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Development of an Array-Type Flexible Tactile Sensor Using PVDF and Flexible Circuitry

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Abstract

This paper represents the development of an array-type flexible tactile sensor using PVDF (polyvinylidene fluoride) film and flexible circuitry. The tactile sensor which has 8×8 taxels is made by using PVDF film and FPC(flexible printed circuit) technique. Experimental results on static and dynamic properties are obtained by applying arbitrary forces and frequencies generated by the shaker. In the static characteristics, the threshold and the linearity of the sensor are investigated. Also dynamic response of the sensor subjected to the variable frequencies is examined. 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 outputs of the sensor are visualized on a personal computer, the shape and force distribution of the contacted object are obtained using two and three-dimensional image in real time. The reasonable performance for the detection of contact state is verified through the experiment.

Key words : PVDF(polyvinylidene fluoride) film, distributed flexible tactile sensor, force distribution, FPC(flexible printed circuit), detection of contact state.

1. Introduction

A tactile sensor is defined as a device or system that can measure a given property of an object or contacted event through physical contact between the sensor and the object. Tactile sensor provides data on the shape, position, and force distribution of a contacting stimulus. Then, tactile sensing is the process of determining physical properties and events through contact with physical objects. Tactile sensors offer exciting possibilities by using in mechatronic devices and measuring instruments in many areas of science and engineering[1~4]. With the goal of enhancing the tactile performance of robots, several technologies have aggressively been investigated. The developed tactile sensor technologies can be categorized to include: piezo-resistive[5], optical[6], capacitive[7], chemical-resistive[8], inductive[9], piezo-electric[10], and acoustic[11].

A number of researchers have investigated piezo-film in robotic sensors. Dario and Rossi[12] have developed a skin-like sensor based on PVDF(polyvinylidene fluoride) film. A combined three-axis force and a slip sensor have been described by Yamada and Cutkosky[13]. So far, the authors have certified that PVDF film have satisfied the demands of tactile sensors, and have proved to be a good output characteristic of the fabricated tactile sensor with 4×4 arrays[14~15].

In this paper, a flexible tactile sensor array

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using PVDF film has been developed with FPC(flexible printed circuit) techniques. The tactile sensor can easily be made according to the needs of practical application with the taxels of arbitrary shape. In order to investigate the properties of the sensor, its dynamic characteristics to the arbitrary forces and frequencies are measured by using the shaker with the force sensor. In the static property the threshold and the linearity of the sensor are investigated. The dynamic response of the sensor subjected to variable frequencies is also examined. The sensor made of PVDF film has many distributed sensing points, so it is sensible to a tactile stimulus in a relatively wide range. The processed signals of the output of the sensor are visualized on a personal computer, so that, the force distributions of the contact object are also obtained.

2. Structure of sensor

2.1 PVDF Film

In the view of a sensor, the structure of the human skin consists of many detectors with high density arranged in as the form of a thin sheet. An ideal tactile sensor requires of the following characteristics: First, a tactile sensor must be thin, flexible, and able to cover a large area, like the human skin. Second, varieties of detectors with high density are arranged. Third, a tactile sensor must be durability to physical external forces and chemical pollution, etc. However, the actual fabrication of a tactile sensor that the characteristics above mentioned is difficult. Therefore, this research concentrated on the developing a tactile sensor for covering a relatively large area, flexibility and durability.

In this research, the PVDF film, which is a very thin film that generates electrical voltage when mechanically deformed, is used to obtain the profile of a contacted object, and can be fabricated with a large area and unusual designs. PVDF film is a compliant, lightweight, tough, plastic film available in a wide variety of thickness and surface areas. Certain properties of piezo-film, such as an extremely wide frequency range, a broad dynamic response, and low acoustic impedance, make it attractive for many applications.

The open-circuit output voltage of the PVDF film as shown in Fig. 1 is given by

$$V_o = g_{3n} X_n t \quad (n=1,\ 2,\ 3) \tag{1}$$

where, g_{3n} is the applied stress in the relevant direction, and X_n is the appropriate piezoelectric coefficient for the axis of applied stress or strain. The first subscript referring to the electrical axis and the second one refer to the mechanical axis. here, t is the film thickness. A tactile sensor with an 8×8 array using PVDF film was fabricated as shown in Figure 2 and the parameters of the PVDF film(AMP Co., USA) used for the fabrication is described in Table 1, where d and g are respectively the ratio of generated electrical charge to applied force and generated electrical voltage to directional stress.

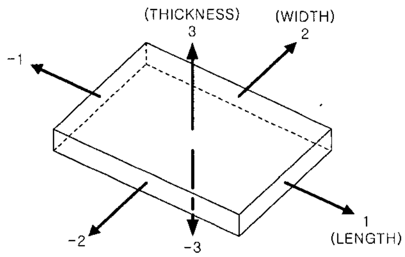


Fig. 1. Numerical classification of axes.

