5.4: A Textile Based Capacitive Pressure Sensor

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Abstract

This paper introduces an approach for decoding the pressure information exerted over a broad piece of fabric by means of capacitive sensing. The proposed sensor includes a distributed passive array of capacitors (i.e. an array where no active elements are involved), whose capacitance depends on the pressure exerted on the textile surface, and an electronic system that acquire and process the subsequent capacitance variations. Capacitors can be made in different ways, though, in our demonstrator they have been implemented between rows and columns of conductive fibers patterned on the two opposite sides of an elastic synthetic foam. Measures performed over a prototype has been demonstrated the reliability of the approach by detecting pressure images at 3 F/s and by measuring capacitances as low as hundreds of fF spaced apart at meters of distance.

INTRODUCTION

The sense of touch plays an important role in everyday life. It provides the body with early contact to surrounding objects. By touching an object, we can tell if it is sharp or smooth; by holding it, we can estimate its weight. Skin is the most extended sensor of the entire human body. The haptic interface gives the first feedback to object manipulation; without sensing the pressure exerted over the skin surface, it becomes quite impossible to measure hand strength in order to pick up an object or simply stroke it gently. Recently, with the development of wearable computing, the need for a wide extended pressure sensor has increased. Such sensors have to be elastic and possibly extendable to cover a three-dimensional surface, robust to work in harsh environment and reliable to supply accurate measurements. Finally, they must be produced at low-cost as to not affect the overall product cost. It should be evident how a wearable computing concept is challenging. It requires new solutions that enable electronic components to fit into clothes. Different architectures have been proposed to resolve the contrasting needs for unobtrusive devices with the computing power supplied by more traditional electronics. A major issue of this new perspective is researching new materials to use as a support for electronics. A fabric substrate is very appealing: it is elastic and extendable [2], supported by a well known technology and produced at low-cost. Some smart pressure-sensors interfacing with a flexible substrate have been developed, but they are either based on electro-optical fabric ([3]) which is not suitable for the low cost market, or they need expensive and cumbersome PCB electronics ([4]).

This paper introduces an approach for decoding the pressure exerted over a broad piece of fabric by means of capacitive sensing. The device described produces an image of the pressure field over the sensing surface, providing both information on the position of the area touched and on the pressure exerted on it.

SMART TEXTILE APPROACH

The system is composed of a distributed passive array of capacitors, as sketched in fig.1, (i.e. an array where no active

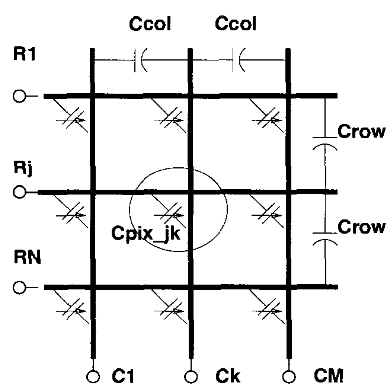

Figure 1. Schematic diagram of a capacitor array, including parasitic capacitors

elements such as transistors are involved), whose capacitance varies according to the pressure exerted over a fabric surface, as well as an electronic system that collects and computes the subsequent capacitance variations. Each capacitor has been made with the coupling capacitance between two conductive strips separated by an elastic and dielectric material. The sensing array results from the crossing of these conductive threads patterned in rows and columns of a matrix. When the dielectric layer between a given row and column of electrodes is squeezed, as pressure is exerted over the corresponding fabric area, the coupling capacitance between the two is increased. By scanning each column and row, the image of the pressure field can be obtained. In our approach the fabric is employed not only as a support for electronics, but also as a sensing element for decoding the pressure

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value. Different techniques can be used to pattern the electrodes over the textile surface. The conductive columns and rows can be simply drawn onto opposite sides of a piece of insulating material using conductive ink. One different approach would be for the sensing device to be implemented in fabric alternating conductive and isolating threads that are glued onto the opposite sides of a supporting layer. The next paragraphs describe these different approaches with details, and discuss the advantages and disadvantages of each one in realizing such a smart textile. For each technique the main features are shown, with particular attention to low-cost production, flexibility and stretchness, since the desired pressure sensor is intended to be wrapped around a three-dimensional (3-D) surface and to act as a sensitive skin.

