5.3: A Large Area Force Sensor for Smart Skin Applications

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Abstract
This paper presents the construction and theory of operation of a large area, flexible, tactile sensor and its applications. The sensing mechanism is based on the novel contact piezoresistive effect. Furthermore, the sensor's resolution, size and shape can be easily tailored to the applications' requirements. This versatility facilitates the use of the sensor in smart applications where tactile information is used to create system intelligence. Future improvements in the tactile sensing arena are discussed along with the potential benefits of using polymer electronics.

Keywords
Flexible, Tactile, Sensor, Smart, Applications, Skin

INTRODUCTION
In this paper, the development and applications of an artificial, flexible, force sensitive skin are presented. This skin consists of an array of force sensing cells i.e. sensels that can measure the spatial distribution and magnitude of forces perpendicular to the sensing area. Tactile sensors have been the subject of extensive research for use in robotic applications. This research originated from the need for robotic hands to detect object geometry, texture, slip or other contact conditions in order to enhance their manipulation dexterity [i]. Various sensor structures have been developed for this purpose based on piezoresistive, piezoelectric, optoelectronic or capacitive force sensing technologies on silicon, printed circuit boards or flexible substrates [ii,iii,iv,v]. Unfortunately, most of these structures suffer from various limitations such as low spatial resolution, small number of sensels, expensive manufacturing processes or thick sensor profiles. In order to take advantage of tactile sensing in applications that require imaging of forces between two large area surfaces (tens to thousands cm^2), a new versatile sensor technology is required. This technology should allow the spatial resolution, force sensing range, sensing area size and substrate flexibility of the skin to be easily tailored to the requirements of each application. Such a tactile skin would facilitate the creation of smart systems; hence the name smart skin. In addition, an ideal skin should be as thin as possible to eliminate its interference with the measured system, should be able to be trimmed to shape without impairing its functionality and be easy to tile into larger sensors [vi]. Suggested specifications for smart skins compared to other tactile sensors are shown in Table 1.

Table 1. Specifications of Representative Tactile Sensors

	Human Skin [i]	Fingerprint Imaging Sensor [vii]	Smart Skin
Resolution (mm)	2	0.1	0.1-10
Sensor Area (mm^2)	25x25	13x20	10^2–10^7
Number of Sensels	10^2	~10^4	10^2–10^6
Sensel Force Range (N)	0.4-10	switch	0.05-100
Linearity	Moderate	-	High
Hysteresis	Low	-	Very Low
Compliance	Yes	No	Yes
Bandwidth (Hz)	100	~10	100
Operating Temperature (°C)	-20 to 60	-10 to 45	-40 to 100

In this paper, a novel force sensing mechanism will be described along with the smart skin fabrication process, the accompanying electronics and representative applications.

THEORY OF OPERATION
The resistance of electrical contacts has been extensively researched with references dating back to 1835 [viii]. It has been found that the contact resistance R_c can be described by the following equation:

$$R_c \propto \frac{\rho}{F} K \qquad (1)$$

where ρ is the resistivity of the contacting surfaces, F is the force applied normal to the contact surfaces and K is a function of the roughness and elastic properties of the surfaces [ix].

Here, we define a novel gauge factor GF_c to characterize the force sensitivity of contact piezoresistive sensors:

$$GF_c = \frac{dS_c}{dF} \propto \frac{1}{\rho K} \qquad (2)$$

where $S_c = 1/R_c$ is the contact's electrical conductance.

It is apparent that for a constant set of surface roughness and elastic properties K, the lower the contacting films' surface resistivity ρ, the larger the force sensitivity GF_c of a contact piezoresistive sensor. This effect can be used to create force sensors of different sensitivities. Generally, the conductance of these sensors can be tailored to vary between zero, for zero external forces, to hundreds of µSiemens, for the maximum force that can be applied before plastic deformation of the sensor occurs. A fixed gain electronic interface can be used to detect this range of conductances.

