System Approach: A paradigm for Robotic Tactile Sensing

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Abstract-**In the pursuit of developing touch sensors or tactile sensing arrays, the emphasis has only been on the sensors. This led to a large number of 'bench top' sensors, very few of which have actually been used in robotic systems. And those that have seen the actual use have almost invariably been used in static contact point imaging rather than the active manipulation or exploration. Perhaps the lack of the system approach rendered many of them unusable. In this work, we present the design of a tactile sensing system taking into account not only the parameters to be sensed but also the physical and operational constraints of robotic system.**

I. Introduction

Like humans, the interaction behaviors of robot with environment can be better understood by physically interacting with it. Without touching the objects, it would be difficult for a robot to know their interaction behaviors which depend on how heavy and hard the object is when hold, how its surface feels when touched, how it deforms on contact and how it moves when pushed etc. Availability of high performance video cameras and the significant research in the area of computer vision has made robot interaction with environment mainly through visual sensing techniques [1], which, at times can be misleading due to lack of direct physical interaction. Surely, some of the information about real world objects e.g. shapes of objects etc. can be obtained from the vision cameras [2] and a further detail can be obtained by moving them around the object. But, moving the robot around the object is not always possible, as can happen with humans as well. And, even if it is possible to move it around the object under observation, the presence of visual inaccuracies due to large distance between robot cameras and the object can make it difficult to explore or manipulate a given object. Of course, such inaccuracies can be reduced by keeping the cameras close to the object, or in other words, somewhere close to fingers on the robot hand (e.g. Eye-in-Hand Configuration) [1] – but not without paying the price in terms of loss of dexterity.

Despite an important role, the lesser use of tactile sensing in robotics, as compared to other sensory modalities e.g. vision and auditory sensing, could partly be attributed to the complex and distributed nature of tactile sensing and partly also to the non availability of satisfactory tactile sensors. In last more than two decades many new touch sensors have been reported [3-6]; by exploring nearly all modes of transduction viz: Resistive/Piezoresistive, based on Tunnel Effect, Capacitive, Optical, Ultrasonic, Magnetic, and Piezoelectric. A range of sensors that can detect object shape, size, presence, position, forces and temperature have been reported in the reviews on tactile sensing [3-5]. A very few examples of sensors that could detect surface texture [7], hardness or consistency [8] are reported. Most of the reported devices are either of the scalar single point contact variety (for intrinsic tactile sensing) or are linear or rectangular arrays of sensing elements (for extrinsic tactile sensing). The production of new designs and improved configurations of tactile sensors still continues apace, but, the touch sensor technology largely remains unsatisfactory for robotics either because the developed sensors are single big size touch elements and are too big to be used without sacrificing the dexterity of robot, or because they are slow, or fragile and also in some cases due to the digital nature of touch sensors i.e. touch or no touch.

Clearly, the emphasis, 'only' on the sensor development has resulted in a large number of 'bench top' sensors, very few of which have actually been used in robotic systems. This is surprising, considering the long history of gripper design for manipulative tasks. We believe that the lack of the system approach has rendered many of them unusable, despite their good design. It is evident from the fact that very few works on tactile sensing has taken into account the system constraints, like those posed by other sensors or by robot controller etc. To the best of our knowledge, only [9] has reported the design of tactile sensing system that also considers system constraints. Overall system performance is dictated not only by the isolated quality of the individual system elements, but also by how system elements integrate to achieve a goal. As an example, the development of tactile sensing arrays for fingertips of a humanoid robot should also take into account system level issues like – availability of space on the fingertip (which decides size of the array), nature of signal going out of array (analog/digital), position of analog sensor front end (on the same chip with array or on separate chip), sources of noise (there are many motors on robots), time response of the sensor with respect to other sensors involved in the closed loop control of the robot, division of functions to be performed locally and centrally etc. Much work needs to be done at system level before artificial touch can be used in real world environment. This will also serve as basis for the development of practical and economic tactile sensing system in future. Inclusion of tactile arrays in the control loop of robot will help

The work presented in this paper has been supported -in part- by the ROBOTCUB project (IST-2004-004370), funded by the European Commission through the Unit E5 -Cognitive Systems.

in exploring deeper issues involved both in the exploration and manipulation. This will not only advance research in robotics but will also help in understanding the human interaction with environment through touch.

