cm × 1.5 cm. Each POSFET taxel on the array is designed to be 1 mm × 1 mm in size, thus ensuring human like spatial acuity. The center-center distance of 1.5 mm between two adjacent taxels ensures human like spatial resolution. The MOS part of the POSFET taxel is obtained by using the n-MOS technological module of a non standard CMOS technology, based on 4 μm p-well ion sensitive FET (ISFET)/CMOS process. The MOS devices are designed with interdigitated structure, for high aspect ratio (W=7500 μm; L=12 μm) and hence large transconductance. The fabrication steps for realizing POSFET touch sensing devices and the tactile sensing arrays are explained elsewhere [11], [5]. The tactile sensing arrays, tested previously, are able to detect dynamic contact events like rolling that vary both in space and time.

III. ACQUISITION SYSTEM FOR PERCEPTUAL TASKS

The POSFET touch sensing devices as well as the tactile sensing arrays have been tested over wide range of dynamic contact forces - as explained in the previous section. However, there are many challenging issues, before these arrays can be integrated on the robot's hands and effectively used thereafter. One of the immediate challenges is designing a suitable read out circuitry for acquiring the tactile data. The read out circuitry is needed to acquire the tactile data from 25 POSFET devices. Various factors such as biasing configuration of POSFET devices, application, availability of space on robot's hand and existing hardware like communication channels etc. on the robot's body, influence the design of read out circuitry. As an example, the tactile sensing array must be scanned in such a way that the POSFET responses to contact force having frequency contents up to 1 kHz can be successfully recovered. Further, the POSFET devices must be used in such a way that they respond to the full range of contact forces (0.01–10N) before MOS transistor switches to a non-operational mode.

A suitable bias configuration for POSFET devices could be using a current source between the source terminal of the MOS transistor and -V_{ss}, as indicated in Fig. 3(A). The arrangement was used in preliminary investigations of POSFET devices and tactile sensing arrays. While suitable for a single POSFET device, this arrangement poses problems at array level for the following reasons: *i)* the acquisition system is to be implemented with commercial off-the-shelf component, and *ii)* the size of acquisition system must be as small as possible in order to place it or to integrate it on the robot hand shown in Fig. 2. A current source to bias each POSFET device in the tactile sensing array, as shown in Fig. 3(B) would mean using 25 different current sources and that the resulting data acquisition system would have a size larger than the robot's hand. Therefore, the ultimate fall out of this configuration would be a working data acquisition system that is however unsuitable for integration with robot's hand.

An alternate arrangement is to use only one current source, instead of using a current source for each POSFET, which is connected between source terminal and -V_{ss} terminal of power supply and switched on only at the instant when the particular POSFET is to be read. With this approach, the POSFET tactile sensing array is scanned by switching the current source and sampling the voltage source. Using only one current source for the entire POSFET tactile sensing array would result in reduced PCB size. However, it has been observed that the time needed to reach a stable bias state, with this switching configuration, increases significantly thereby making this configuration unfeasible. An example of increased transient time is shown in Fig. 4(a), where the drain current (I_D) is plotted for 300 seconds (5 minutes) after applying a drain-source voltage with the experimental setup depicted in Fig. 4(b). The reasons for such transient time behavior, as well as its origin, and how it could be controlled are currently being investigated. One possible reason for this behavior could be the using POSFET device with its gate floating.

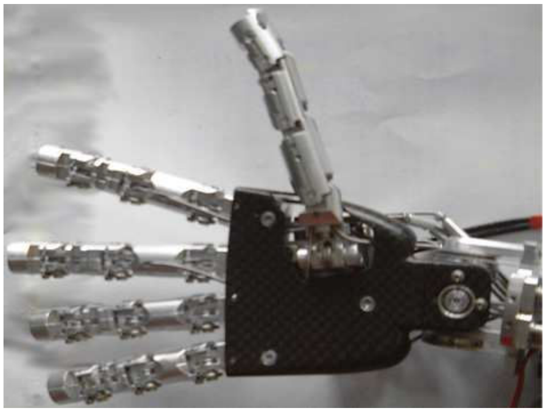


Fig. 2. The hand of humanoid robot 'iCub' [6].

