15th Triennial World Congress, Barcelona, Spain

DISTRIBUTED FLEXIBLE TACTILE SENSOR USING PIEZOELECTRIC FILM

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Abstract: The prototype of the tactile sensor which has 8 × 8 array using piezoelectric film was fabricated. In the fabrication procedure, the electrode patterns and the common electrode of the thin conductive tape are attached to the both sides of the 28 μm thickness piezoelectric film using conductive adhesive. The sensor is covered with polyester film for insulation and attached to the rubber base for a stable structure. The proposed fabrication method is simple and easy to make the sensor. The sensor has the advantages in the implementing for practical applications because its structure is flexible and the shape of the each tactile element can be designed arbitrarily. The signals of a contact force to the tactile sensor are sensed and processed in the DSP system in which the signals are digitalized and filtered. Finally, the signals are integrated for taking the force profile. The processed signals of the output of the sensor are visualized in a personal computer, the shape and force distribution of the contact object are obtained. The reasonable performance for the detection of the contact state was verified through the sensing examples. *Copyright © 2002 IFAC*

Keywords: sensor, signal processing, force, filtering, robotics

1. INTRODUCTION

In the near future, it is expected that robots will play an important roles in social welfare, medical treatment, services in home or office, and so on, coexisting with humans in the same work space. In this case it is strongly desired for these robots to have machinery to maintain safety to human. Considering safety for human, it is necessary to develop the robot which can attenuate the impact to guarantee the safety. For this feature some technologies, such as mechanism, control algorithm and sensing strategy must be considered and developed cooperatively.

Confining our interest to the sensing strategy, the tactile sensor is a necessary devices for realizing service robots. Such a sensor provides data on the shape, position, and force distribution of a contacting stimulus. This tactile sensing is the process of determining physical properties and events through contact with physical objects. Also tactile sensors offer exciting possibilities for use in mechatronic devices and measuring instruments in many areas of science and engineering(Lee and Nicholls, 1999; Johnston et al., 1996; Son and Howe, 1996; Howe, 1994). With the goal of enhancing the tactile performance of robots, several technologies are aggressively being investigated. The developed tactile sensor technologies can be categorized to include: piezo-resistive (Beebe et al., 1995), optical (Hok et al., 1989), capacitive (Fearing, 1987), chemical -resistive (DeRossi et al., 1989), inductive (Hackwood et al., 1985), piezo-electric(Kolesar et al., 1992), and acoustic(Brown, 1985).

A number of researchers have evaluated piezo film in robotic sensors. Dario and DeRossi(1985) have developed a skin-like sensor based on PVDF (polyvinylidene fluoride) film. This sensor contains two force-sensing layers and has the additional capability of sensing thermal properties. A combined three-axis force and slip sensor has been described by Yamada and Cutkosky(1994). The applied force is resolved into three axes and slip is detected by a piece of piezoelectric film moulded into the head. So far, the authors have certified that PVDF film satisfied the demands of tactile sensors, and also proved good output characteristic of the fabricated tactile sensor with 4 × 4 array(Yu et al., 2001).

In this paper, a flexible tactile sensor array for service robots using PVDF film for the detection of the contact state has been developed. PVDF film has flexibility and is excellent in sensitivity and dynamic response. The prototype of a tactile sensor which has 8 × 8 array was fabricated. The sensor made of PVDF film has many distributed sensing points, so it is sensible to a tactile stimulus in relatively wide spatial range. The processed signals of the output of the sensor are visualized in personal computer, the shape and the force distribution of the contact object are also obtained. The reasonable performance for the detection of the contact state was verified through

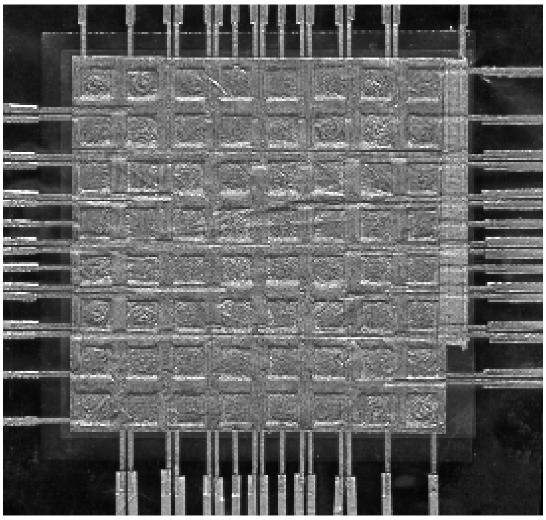


Fig. 1. Photograph of the tactile sensor

the sensing examples. In the application of the tactile sensor to service robots, the easiness for implementing to the robot bodies with the various configuration should be considered sufficiently. The sensor fabricated in this research is flexible, and the size and shape of the each tactile element can be designed and fabricated arbitrarily, which offers the advantages in the implementing for various practical applications. Also the proposed fabrication method is simple and easy to make, so that, the sensor can be made in the laboratory without using any special equipment.