In this work, we present the design of a complete tactile sensing system taking into account not only the parameters to be sensed but also the physical and operational constraints of robotic system. Although the work presented here mainly refers to tactile sensing for parts like fingertips that require high-density of touch sensors, it can also be applied to low-density touch sensors areas like large skin applications. This paper is organized as follows. Section II presents an overview of the robot tactile sensing system. Section III discusses the design constraints and specifications involved in acquiring the tactile data. In Section IV, the architecture of the sensor system is described along with the solutions to be adopted to overcome the stringent system constraints. Conclusions are then drawn in section V.

II. Tactile Sensing System of Robot

The development of tactile sensing system requires the understanding and design of sensor system architecture at all levels, starting from the sensing the external stimulus to the action taken based on this stimulus. In general, this would include following functions:

1) Transduction.
2) Read out and signal conditioning.
3) Data transmission.
4) Model construction of contact object.
5) Control action.

The hierarchical functional and structural block diagram of complete tactile sensing system is shown in Fig.1, in which, the complex tactile sensing process is systematically divided into sub processes. Such a division helps in designing various parts of the system, to a desired level of complexity, according to the tactile sensing mechanisms involved during interaction with environment. The levels from bottom to top depict the sensing of signal, perception of real world and ultimately the initiation of action by controller. The level of complexity increases from low to high with more computation intensive processes occurring at the top. The signal flow in the functional block diagram is somewhat similar to that of human tactile sensing system [10]. Various functional levels are described below, starting from bottom.

Transduction of contact data constitutes the lowest level of the system. This involves measurements like magnitude and direction of forces, distribution of force in space, temperature etc. An accurate reconstruction of contact details requires a sufficient number of sensing elements placed within the space available; for example, on the robot finger (as generally fingers are involved in interaction with environment, through touch). This places a constraint on the method of transduction to be

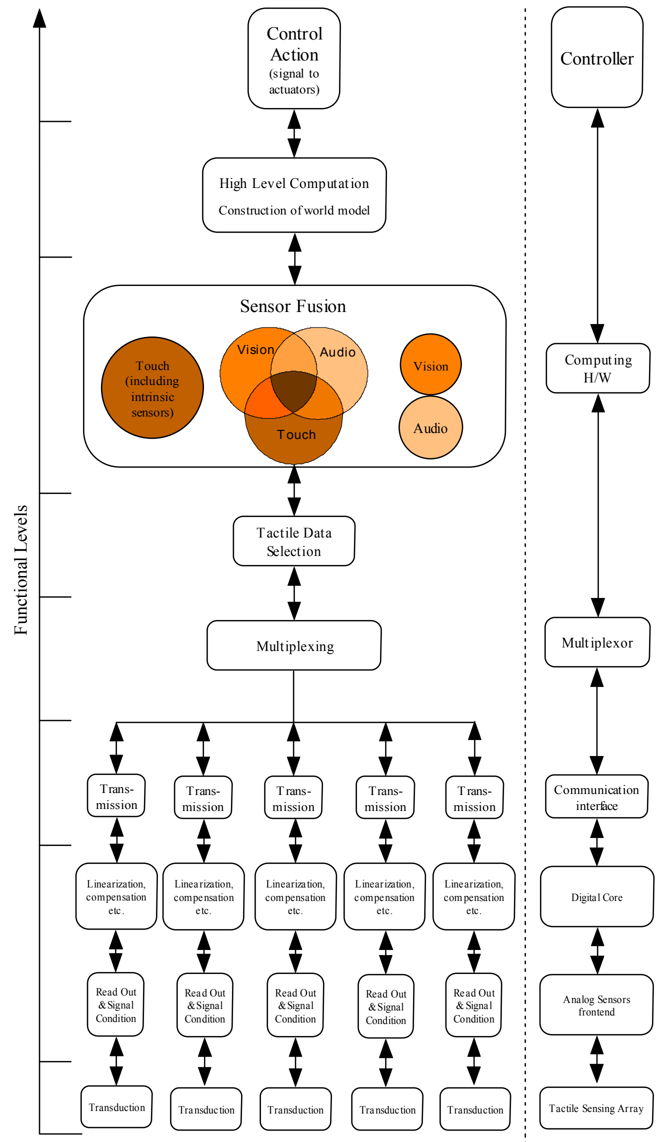

Fig. 1. Hierarchical functional and structural block diagram of Robot tactile sensing system.

used. Speed of response also places a constraint on the type of transduction method. The transduction of touch signal can be done either by single sensor or with array of touch sensors. The requirement of fast response places a constraint on the number of touch sensors on the array.