A - Woven Circuit

The technology of drawing a pattern with the textile threads of different colors (as shown in fig.2), can be employed, using a mix of conductive and isolating fibers, to realize a flexible circuit embedded in the fabric, something which we will call Woven Circuit (WC), somehow similar to PCB technology.

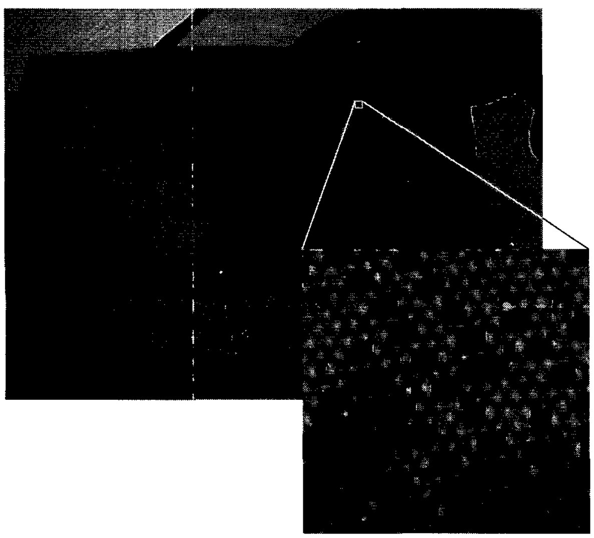

Figure 2. Textile technology for drawing patterns.

With this approach, a resolution of about $200\mu m$ for both minimum width and spacing of the wires may be achieved. Provided that the conductive threads are not implemented with a single conductive wire but with multiple twisted conductive fibers the fabric also has a good resilience (no memory of the shape it assumes when pressed). Moreover this solution allows to implement both electrodes and routing of both sides of the sensor on a single piece of fabric, as shown in fig.3. Since this kind of fabric can be produced by programmable automated machines its cost in volume is low (in the order of $18\$/m^2$).

The main drawback of this solution is that the routing channel

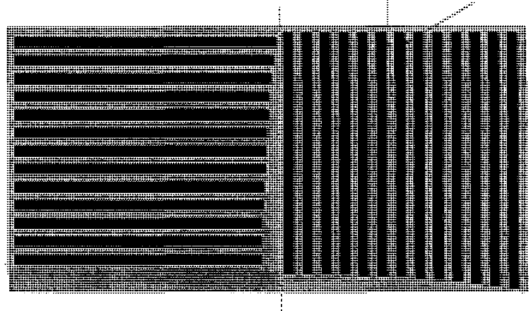

Figure 3. Sensor implemented on a single piece of fabric with conductive patterns drawn on it.

for connecting the electrodes to the PCB at the corner of the sensor has a non neglectable size.

B - Embroidered Circuits

Drawing a conductive pattern on a piece of fabric can also be achieved by embroidering the fabric using a conductive thread [1]. We will call this Embroidered Circuit (EC).

For EC, mechanical flexibility is expected to be worse, as compared to the WC, since for drawing the electrodes, which have a considerable width, a dense zig-zag pattern should be used, compromising the overall elasticity and resilience. Cost would also be higher, in volume, as compared to WC. On the other hand, the routing could probably be relatively more complex thanks to the control on the embroidering machine needle.

C - Textile Electrodes Bundled Routing

This solution uses for the electrodes a simple textile pattern of alternating conductive and isolating strips, while the routing is achieved by soldering wires connecting each electrode strip with the PCB for the readout. The wires may be bundled together and stuck to the fabric. We will call this approach Textile Electrodes Bundled Routing (TEBR). A sketch of this embodiment is reported in fig.4.