2. PIEZOELECTRIC FILM AND SENSOR STRUCTURE

The open-circuit output voltage of the PVDF film is given by

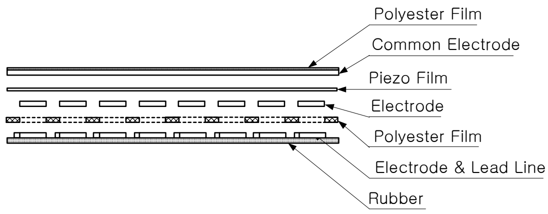
$$V_0 = g_{3n} X_n t \ (n = 1, 2, \text{or } 3), \tag{1}$$

where, g_{3n} is appropriate piezoelectric coefficient for the axis of applied stress or strain, where, the first subscript refers to the electrical axis and the second one refers to the mechanical axis. Also X_n is applied stress in the relevant direction, and t is the film thickness.

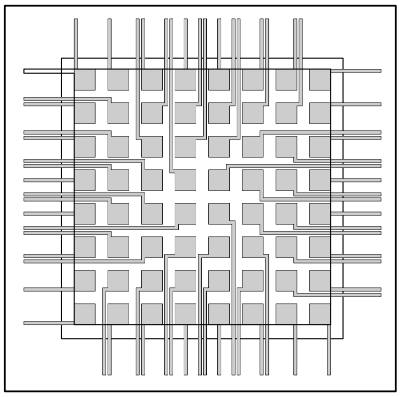
The tactile sensor with 8 × 8 array using PVDF film was fabricated as shown in Figure 1 and the parameters of the PVDF film(AMP Co., USA) used for the fabrication is described in Table 1. The structure of the tactile sensor is shown in Figure 2. In the fabrication procedure of the sensor, the electrode patterns and common electrode of the thin conductive tape are attached to the both sides of the PVDF film using conductive adhesive(3M Co., #1181). The patterns of the layers used for the fabrication of the sensor are shown in Figure 3. The size of the tactile element is 5 × 5 mm, but this size can be downsized for the needs, and the shape of the tactile element can be designed arbitrarily according to the needs of a practical application. The lead lines

Table 1 Parameters of PVDF film

Parameter	Value	Unit
Thickness t	28	μm
Piezo Strain Constant d_{31}	23	$(10^{-12}) C/N$
d_{33}	-33	
Piezo Stress Constant g_{31}	216	$(10^{-3}) Vm/N$
g_{33}	-330	
Capacitance C	380	pF/cm^2

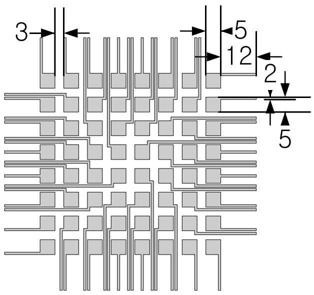


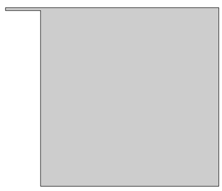
(a) Side view of the sensor



(b) Upper view of the sensor

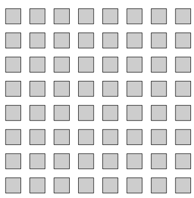
Fig. 2. Structure of the tactile sensor

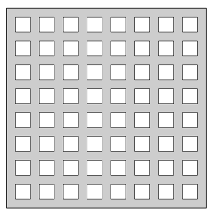




unit: mm

(a) Electrode and lead line (b) Common electrode





(c) Electrode (d) Polyester film

Fig. 3. Patterns of the layers used for the fabrication

are attached to the electrode patterns for sensing the contact force applied to the each tactile element. The sensor is covered with polyester film for insulation and attached to the rubber base for making stable structure. So the sensor has the sufficient durability to various and dynamic applied forces. Also the structure of the sensor is sufficiently flexible for implementing to a robot parts with various configuration.