The second level involves the signal conditioning and read out, which greatly depends on the type of transduction method used in previous level. In Fig. 1, this level has been divided into two parts: analog sensors frontend and digital core. Some low level computations like simple scaling (amplification) and segregation of the data from different kind of touch sensors (e.g. force, temperature etc) can also be made at this level by analog sensors frontend. Digital core is used for linearization, compensation (like temperature compensation, if the transducer performance changes with temperature), compressing information, slip detection, texture recognition etc. In order to maintain a better signal to noise ratio, it is desirable to keep the signal conditioning circuit close to the transducers array (for example, if the transducer arrays are placed on the distal phalange of robot fingers, then conditioning circuits can be placed on the adjacent phalange, if space constraint doesn't allow the same to be placed on the distal phalange). A System on Chip (SoC) approach would be ideal in this case which is the also the goal of the work presented here. The initial choice of transduction method and conditioning circuit are important from system point of view, as they set the bandwidth limits of data accessed by the higher levels of the system.

The third level involves the transmission of collected information to higher levels through communication interface. The desired operation speed, noise and number of wires put a constraint on the type of communication channel used for interaction with higher levels. The transmission of digital data can be done either serially or by CAN bus. CAN bus is generally a preferred choice due to high real-time capabilities, fast transmission (up to 1 Mbit/s) and high transmission reliability. High transmission reliability makes CAN bus preferred choice over wireless transmission also because of the safety issues involved during robotic interaction with the environment – even though wireless transmission would be an ideal solution as it helps in reducing wiring problems.

The fourth level involves the multiplexing of tactile data coming from different parts, for example, from different fingers during a typical manipulation/explorative task.

Due to large number of sensing elements, the data size also multiplies. Not all the data collected from various parts is useful and hence useless data can be rejected. This is basically the function of fifth level in the hierarchy of tactile sensing system shown in Fig.1. For example, a grasp may not involve all the fingers and hence the data obtained from the fingers other than those involved in the grasp can be rejected. This argument is also valid for certain patches on the tactile array on a particular finger involved in grasping. Based on the task, involvement of a scheme for reading data from certain predetermined tactile sensor elements can be useful. This requires addressing of all the touch sensor elements; which is the reason why the data transfer in Fig. 1 is shown as bidirectional.

The next level is Sensor Fusion. At this level, the signals from different kind of sensors are collected. In case of humanoid robot, these signals could be from touch sensors (both extrinsic and intrinsic), from vision sensors and from audio sensors. In humans, the interaction with environment involves the statistical combination of sensory data from different sensing modalities [11], for example, touch and vision, as shown in Fig. 1. Some attempts of robot control involving different sensing modalities has also been reported in past [12, 13]. Availability of fast and efficient vision and audio sensors places a constraint on the speed with which tactile data should be obtained, if the data from different sensing modalities are involved in robot control.

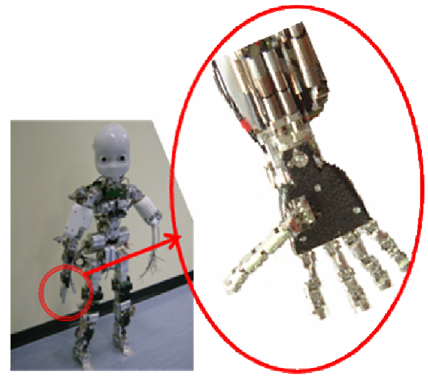

Fig. 2 Humanoid robot, 'icub' with the hand shown in inset.

Higher level computations are done at the seventh level to obtain the model/image of the environment (object in contact), based on the data obtained from earlier level (from independent sensing modalities or fused data of different sensing modalities). This level doesn't impose any major constraint on design of lower levels of tactile sensing system. A dedicated computing hardware is required to perform the functions of this level and those of earlier two level i.e. data selection, sensor fusion and model construction.

At the highest level, the control algorithms are implemented. For a reliable control of complex tasks, the tactile sensing parameters like sensor density, resolution, speed and location are particularly important. Thus, the final design of tactile sensor and associated electronics circuitry, is the result of many trade-offs.