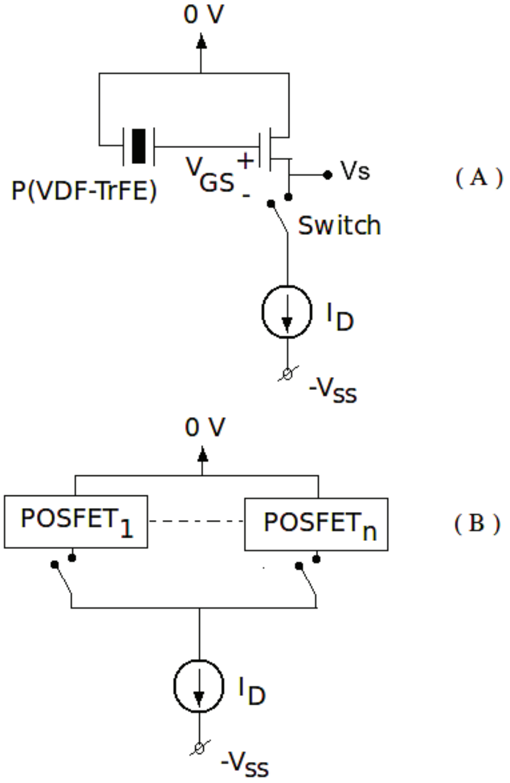
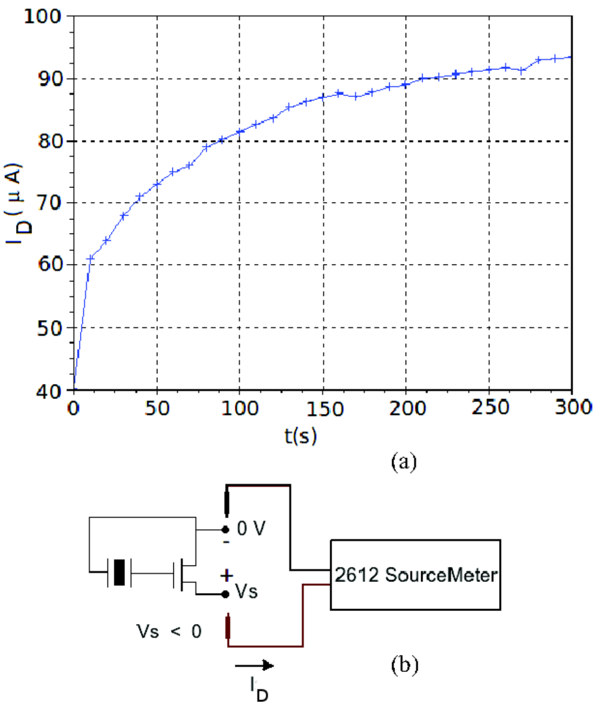


Fig. 3. POSFET bias. (A) POSFET in drain common and current source. (B) Switched current source configuration for bias (this case study $n = 25$).

In order to avoid the large transient time and also using 25 non-switching current sources, it is proposed to use resistance, R, for biasing the POSFET devices as shown in Fig. 5. The resistance provides a constant bias point (i.e. there is non-switching bias) and also the size of PCB gets reduced. The value of resistance must be suitable to bias the MOS in saturation and weak inversion. Since the POSFET is working in floating gate mode, the gate source voltage V_{GS} is not controlled and the resistance value is determined by empirical evaluation i.e. by means of an iterative process with source voltage and source current characterization. This resistance value must approximately be $R = 20k\Omega$. Due to fabrication process-induced spread in the MOS parameters, there could be minor deviations in the resistance value for various POSFET devices on the array. The usage of resistor provides permanent bias, however, at the same time it results in reduced gain (below 1 V/V).

A. *Proposed data acquisition system*

Keeping in view the issues about POSFET biasing, discussed previously in this section, the new data acquisition system is proposed and shown in Fig. 6. The proposed data acquisition system consists of three sections, clearly indicated in Fig. 6. The section 1 consists in the POSFET tactile sensing array and the resistance bank for biasing the



(a)

(b)

Fig. 4. (a) The drain current I_D during transient, before reaching the stable bias point. At time $t = 0$ is applied a voltage drain source $V_{DS} = -4.8V$ with the 2612 dual-channel source meter [12], as shown in (b).