Table 1. Parameter of the PVDF film.

Parameter	Symbol	Values	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

2.2 Structure of the sensor

Figure 3 shows the structure of the tactile sensor fabricated using the advantage of FPC and its difference with existent PCB(Printed Circuit Board) is very gauzy due to the use of polyester film by insulation and to the fact that the whole thickness of the sensor is about 230㎛. The size of the taxel element is 5×5 mm, but this size can be downsized if necessary, and the shape of the taxel element can also be designed arbitrarily according to the needs of a practical application. In the fabrication procedure of the sensor, the electrode patterns and the common electrodes are attached to the both sides of the PVDF film.

The patterns of the layers used for the fabrication of the sensor are shown in Fig. 4. The size of the tactile detection element is 5 mm ×5 mm, the space between them is 3 mm, the thickness of the lead line is 0.3 mm, The whole size of the tactile sensor is 213 mm×165 mm and the size of the detection area is 61mm×61 mm. The lead lines are attached to the electrode patterns to sense the contact force applied on the each taxel. The fabricated tactile sensor is covered by a polyester film for insulation. So it has sufficient durability for various and dynamic applied forces. Also the structure of the sensor is sufficiently flexible enough to be implemented to robot parts using various configurations.

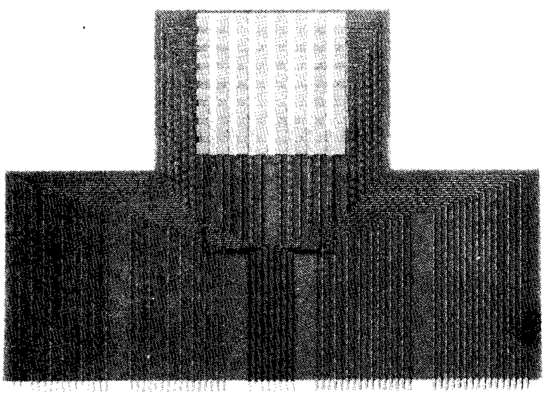


Fig. 2. Photograph of the tactile sensor using PVDF.

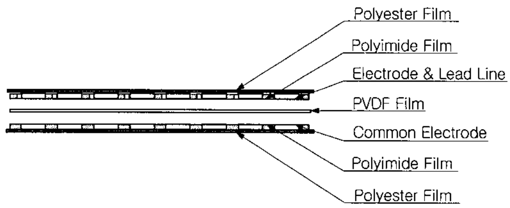
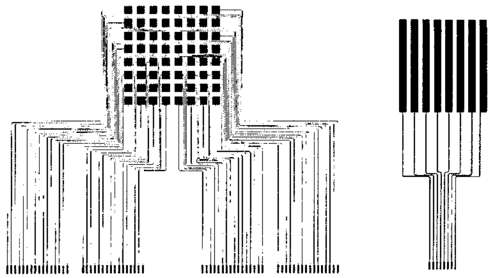


Fig. 3. Structure of the tactile sensor.



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

Fig. 4. Pattern of layers used for fabrication of the tactile sensor.

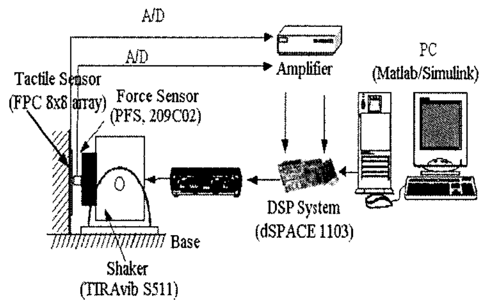


Fig. 5. Configuration of the experimental set-up.

3. Output characteristics of the sensor

In order to investigate the properties of the tactile sensor, the output of a tactile sensor is measured by applying arbitrary forces and frequencies generated by the shaker. In the static property, the threshold and the linearity of the sensor are investigated. Also, the dynamic response of the sensor subjected to variable frequencies is examined.

Figure 5 shows the configuration of the experimental set-up built to obtain the output characteristics of tactile sensor. The signals of the force applied to the tactile sensor and the voltage from the force sensor(PFS, 209C02) are recorded and processed in the DSP system (dSPACE 1102) and in a personal computer.