Our approach for development of tactile sensing system is to climb the hierarchical ladder of tactile sensing system from hardware intensive bottom. The work presented here is related to the three lowest levels of the functional diagram shown in Fig. 1. For the lowest level, we have developed POSFET (Piezelectric Oxide Semiconductor Field Effect Transistor) based tactile sensing arrays which are to be placed on the fingertips of the humanoid robot, 'icub' [14], shown in Fig. 2. To perform the second and third level functions, we are developing analog sensors frond end, digital core and communication interface.

III. Towards Implementation

The first step towards implementation of tactile sensing system is to fix the system requirements. The system requirements presented below are divided here into two parts; those related to sensor and those related to conditioning electronics.

A. *Sensor Requirements*

In absence of any rigorous artificial tactile sensing theory that can help in specifying important system parameters such as sensor density, resolution, location, bandwidth etc. one can turn to human tactile sensing to get some initial cues. Following the information on human tactile sensing system, one can formulate some basic design features of artificial tactile system for a general robotic system intended to be used in real world environment. Few such studies have been reported in literature [3-5], following which some design factors for artificial tactile sensing are presented below:

1) The distributed nature of receptors calls for using various kinds of miniaturized sensors arranged in matrix. Number of elements in the array may vary with its desired physical location on the robot.
2) The spatial resolution of the array of sensors should be about 1-2 mm, which translates to an approximately 10 x 15 element grid on a fingertip-sized area.
3) In general, the sensor should demonstrate high sensitivity and broad dynamic range. Force sensitivity range of 0.01 – 10 N (~1g – 1 Kg) with a dynamic range of 1000:1 would be satisfactory.
4) It should be multifunctional i.e. in addition to the detection of forces, touch sensor should be able to detect other interaction behaviors like hardness, temperature etc.
5) Linearity and low hysteresis are desired. Although non-linearity can be dealt with through inverse compensation, the handling high hysteresis is difficult. Output from the tactile sensor should be stable, monotonic and repeatable. It is interesting to note that the human tactile sensing is hysteric, nonlinear, time varying and slow. But, perhaps the presence of large number of these 'technologically poor' biological receptors enables central nervous system to extract useful information.
6) The artificial tactile sensor should be fast. This is particularly true, if the tactile sensor is part of the control loop. In general, for real time contact details, each touch element should have a response time lesser than 1 ms, or a similar value related to the total number of elements.
7) In addition to above factors, the artificial tactile sensors should be robust and thus must be capable of withstanding harsh conditions of temperature, humidity, chemical stresses, electric field etc.

However, it should be noted that these characteristics, like any other design factors, are application dependent and thus should not be considered as definitive.

B. Electronics Circuitry Requirements

Dimension of the chip, depends on availability of space on the robot. For the fingertip of robot the dimension of chip (including sensor) should be approximately 13 mm x 15 mm.

Scheme of Addressing: To reproduce the image of contact object, each touch element on the array needs to be addressed. This can be done by selecting rows and columns separately or by addressing individual touch elements. In our case, access to individual POSFET based touch sensor is preferred. For a 5 x 5 array, there must be 5 address lines.

Pre-charge bias arrangement: In applications involving piezoelectric materials as transducer a voltage fluctuation is observed in output during application of external load. This can be reduced by pre-charge bias technique [15].

Noise: Apart from many sources of noise in robot, the variation in temperature can be a source of noise in our case, due to choice of piezoelectric polymer as transducer material. Total noise from the system puts a constraint on the resolution of ADC and hence on the resolution of parameters to be measured. To get 1000:1 dynamic range of forces, a 10 bit ADC is required.

Cross talk: In order to measure the value of force at addressed touch element, the read out circuitry must be insensitive to parasitic due to touch elements in neighbouring rows and columns. In our earlier sensor design [16], a 25% mechanical cross talk was observed. One reason for high cross talk was the presence of uniform metal layer on one side of polymer. The cross talk is expected to go down in the POSFET based tactile sensing array, as in this case the metal electrodes have been patterned to be present over the touch element only. Any electrical cross talk (change in capacitance of polymer due to adjacent touch elements) can be reduced by grounding touch elements other than the one which is being read.

Read out time: While interacting with environment, the image of contact object may be reconstructed if tactile sensing array is scanned with some minimum frames per second. This must also take into account the read out time of other sensors and also the bandwidth of controller. For the 100 Hz frequency of robot arm controller and 30 frames per second reading of vision sensor, for example, assuming 100 frames per second, the read out time for 5 x 5 array, at the 100 frames per second is 0.4 ms (= 1/ (5x5x100)). For very dense arrays, the read out time is very less and at times can be unrealistic. Thus, the number of touch elements on array depends on the read out circuitry.