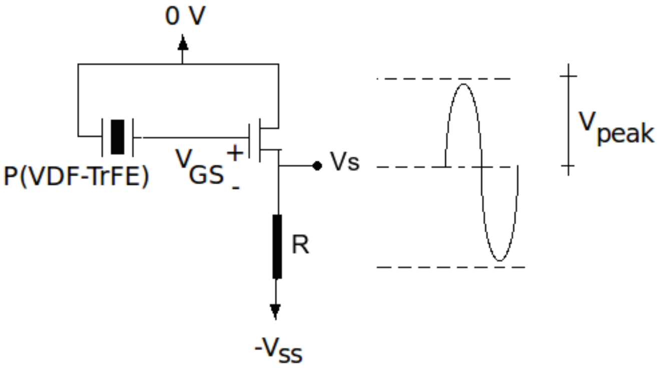


Fig. 5. The POSFET common drain configuration with resistance R between source terminal and negative power supply. The output amplitude V_{peak} is assumed to be $0.5V$ as maximum value over the range of dynamic contact forces.

POSFET devices. Since the array has 25 POSFET devices, the user configurable jumpers are used so as to select the requested 16 taxels to be sampled (in this first prototype it will be used only 16 taxels that is the maximum number of AD channels that the microcontroller features). The section 2 consists of the filtering stage. The BPF (band-pass filter) used in this section is a Butterworth second order low-pass filter, implemented with modified Sallen-Key topology, with DC-decoupling and level shift.

The first and second poles of the filter are placed at $1\,Hz$ and $1\,kHz$ respectively and the gain is $G = 3.6V/V$. Fig. 7 shows the implemented filter and the simulated frequency response of the filter is given in Fig. 8.

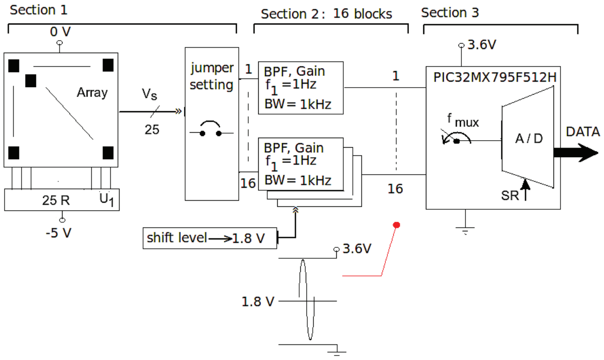
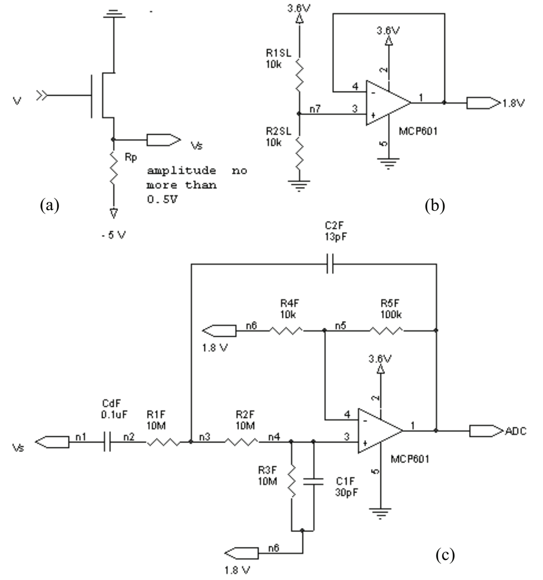


Fig. 6. The block diagram for the proposed read out circuitry.



(a)

(b)

(c)

Fig. 7. (a) MOS transistor where V represents the voltage from the taxel. (b) Circuit for level shift implementation. (c) Designed filter with shift level.

The section 3, in Fig. 6, consists of microcontroller PIC32MX795F512H from Microchip Technology Inc. [13]. The key features of this microcontroller are: up to 16 analog input pins, 64-Lead TQFP case (Thin Quad Flat Pack 10x10x1 mm), operating voltage range of 2.3V to 3.6V and 10 bits AD converter (for full scale voltage $V_{FS} = 3.6V$ with $n = 10$ the resolution is 3.5 mV). Internal circuits of the microcontroller can control different standard protocols such as: USB (Universal Serial Bus), Ethernet and CAN (Controller Area Network).