3. OUTPUT CHARACTERISTICS OF SENSOR

In order to investigate the characteristics of the sensor, the sensor outputs to the arbitrary forces are measured using cantilever beam with translational motion.

Figure 4 shows the experiments for sensor calibration in which the output of the strain gages(CAS Co. AE-11-S30N-120-EL) attached to the cantilever beam and the tactile sensor are compared for calibration. The strain to the applied force is obtained as

$$\varepsilon = \frac{6Fl}{Ebh^2} \ , \qquad (2)$$

where, ε is the strain [m/m], E is the young's modulus of the beam, F is the weight [N], l is the length from the strain gage to the touch point, h is the thickness and b is the width of the beam.

The signals of the applied force to the tactile sensor and the strain from the gage are sensed and processed in the DSP system(dSPACE 1102) and personal computer. The time response characteristics are shown in Figure 5, which also shows the relationship between the applied force and the output of the sensor when a square wave force is applied to the sensor using the mechanism of the translational motion. The output of the sensor tracks the applied force profile reasonably with the time delay of about 10ms. The negative output of the sensor after applying the force is due to the flexibility of the sensor structure and the output disappears instantly.

The relationship between the applied forces and the outputs of the sensor is shown in Figure 6. The horizontal axis is the amplitude of the applied force and the vertical axis is the output of the sensor. According to the results shown in Figure 6, the output of the sensor is linear with a negligible deviations. Each tactile element in the sensor represented the linear response(0.1377 N/mV) for the applied forces spanning 1.3 N to 10 N. The output of the sensor is approximated by

$$Y = 0.14X - 0.23 \ , \qquad (3)$$

where, X is the amplitude of the applied force and Y is the output of the sensor.

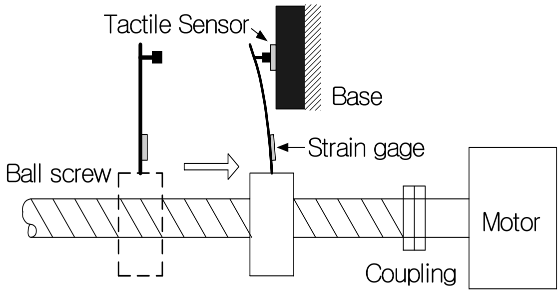
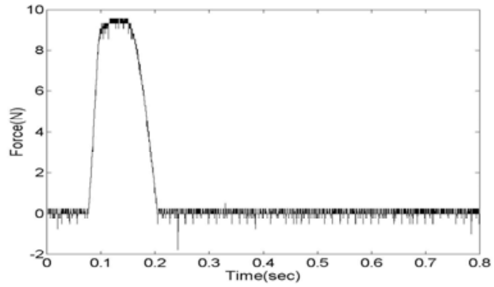
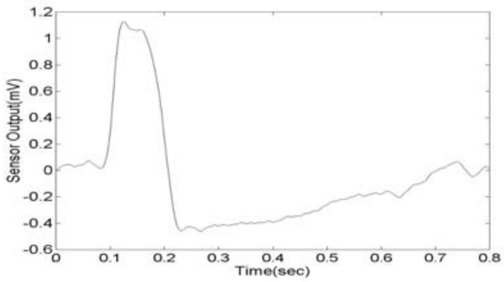


Fig. 4. Experiments for sensor calibration



(a) Applied force



(b) Output of the sensor

Fig. 5. Output of the sensor to the applied force

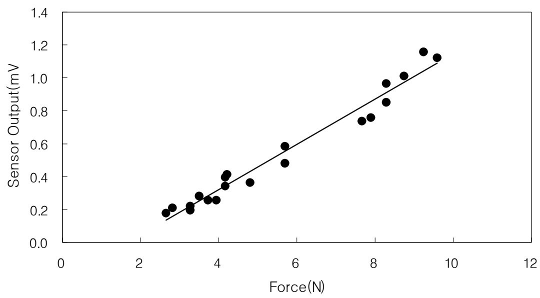


Fig. 6. Output characteristics of the senosr

The sensor output due to the applied sinusoidal forces with some varying frequencies from 1Hz to 100Hz is obtained. By the experiment, the sensor output represents the dynamic variation of the applied forces reasonably with some time delay due to the signal processing in the system. This feature will be very useful for dynamic manipulation using the developed tactile sensor. As an example, the output of the sensor by the sinusoidal force of 30Hz is shown in Figure 7. The sensor output shows the time delay of about 60ms due to the signal processing. Figure 8 shows the frequency response