SYSTEM DESCRIPTION

Smart Skin Construction

The skin prepared in this work consisted of two 25µm thick polyester sheets, which were laminated together with adhesive in the non-sensing area (Fig. 1). These sheets carried parallel, thermoplastic, Ag-filled polymer conductive traces covered by a thermoplastic semiconductive ink of resistivity ρ. Screen-printing technology was used to deposit all the materials on the sheets. The two sheets were oriented together so that their traces formed a grid, with the semiconductive layers facing each other. Each cross section of the grid formed a contact piezoresistive force sensor. The application of external forces resulted in a change of the sensels' conductance.
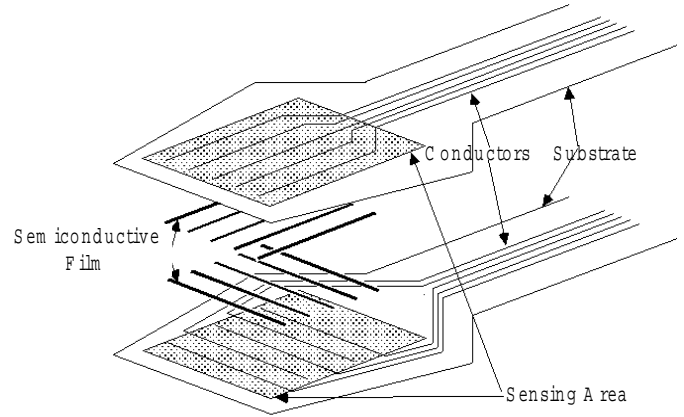

Figure 1. Smart Skin Structure

Interface Electronics

Multiplexing electronics were used to scan the array of sensels (Fig. 2). Each sensel can be modeled as a force variable resistance R_c, or conductance S_c, connected in parallel with a parasitic capacitance C_p. A control circuit sequentially connects each driving column to a drive voltage V_{DRIVE} while the rest of the lines are grounded through the R_{drain} resistance. The conductance S_c of each sensel on the driving column is read through an operational amplifier (op-amp) circuit whose output V_{out} is given by:
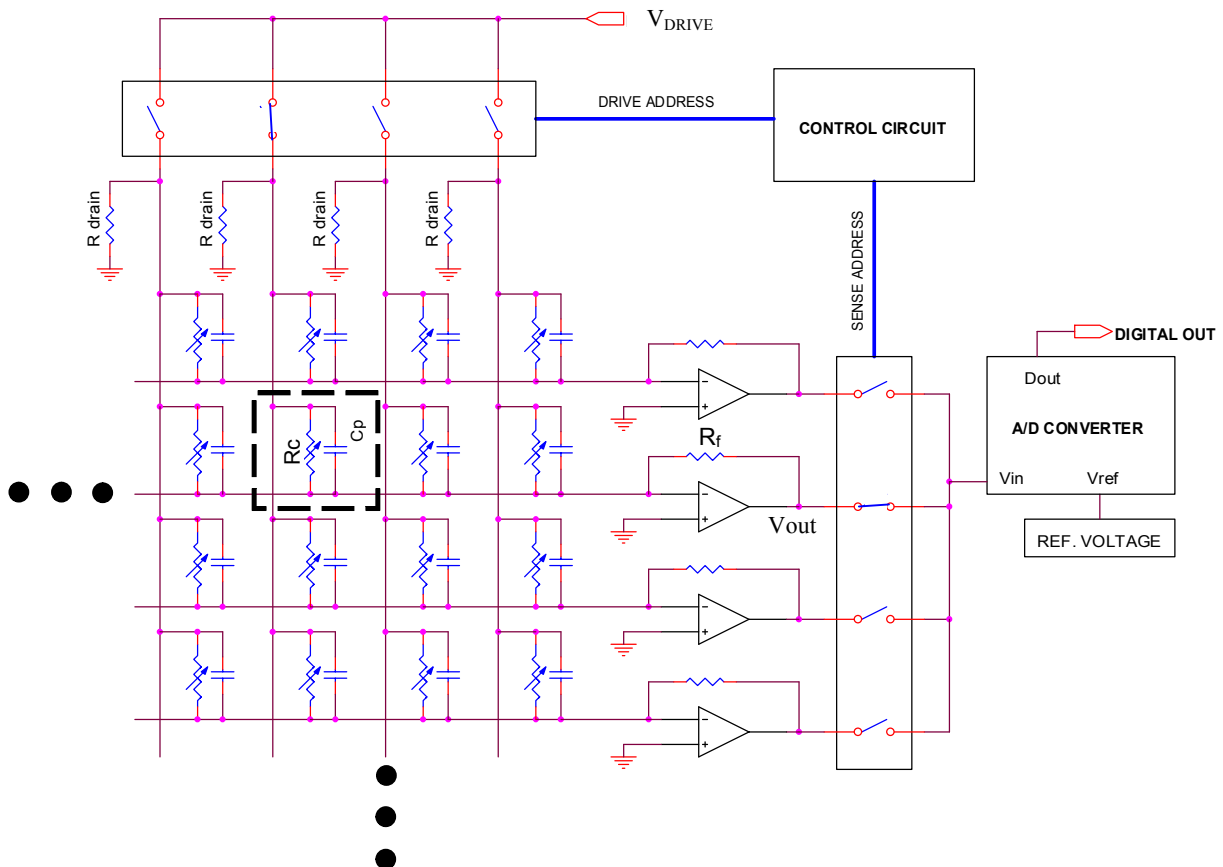
$$Vout = -V_{DRIVE} R_f S_c \qquad (3)$$

where R_f is the op-amp's feedback resistance. After that, the control circuit multiplexes each op-amp output to an 8-bit, high speed, analog to digital converter, whose output is fed into a computer for further data analysis.