B. *Main parameters of data acquisition system*

The parameters to be considered during the design stage are defined in this section. Considering, BW to be the signal source bandwidth, n to be number of channels, n_b to be the number of bits of the AD converter, N_R to be the Nyquist rate ($N_R = 2BW$), EBR to be the effective bit rate, $EBR = nN_R.n_b$, k to be the oversampling factor, and f_s to be the single channel sampling frequency (where, $f_s = N_R k$). Similarly, $S_R = nf_s$ is the sample rate in $[samples/s]$

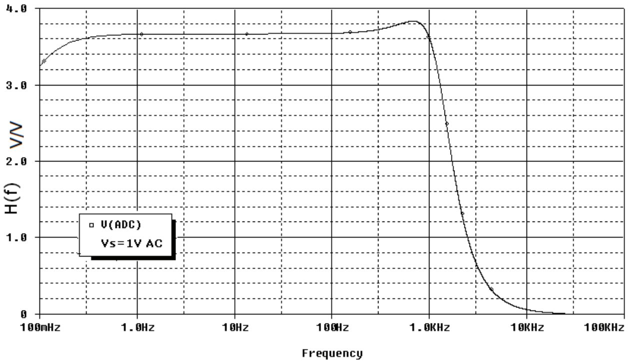


Fig. 8. Simulation of the filter frequency response.

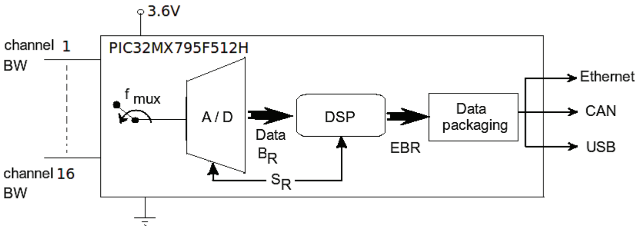


Fig. 9. Selected microcontroller and main data acquisition features considered for the design process. Parameters are described in Section III.B

and $B_R = S_R n_b$ is the bit rate in $[bits/s]$. With this notation, the parameters of the proposed data acquisition systems are as follows: $BW = 1kHz$, $n = 16$, $k = 5$ and $n_b = 10bits$. Hence, we have $f_s = 2BWk = 10kHz$ (sampling frequency for each single channel) $S_R = nf_s = 160kSamples/s$, and bit rate $B_R = 1.6Mbits/s$. Moreover, $EBR = 16 \times 2kHz \times 10 = 320kbits/s$. It is important to reduce the bit rate from the B_R value to EBR. It can be done in the microcontroller by using DSP (digital signal processing techniques) such as k-decimation or smooth-moving averages. This allows the use of USB as bus for communication to the computer and data transmission.

IV. CONCLUSIONS AND FUTURE WORKS

The development of POSFET based tactile sensing system has been presented. The work presented here extends the previous work on tactile sensing devices and arrays towards, the tactile sensing system. The POSFET devices based tactile sensing arrays have been designed to have spatio-temporal features similar to that of receptors in the human fingertips. The biasing schemes of POSFET devices and the problems thereof have been discussed. Keeping in view application requirements and the existing hardware on robot's body, the data acquisition system has been designed and presented. Though, primarily developed for fingertips of the humanoid robot 'iCub', the bigger overall size, due to off-the-shelf electronics, does not allow the tactile system to be placed on the fingertips. Instead, the tactile sensing system presented here will be integrated at robot's palm.

By realizing touch sensing devices on silicon, one can take advantage of the standard integrated circuit technology and also develop complex electronic circuitry on the same chip. Future work will involve miniaturizing of the tactile sensing system so as to fit it into the fingertips of robot. For this purpose, the full tactile sensing system on chip (SOC) or in a package (SIP) can be a good solution. Keeping this in view, attempts will be made to realize on chip circuitry for local data processing. This will not only improve the real time capability of the tactile sensing arrays but also make way for local processing of the tactile data - as done in humans. Realization of the arrays on flexible substrates will further improve their utility in robotics and other areas.

V. ACKNOWLEDGMENTS

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