The resolution of textile technology is quite satisfying for the purpose of implementing the electrodes. Since the routing is achieved by wires the area overhead of the routing should become almost negligible, since the wire can be bundled to occupy less area. Cost would be the lowest among proposed techniques for the sensor fabric (just a simple pattern of parallel stripes, conductive/non-conductive), but the soldering of the bundle of wires should be added. If achieved by automated machines the cost should be affordable in volumes, although probably worse than that of WC.

What is most appealing of this solution is that the PCB-sensor connection is achieved by the same routing wires which are soldered to the PCB.

On the other hand, two pieces of fabric, applied to the oppo-

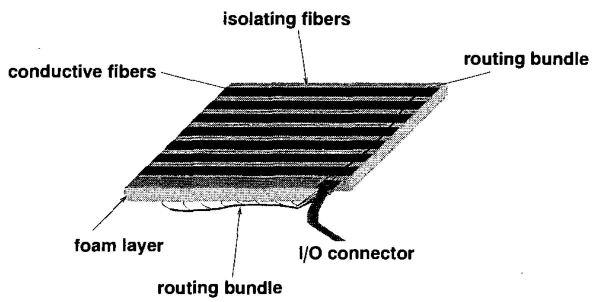

Figure 4. Textile Electrodes Bundled Routing (TEBR) technology.

site sides of the foam layer are needed.

D - Conductive Paint

In this arrangement a conductive paint is patterned on the sensor substrate-fabric by a process similar to air-brushing. Again, this is similar to PCB technology apart from the fact that the substrate is a piece of fabric instead of fiberglass, and the conductive layer which is deposited is an elastic conductive paint instead of copper. We will call this solution Conductive Paint Circuit (CPC). The mask determining the pattern may simply be a contact mask with openings, but other solution may be alternatively employed (like those used to print patterns on textiles). What is envisaged is the realization of a complex pattern on a single piece of fabric as reported in fig.3.

Sensor-PCB Connection

Two solutions are envisaged as the most practical for connecting the sensor electrodes to the readout PCB (which may be at the corner of or separate from the sensor), along with the bundled routing which has been described before.

A - Pin Array

The PCB hosting the readout chip may be provided with pins which establish a contact with corresponding wires in the fabric. A female connector may be used to tighten the connection. This solution may be used with various different arrangements of the pins, namely in 2D or linear arrays, as shown in figs.5.

B - Conductive Glue

The PCB hosting the readout chip may be provided with copper pads in positions corresponding to the conductive pads on the fabric to which they will be connected. The connection is established by a conductive glue based on conductive glue.

Surface Finishing

In order to avoid shorts (e.g. by a metallic ring on a finger) between electrodes on the side of the sensor which can be touched by the user, an isolating finishing can be applied to the sensor surface. Techniques similar to those skilled in the art a velvety finish may be applied. Alternatively, a further layer of fabric (optionally decorated) may be thermally soldered to the surface.