Some low level computations like temperature compensation, averaging etc. can be performed on the chip itself. For example, if the temperature variation is high, then voltage output of each touch element needs to be compensated (if the response due to force only, is desired). The system has

TABLE I.

SYSTEM REQUIREMENTS

Sensor Requirements		Electronic Circuit Requirements	
No. of sensor elements	25	Dimension of Chip (with sensor)	13 mm x 15 mm
distance between sensor elements	1mm	Addressing	Independent access to each touch element
Transduction method	Piezoelectric	Pre-charge Biasing arrangement	Due to piezoelectric polymer
Dimension of sensor array	7 mm x 7mm	Resolution of ADC	> Noise 10 bits (force requirement)
Hysteresis	Low	Cross talk	Low
Force range	1gmf-1000gmf	Read out time	< 0.4 ms

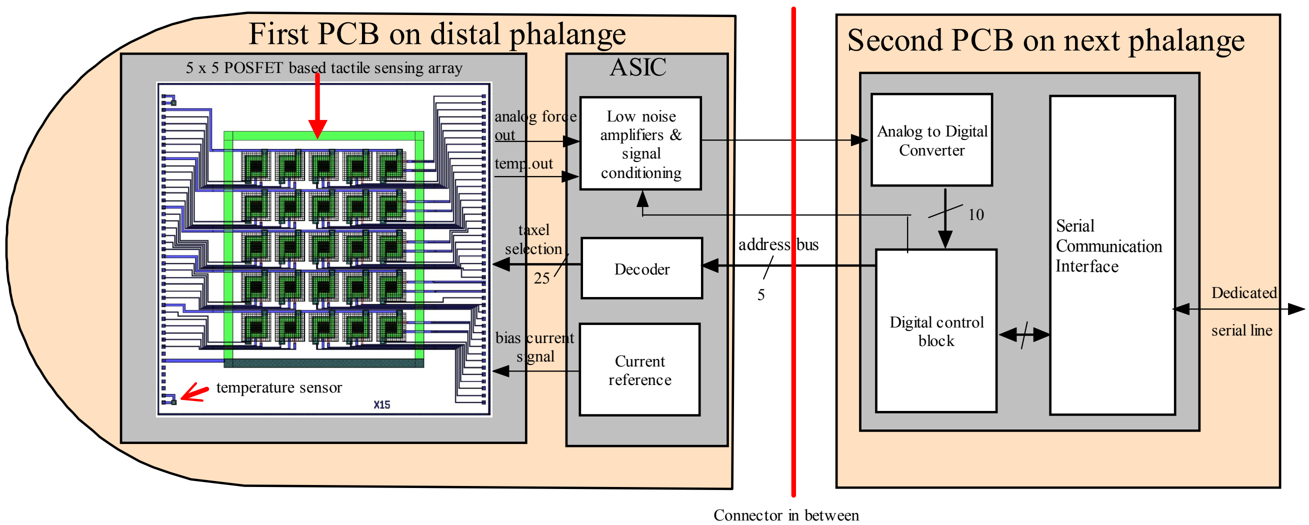

Fig. 3: System architecture (first phase) of tactile sensing system. The tentative location of different chips of the robot finger is also shown.

to perform a total of 5 x 5 x (2 address write +1 touch element read + 1 temperature compensation) = 100 operations for each measurement. Furthermore, the device may be required to store the computed value for comparison, if required. Another example of on chip operation could be the detection of slip when robot picks an object. Such an operation requires a total of 5 x 5 x (2 address write +1 touch element read) + Store the data to compare it with the touch element values obtained in next frame. Change in values of touch elements along a line will reflect the slip perpendicular to this line. Working at frame rate of 100 frames per second, the resulting minimum system clock frequency should be about 10 KHz.