System Specifications

The data collected was used to generate a real-time, color-coded, force distribution image on the screen of a computer system. The described hardware system could support an array of 52x44 sensels with a scanning frequency of 225 frames per second. Multiple systems can be connected in parallel and multiplexed to scan larger sensor arrays e.g. 8 systems can be used to drive 8x52 lines and sense 8x44 lines resulting in more than 149000 sensing cells. Moreover, the sensor array can be easily trimmed to the desired dimensions provided that the sensel interface electrodes are placed in the center of the smart skin and not on the perimeter of the sensor area (Fig. 1). Therefore, any trimming will not accidentally inactivate complete lines or columns.

The resulting smart skin was thin (circa 100 μm) and flexible and therefore its effect on the system under measurement is minimal. The resolution of the array is limited only by the resolution of the printing technology. For screen-printing on large area substrates (thousands of cm^2) where registration accuracy becomes more demanding, the highest practical sensor resolution is around 250 sensels/cm^2.

TYPICAL APPLICATIONS

The smart skin sensor system offers a unique solution to the measurement of real-time pressure profiles on flat, curved, rigid or soft surfaces and can be used to improve the quality of industrial processes as well as of commercial products. One of the most demanding applications is the measurement of static and dynamic tire footprint pressure distribution patterns to set up the suspension of race vehicles, to design tire manufacturing and molding machines or predict roadway surface wear patterns (Fig. 3). Also, the tactile sensor can be used as a diagnostic tool in the process of chemical-mechanical silicon polishing to balance the forces acting on the wafer during polishing. Moreover, a smart skin can be trimmed to the size of a shoe and inserted in the sole to analyze and improve the shoe's comfort or the technical skill of an athlete, diagnose diabetic ulcers or identify potential health problems associated with the use of shoes with high heels (Fig. 4).

NOVEL APPLICATIONS

Tactile information can also be useful in novel areas such as biometrics and ubiquitous computing in smart floors and smart objects.

Biometrics

Hand geometry is one of the physical characteristics of human beings that can be used to recognize or authenticate their identity. The length, width and surface area of the palm and fingers can be extracted from the pressure image of the hand and then used to create a template for each user during an initial registration process (Fig. 5). Thereafter, each time the user's hand is placed on the sensor, the above hand geometry variables are recorded and compared to the stored template for identity verification. Furthermore, the pressure distribution of the hand can be used as an additional verification variable in the template or even as an anti-tampering security mechanism against the use of hand molds.
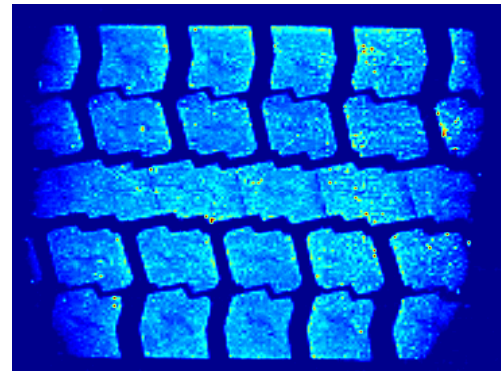

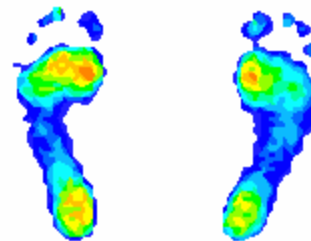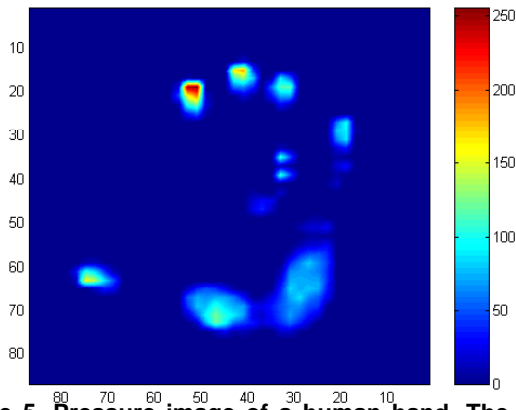**Figure 3. Pressure image of a tire**

Figure 4. Ordinary pressure distribution of feet

Figure 5. Pressure image of a human hand. The scale on the colorbar represents the amount of force in arbitrary units.