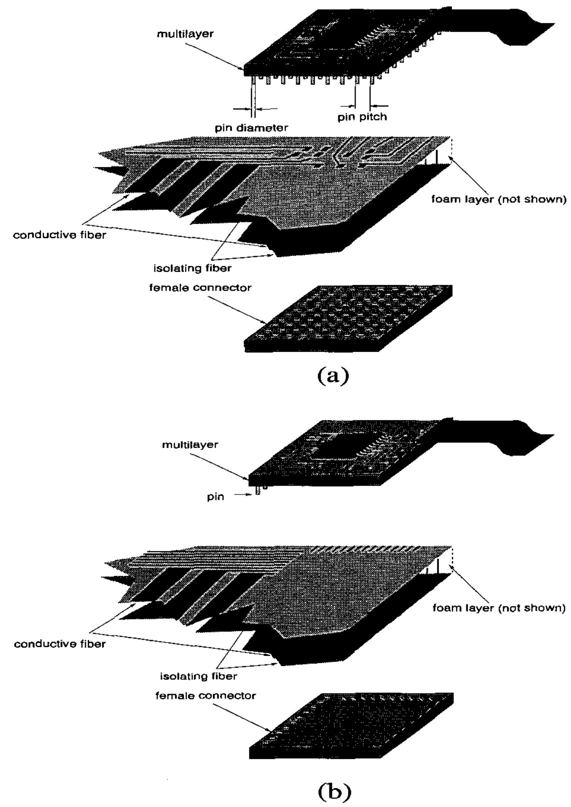

Figure 5. 2D (a) and 1D (b) Pin Array connector embedded in the PCB

SENSING PRINCIPLE

The principle of sensing the capacitor array is displayed in Fig.6. In this arrangement, a sinusoidal wave is applied onto the vertical line of the corresponding pixel so that the charge variation on the horizontal one is read-out by means of a charge amplifier. The peak-to-peak output sine wave encodes the value of the capacitance of the addressed node. The purpose of the feedback resistance, R_r is due o the following: at the time that switches are enabled to address the pixel, the input sine wave will not be, in general, at its mean value, thus injecting a constant charge offset into the amplifier that could drive it into saturation. By placing a resistor into feedback loop, it is ensured the clearing of the offset after a time constant because the amplifier acts as a high-pass filter of canonical transfer function:

$$H(j\omega) = \frac{V_o}{V_i}(j\omega) = -\frac{j\omega R_r C_{pix}}{1 + j\frac{\omega}{\omega_r}} \quad \text{where, } \omega_r = \frac{1}{R_r C_r}.$$

Thus, the offset due to the time of switching will vanish with

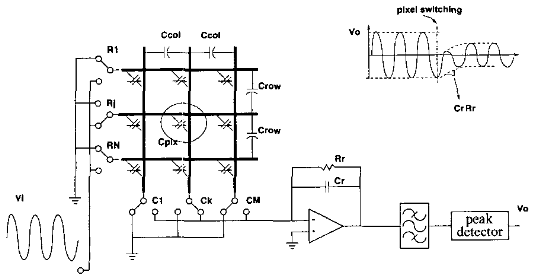

Figure 6. AC sensing scheme

a time constant $\tau = R_r C_r$. On the other hand, the output peak-to-peak amplitude will switch almost instantaneously to the new value, since the frequency of the sinusoidal input is in the pass-band of the inherent high-pass filter.
It should be noted that the charge injected on the virtual ground node of the opamp should depend only on the pixel capacitance. Thus injection by large parasitic capacitances due to neighboring columns (C_{col}) should be ruled out, as well as injection by pixels in the same column. Since the virtual ground node is at a fixed voltage level, grounding all columns but the selected one allows us to avoid injection from the neighboring columns by way of C_{col}, while grounding all rows but the selected one allows us to avoid injection from pixels in the same column.
This mode of operation is of paramount importance for getting a good signal to noise ratio and contrast, since typically the C_{pix} may be about one order of magnitude lower than C_{col}, and the total capacitance from pixels in the same column is equal to the number of rows minus one ($N-1$), which may be even two orders of magnitude larger than C_{pix}.
At the end of the stage, the output voltage may be filtered, and digitized by conventional building blocks.

Sensing with Feedback

Another read-out scheme, called feedback sensing, is provided. In this case the capacitors of the array become the feedback capacitor of the charge amplifier and the sinusoidal wave is applied to one terminal of C_r. The output voltage variation encodes the value of the capacitance of the addressed node, according to the relation:

$$\Delta V_o = \Delta V_i \frac{C_r}{C_{pix}}$$

By using this architecture the output voltage is inversely proportional to the pixel capacitance. The IO characteristic thus emphasizes the portion of the capacitance range corresponding to small capacitance values.