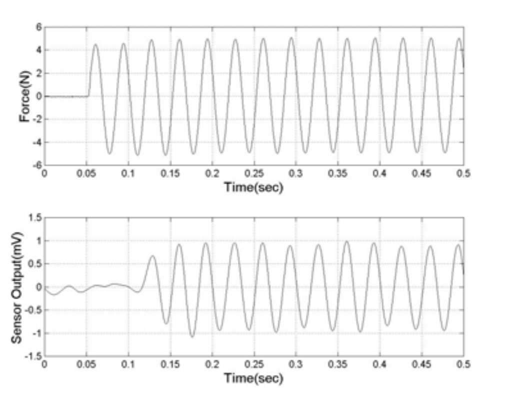


Fig. 7. An example of the sensor output by the sinusoidal force(frequency: 30Hz, amplitude: 4N)

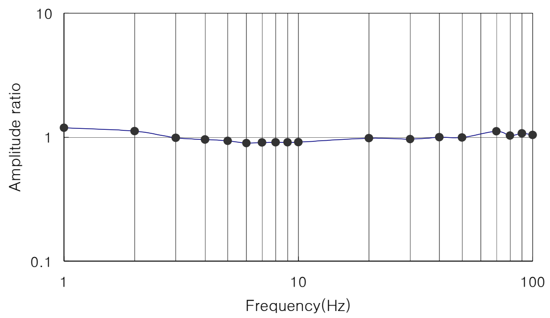


Fig. 8. Frequency response of the sensor

of the sensor with respect to the sinusoidal forces with varying frequencies from 1Hz to 100Hz. We can see that the sensor has the almost constant gain through the broad range of frequencies.

4. SIGNAL PROCESSING

4.1 Configuration of signal processing system

The configuration of the signal processing system is shown in Figure 9. The outputs of the sensor are scanned sequentially by the analog multiplexers Maxim, MAX306) and processed in the DSP system(dSPACE 1102), and the obtained information about the contact state is visualized in personal computer.

4.2 Signal processing

T The block diagram of the signal processing flow is shown in Figure 10. In order to manipulate the output signals of the 8 × 8 array, four 16-channel analog multiplexers are used. The signals of the 64 tactile elements are scanned sequentially with the sampling rate of 1.6ms. The signals from the sensor according to the applied forces are digitalized and filtered for noise rejection, and then amplified. In the filtering operation, the DC offset is rejected by the high-pass filter with the cutoff frequency of 0.5Hz. The noise due to the AC power source and the high frequency noise are eliminated by the notch filter with the

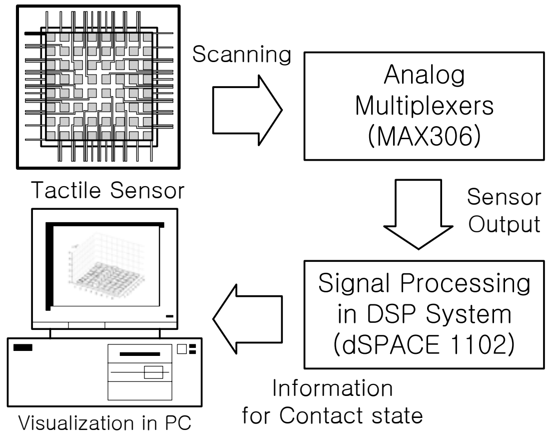


Fig. 9. Configuration of the signal processing system

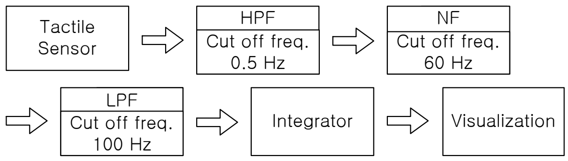


Fig. 10. Block diagram of the signal processing flow

cutoff frequency of 60 Hz and the low-pass filter with the cutoff frequency of 100Hz respectively. Finally, the signals are integrated for taking the applied force profile since the outputs from the sensor represent the variation of the applied forces with respect to time. The processed signals of the output of the sensor are visualized in personal computer, the shape and force distribution of the contact object are also obtained in real time.

5. SENSING EXAMPLES AND DISCUSSION

The reasonable performance for the detection of the contact state is verified through the experiments. In the visualization of the contact state, the 3-dimensional graph shows the contact position, the shape of the object and the force distribution after signal processing. Table 2 describes the load shapes applied to the sensor and the detection of the contact state investigated through some sensing examples. In the 3-dimensional graphic representation, the xy-plane corresponds to the tactile element positions in the sensor matrix, and the z-axis maps the associated response values.