IV. System Architecture

The architecture of lowest three levels of the tactile sensing system is shown in Fig. 3. The total tasks are divided into three parts: development of the POSFET based tactile sensing array; development of dedicated electronic circuitry and integration of whole system - in a single package (SIP) in the first phase and on a single chip (SOC) in the second phase

The POSFET based tactile sensors arrays have been designed for the fingertips of robot and they are now in fabrication. The tactile sensing array, as shown in Fig. 3, comprises of 5 x 5 POSFET (Piezoelectric Oxide Semiconductor Field Effect Transistors) based tactile sensors [16, 17], obtained depositing the piezoelectric polymer (PVDF-TrFE) film on the gate area of MOSFET. The charge of the piezoelectric polymer generated due to applied force, modulates the charge in the induced channel of MOSFET, which is then converted into a voltage value by means of readout circuitry that can be embedded into the chip. While the piezoelectric polymer film as sensing element improves sensors time response; the tight coupling of sensing material (PVDF-TrFE) and electronics using MOS technology will improve force resolution, spatial resolution and signal to noise ratio. As an example, with the extended gate approach used in [15], the 8 x 8 tactile sensors array was scanned in around 50 ms and thus the response bandwidth of 25 Hz was achieved. With POSFET based touch sensors and whole system on chip (SOC), which is our final goal, the bandwidth can be pushed to >100 Hz, which is desired for involving touch sensing into robotic arm control. As an example, for 5 address lines for 25 (N_s) touch elements, 10 bits of data per touch element (N_d), assuming POSFET response time as 50 µs (T_r), delay of 50 µs during addressing (T_a) and delay of 50 µs during transmission of data (T_t), the scanning frequency of entire array can be obtained by substituting the corresponding values in following equation:

$$F_s = 1/\left(N_s^*(T_a + T_r + T_t)\right) \quad (1)$$

Thus, assuming number of data lines to be equal to the transmitted data bits, the scanning frequency is about 270 Hz and the communication bandwidth is 67.5 Kbits/sec. It should be noted that with POSFET based touch elements and SOC approach, the delay and response times are expected to less than those assumed in above example. In other words, the scanning rate of array would be faster.

For the feasibility and reliability of prototype implementation, the ad hoc System in Package (SIP), with dedicated chips - tactile sensing array, analog frontend, Digital Core and Interface (all in one package), could be the starting point. The main functional blocks of the SIP, as shown in Fig. 3, are: a) POSFET based tactile sensing array; b) analog sensors frontend; c) digital core and serial communication interface. To optimize the performance a dedicated implementation of the analog sensors frontend is mandatory. Thus, an Application Specific Integrated Circuit (ASIC) will be designed and manufactured for this purpose, taking into account the system requirements given in Table I. The analog sensors frontend will provide sensors, the necessary bias-voltage and currents to acquire the sensors signals with minimal noise (i.e. on chip filtering to remove out of band noise components). And, if necessary, the signals are amplified, to make the noise introduced by subsequent stages, less critical. The signals are then converted to digital values. Functions of digital core are to address touch sensors; to extract and compress information from the tactile sensors array; to compensate for non linear and pyroelectric effects which may affect measurement; and to drive the analog frontend control signals, etc. Moreover, the digital core manages the interface to the communication channel. The prototype tactile sensing system will be interfaced either with CAN bus or with a dedicated digital serial line (a digital interface is almost mandatory to protect the sensor data from noise due to the fact that the robot controller cards can be further away from the sensors). The bandwidth and connectivity (constrained by the overall size of the fingertip) with the electronics existing on the humanoid robotic hand/arm will be considered according to system requirements.

A major breakthrough in robot tactile sensing would be 'System on Chip' (SOC) implementation of tactile sensing system. Presence of analog sensor front end, digital core and communication interface along with tactile sensors array on same chip is expected to improve (among others) the speed, bandwidth, signal to noise ratio (keeping in view many sources of noise on humanoid), overall sensitivity, efficiency and robustness. Apart from these, with SOC approach, the problem of wiring complexity- a key robotics problem - can also be effectively dealt with. Thus, rather than an alternative solution, SOC is the requirement for the tactile sensing system.

V. Conclusion

The tactile sensing system of robot is presented. Instead of coming up with 'Yet another touch sensor,' only, the need to develop the tactile sensing system for robot has been presented. The system requirements are outlined, based on which, the system architecture is presented. The system architecture (tactile sensing arrays + analog front end +digital core+ communication interface) will be implemented by SIP (System in Package) approach, in the first phase and by SOC (System on Chip) in the second phase. SIP approach is preferred in first phase, to study the feasibility and reliability of system, as SIP allows simpler designs, easy design verification, processes with minimal mask steps and the use of optimized technologies for different functions. This will also provide an opportunity to compare the SIP and SOC approaches, in terms of cost and performance improvement for this application.

Acknowledgment

We are thankful to Dr. Leandro Lorenzelli, FBK-IRST, Trento, Italy for the support on the development of tactile sensing arrays.

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