Input Dynamic Range

The proposed solution is suitable for working in environment characterized by a wide pressure range. Using the sensing scheme described in fig.6, it becomes clear that, in the event of a great pressure is applied over the fabric surface, the system needs a high value feedback capacitor to avoid the charge amplifier saturation. On the contrary, if a light pressure has to be detected (resulting thus in a small coupling capacitance value), the system needs a small value feedback capacitor in order to obtain an intelligible voltage variation from the charge amplifier output. The described sensor features the run-time adoption of feedback and feed-forward read-out schemes; furthermore the value of the feedback capacitor is not fixed, but it can vary to accommodate for different operating conditions. In this way an input dynamic range of $100fF$ - $10pF$ is achieved.

EXPERIMENTAL RESULTS

A prototype 24×16 pixels sensor with a readout board has been implemented to validate the design (fig.7). The pixel pitch is $8mm$ which is about the same as the tactile resolution of human back skin. The electrodes are implemented as strips of conductive fabric thermally soldered to the two opposite sides of a foam layer, and are connected to the board by non-shielded wiring.

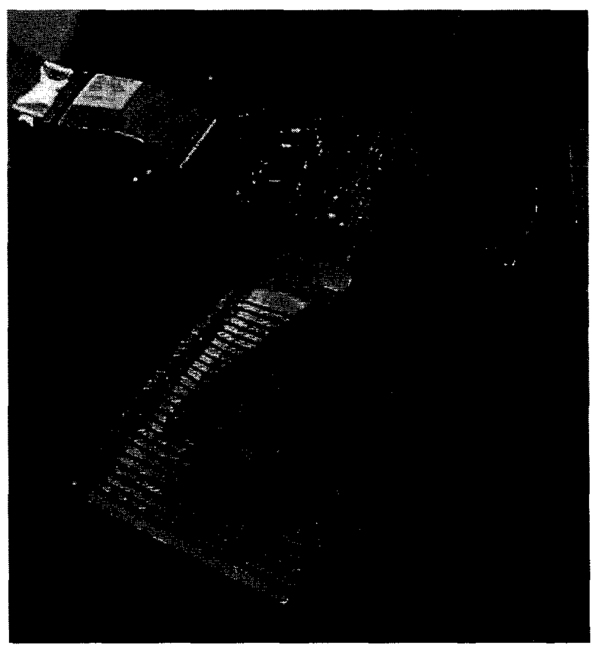

Figure 7. Prototype board.

The board uses conventional MOS switches and operational amplifier and has been implemented on a board. The output of the charge amplifier is digitized by an A/D converter, then data are collected by a general purpose digital acquisition board and the images are displayed in real time at about 3 F/s onto a PC monitor. The use of fabric for implementing both substrates and conductive patterns allows us to obtain