The sensor response in the case of bar shape contact is shown in Figure 11. According to the figure the bar shape force is applied to the 5th column tactile elements. In the figure the non-contact region represents some force distribution because of the bending of the sensor sheet. However the represented forces of the non-contact region can be neglected because the magnitudes of the forces are very small comparing the true region due to the applied forces.

The sensor response in the case of a doughnut-shape contact is shown in Figure 12. The figure represents the almost doughnut shape force distribution. In the figure the inner region of the doughnut shape shows

Table 2 The load shpes and the detected mean forces

Dim. & Result \ Load shape		Bar	Doughnut
Dimension(mm)		60(length) × 5(width)	40(outer diameter) × 30(inner diameter)
Detected mean force(N)	Contact region	7.866	2.074
	Non-contact region	0.123	0.262

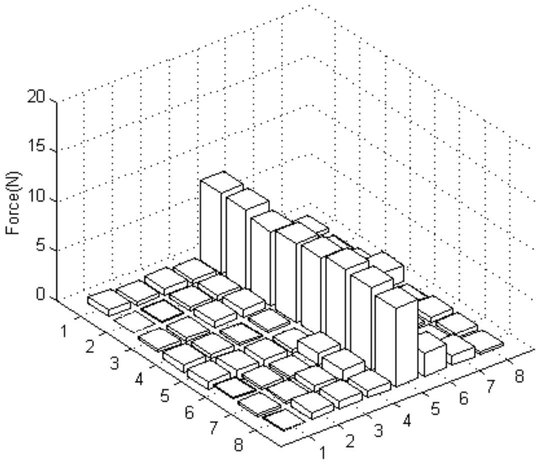


Fig. 11. Sensor response in the case of bar-shape contact

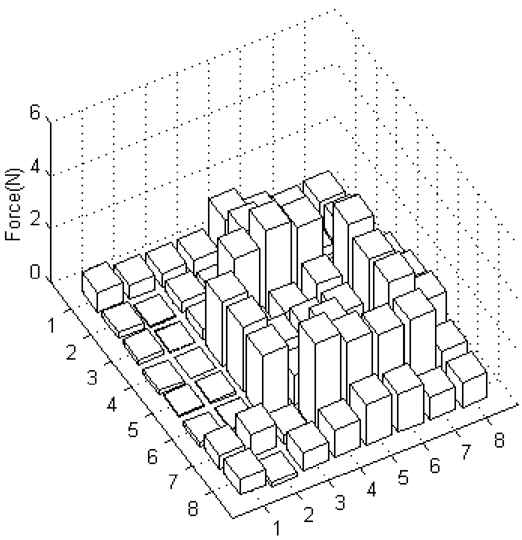


Fig. 12. Sensor response in the case of doughnut-hap contact

some force distribution due to the sensor structure. This phenomenon will disappears by making the sensor with the more flexible structure.

The detected mean forces of the sensing examples are given in Table 2. By the table the detected force of the non-contact region with respect to the applied force is 1.56% and 12.63% in case of the bar shape and the doughnut shape respectively.

6. CONCLUSION

The objective of this research is to fabricate and evaluate the performance of the flexible tactile sensor array realized by capacitively-coupling piezoelectric PVDF film with the thickness of 28 μm . The proposed fabrication procedure is simple and easy to make the sensor in the laboratory without using any special equipment. So the tactile sensor array with the tactile elements of arbitrary shape in geometry can be fabricated easily according to the needs of the practical application. Also the stable signal processing algorithm was designed for the noisy and weak signals from the sensor. The sensor system shows the reasonable response to applied dynamic forces with various frequencies in realtime. It will be very useful features for dynamic contact or manipulation using the developed tactile sensor. The information of the dynamic contact state obtained through the signal processing system was visualized in the personal computer for user interface. In the experiment the two types of object were applied to the sensor, as a result, we can see that the sensor has reasonable performances.

For the more flexible structure and reliable output characteristics, we are now making the new sensor by using FPC(Flexible Printed Circuit) technique. Also the design of the compact signal processing system is considered for portability and practical applications.

ACKNOWLEDGEMENT

This work was supported by the Mechatronics Research Center of Chonbuk National University funded by Korea Science and Engineering Foundation.

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