Ubiquitous Computing

The incorporation of computer-based intelligence into objects with which human beings interact facilitates the creation of ambient intelligence. The response of objects and environments to a human input can become a function of the user's habits, personality, mood or behavior. Sensors are expected to be an integral part of such a system. Potential intelligent applications that require the use of tactile sensors will be described in this section.

Smart Floors
A smart skin embedded in the floor can be used to identify people by analyzing their footstep force profiles [x]. Moreover, a sensor that covers the whole floor area would be able to locate and track the position of multiple users in a smart home. Such a smart home can automatically adapt its local environment to the user's preferences such as ambient light, music, temperature etc.

Smart Marketing
A smart skin placed in front of shopping windows, advertising stands or product areas in retail shops would be able to gather valuable marketing information. The skin can be well hidden so that it is not interfering with people's behavior. The amount of traffic in front of these areas, the attractiveness of products and the effectiveness of advertising stands can be measured over the course of a day. Computer software can process this information to produce reports in real time as well as to differentiate adults from kids. The latter differentiation is possible by analyzing the people's weight, shoe size and dynamics of their motion. Dynamic product demonstration areas would therefore adapt their behavior to the customer's age in order to maximize the product's appeal to different ages or to protect kids from exposure to an inappropriate advertising content.

Virtual Reality
Also, smart skins can be used to enhance the human – computer interaction in virtual reality applications or in computer games. It is possible to gather information for multiple users simultaneously regarding their direction and dynamics of motion or the shifting of their bodies' center of weight. This data opens up opportunities for training in dancing, boxing or virtual combating. Also, it allows the creation of highly interactive multi-user computer games.

Human Safety Analysis
Furthermore, a human body covered with a smart skin can record the area, intensity and duration of body stresses or impacts developed during sport activities (e.g. rugby), work (e.g. acceleration-induced stresses on pilots) or accident situations (e.g. car crashes). This information would be useful in the design of improved protective clothing, protective gears and stress absorbing materials.

Smart Objects
Objects such as computer mice, keyboards or chairs equipped with smart skins may be used to recognize the user's emotion by analyzing grip forces or object handling behaviors. Computers or other interactive devices can then adapt their responses to the user's emotions much like a human being would do. This add-on object's functionality is called emotional intelligence [xi]. Furthermore, in business or life-critical decision making situations the execution of human commands by computers may be delayed or require verification at a later stage if the emotion of anger or frustration is detected.

DISCUSSION

The smart skin presented here consisted of a screen-printed array of passive contact piezoresistive sensors. Generally, the force sensitivity of these sensors may vary from cell to cell due to limitations in the screen printing technology such as non uniform resistivity or uncontrollable surface roughness of the semiconductive ink. Any alternative manufacturing technologies are required to address the sensitivity evenness problem and combine the low production cost, high yield, large sensing area and substrate flexibility with finer sensing resolution for the most demanding applications, active sensitivity compensation for every cell and infinite expandability with a single interface handle. A candidate architecture may borrow elements from the structure of modern charged coupled devices (CCDs). An active, large area, tactile sensing system where each sensel is paired with its own circuit for compensation and data communication may become possible with the advent of polymer electronics. Although the latter are still developed in the research lab only, it is expected that commercial applications will soon find their way to the market. Smart skins can benefit from the technology developed for the fabrication of flexible displays based on ink-jet printable organic electronics [xii]. Ink-jet printing of smart skins is expected to allow a higher

sensing resolution and lower setup costs for customized sensor designs. Unfortunately, polymer electronics still suffer from low operating frequencies (kHz) [xiii], which would make their use suitable only for applications that require low tactile image frame rates.

Semiconductive or capacitive electronic textiles are also emerging as an alternative, low-cost, smart skin technology [xiv]. These sensors can be made of stretchable materials unlike polyester of polyimide, which are only flexible. Nonetheless, stretchable smart skins will suffer from low spatial accuracy; it is difficult to determine the exact position of each sensel on a stretched skin. These skins are expected to be more suitable for wearable electronic applications with moderate resolution and low force sensing accuracies. It is anticipated that their production cost will be very low allowing their rapid establishment in applications with low sensing requirements.

CONCLUSIONS

The novel force sensing mechanism of contact piezoresistance has been used to create a versatile, flexible, smart skin. The skin construction and the basic interface electronics have been presented. It was shown that the information recorded by tactile sensors can benefit a wide range of applications in the area of medical diagnostics or industrial process control. Furthermore, tactile information enables the development of smart homes and objects, enhanced training environments, better human safety or comfort products and enhanced human-computer interfaces. Polymer electronics are a promising technology that could be used to increase the skin resolution, improve the force sensing accuracy and lower the production cost of customized sensors.

ACKNOWLEDGEMENTS

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