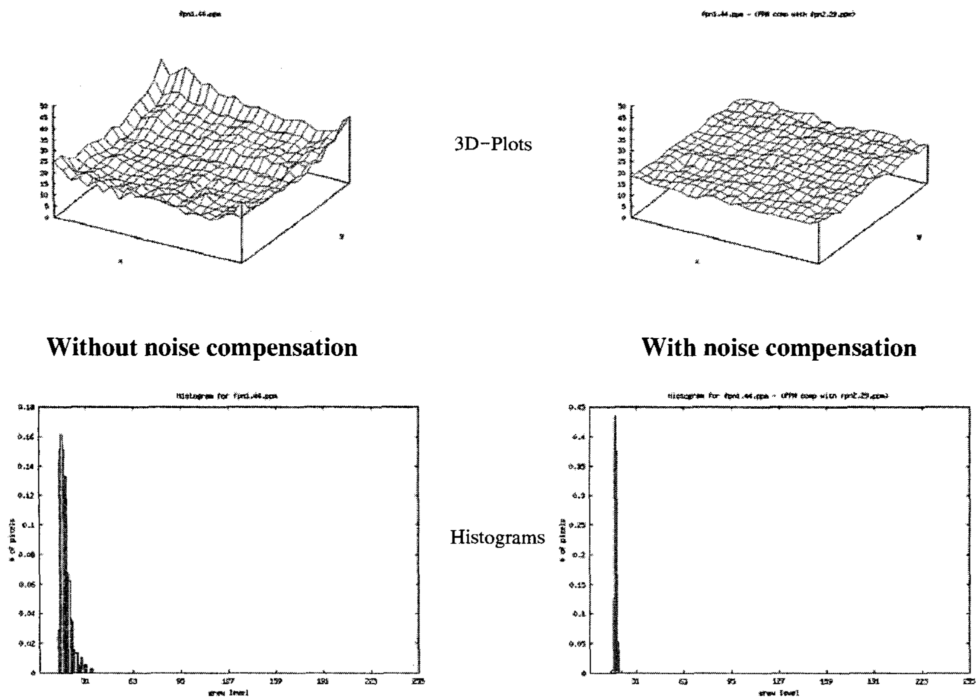

Figure 8. Fixed Pattern Noise Compensation. Noise as a reference image.

a flexible and partially extensible pressure-sensor. The main drawback of this approach is the introduction of non idealities and differences between pixels of the sensor array. This kind of noise (Fixed Pattern Noise FPN) seriously affects the sensing fabric according to the resting position, for example. Furthermore, the use of a foam layer as the sensor substrate introduces strong non-linearities in pressure versus capacitance function. This can seriously affect the perception of weak pressure values such as those generated by gentle stroking. In order to compensate for these effects, reduce thermal noise and adjust pixel response, the proposed readout system features on-board post-processing of the acquired images.

Fixed Pattern Noise. Fixed pattern noise is a phenomenon due to electrode roughness (resolution accuracy in textile technology), to non-uniform dielectric layer (thickness not constant across the fabric surface) and to the adaption to the wrapped object (2-D piece of fabric wrapped around a 3-D surface). Its main effect is a great spread in capacitance values at the rest position. The left side of figure 8 shows a 3-D plot and an histogram of the measured capacitance values acquired from a square piece of fabric without pressure being exerted. Non idealities and mismatches result in different pixel values even in adjacent areas of the fabric surface. Various techniques can be performed to reduce this offset. One simple way is to subtract from the current pixel signal a corresponding reference value measured at the rest position. These zero values are stored in the system RAM and used by the embedded FPN-cancellation routine during run-time pixel processing. The right side of figure 8 shows the 3-D plot and the histogram of the capacitor array measured from the same piece of fabric after the adoption of the described compensation. The undesired spread in pixel values is strongly reduced and the absence of exerted pressure is correctly translated into an uniformity among the capacitance values.

Gamma Correction. The relation between pressure and capacitance values is usually strongly non-linear. To counteract this, a compensation similar to the gamma-correction used in image processing can be implemented to enhance the perception of weak signals like those generated by gentle stroking. Figure 9 shows the effects of such correction implemented as a look-up table and processed by the on-board software.

Acquired Images. Examples of images acquired by the board are illustrated in the figures below. The image of fig. 10 shows a palm hand pressed onto the artificial skin plane while fig. 11 illustrates a fist.

All the above images are not treated by any smoothing software. In the case of a simple treatment of the image, the fist figure would appear as illustrated in Fig.12.

The tests performed over the board have led to an estimation of the parasitic capacitances: the pixel capacitance, C_p is ranging from $300fF$ to $1.2pF$ while the inter line capaci-

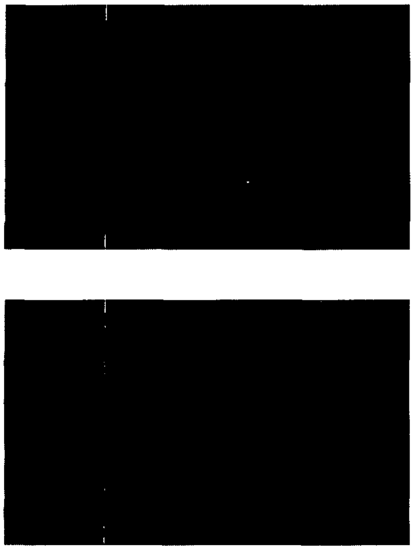

Figure 9. Effect of a Gamma Correction on a pressure image as results from a light stroke.

tance can be as high as $2.5pF$.

CONCLUSIONS

An innovative pressure-sensitive fabric and a solution for the array read-out, which features run-time data post-processing, have been presented. The system produces an image of the pressure field, providing both information on the area touching the surface of the sensor and on the pressure exerted. The emphasis in this solution is on detection of small pressures (e.g. light stroking) being applied over a relatively wide area. The architecture proposed enables us to measure a coupling capacitance variation of about $100\ fF$ induced by a light pressure exerted over a $1\ m^2$ fabric surface. Furthermore, the use of a simple capacitive sensing scheme results in a robust sensor even if exposed to strong mechanical stresses

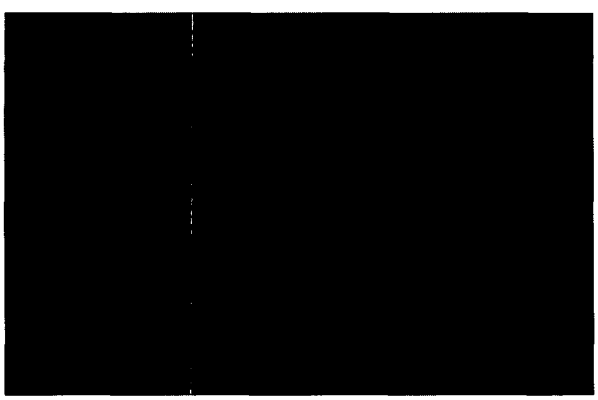

Figure 10. Image of a palm hand

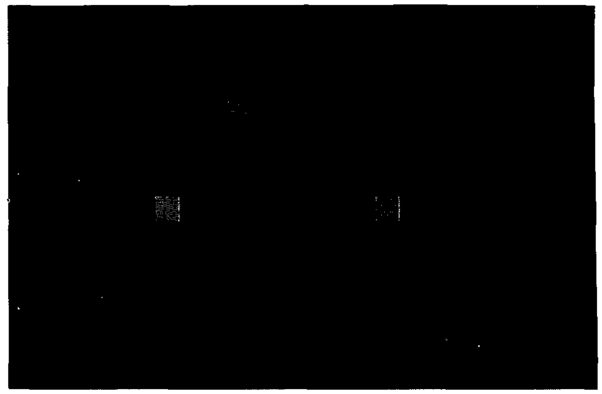

Figure 11. Image of a fist

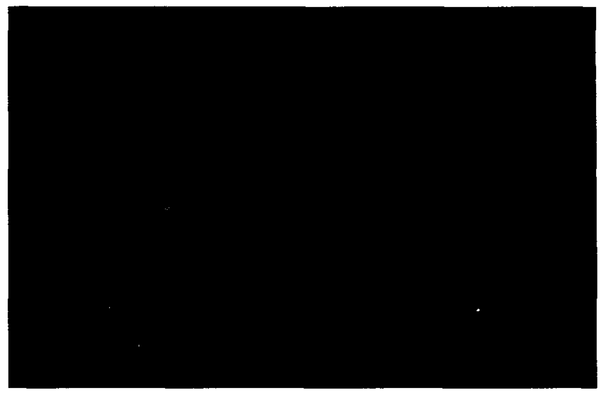

Figure 12. The same fist as in fig.11 after a smoothing algorithm processed by embedded software.

(impacts, compression) that are incompatible with the working conditions required by more sophisticated sensors, such as piezoelectric devices.

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