The outputs of the sensor take into account the noise of DC offset and 60Hz due to AC power source. In the design of the filter, these two frequencies of noise are considered as cutoff frequency. The output of the sensor tracks the applied force profile reasonably with a time delay of 60msec due to the filtering operation. The relationship between the step forces applied by the shaker and the outputs of the sensor is shown in Fig. 6. The horizontal axis is the amplitude of the applied force and the vertical axis is the output of the sensor. The threshold of the sensor is about 0.5N. The signal of the sensor has the low ratio of the sensor output to the noise due to the sensor structure. So it is difficult to detect applied forces lower than the threshold. However, it is possible to detect smaller forces by modifying the structure of the sensor. According to the results shown in Fig. 6, the output of the sensor is linear with negligible deviations. Each taxels in the sensor represent a linear response (1.12 mV/N) for the applied forces spanning from 0.5 N to 8 N. The output of the sensor is defined by

$$Y = 1.12X - 0.12 \qquad (2)$$

where, X is the amplitude of the applied force and Y is the output of the sensor. Also, the approximated equation (2) is obtained by square root method.

The dynamic response of the sensor system is also obtained by applying dynamic forces with frequencies varying from 1Hz to 40Hz to the sensor. In 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.

Figure 7 shows the dynamic response of the fabricated tactile sensor. As an example, the dynamic response by the sinusoidal force of 15Hz is shown in Fig. 7 in which the vertical axes are the applied force induced by the shaker and the sensor output respectively. The sensor output shows a time delay of 60ms due to the signal processing. Figure 8 shows the frequency response of the sensor to an applied sinusoidal force. In Fig. 8, the horizontal axis is the frequency of the applied sinusoidal force and the vertical axis is the gain of the sensor output.

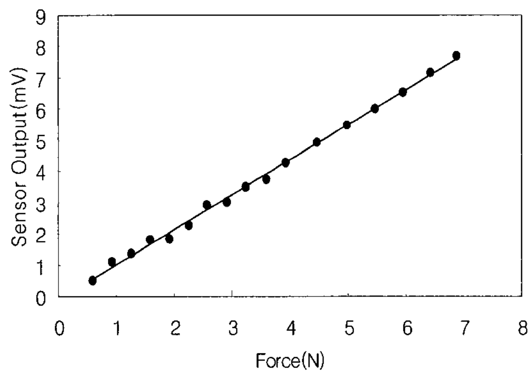


Fig. 6. Static characteristics of the sensor to the applied force.

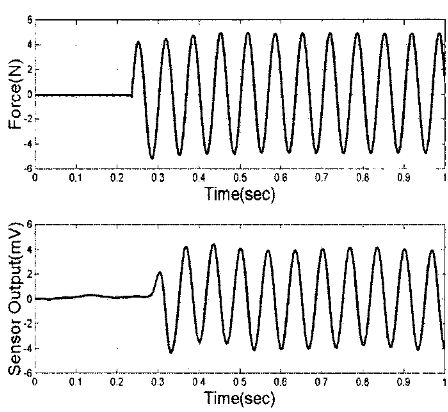


Fig. 7. Example of the dynamic response by the sinusoidal force (frequency: 15Hz, Amplitude: 4.3N).

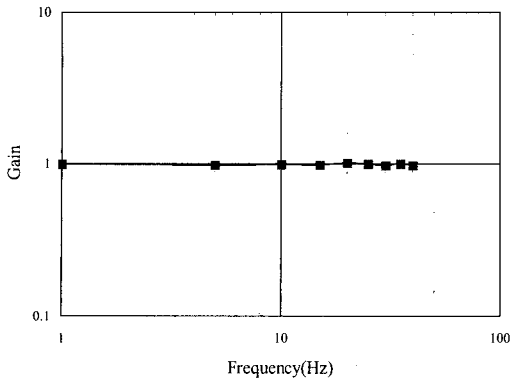


Fig. 8. Frequency response of the tactile sensor.

4. Signal Processing

The configuration of the signal processing system is shown in Fig. 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 of the contact state is visualized in a personal computer.

In order to manipulate the output signals of the 8×8 array, four 16-channel analog multiplexers are used. The signals of the 64 taxels are scanned sequentially with the sampling rate of 1.6ms. Figure 10 shows the functional diagram of MAX306 16-channel multiplexer. The switch is derived by the control terminal (A0, A1, A2, A3 and EN), ±12V is supplied to the input terminal for the electric power (V+, V- and GND) and the entered signals from input terminal (NO1~NO16) are sent to DSP system through the output terminal (COM).

The block diagram of the signal processing flow is shown in Fig. 11. The signals from the sensor according to the applied forces are digitalized and filtered in order to obtain the force profile. In the filtering operation, the DC offset is rejected and the noise provoked by the AC power source and high frequency noise are eliminated by the band-pass filter(BPF) with the cutoff frequency of 0.5Hz and 40Hz respectively.

Finally, the signals are integrated for taking the applied force profile since the outputs from the sensor represent the variation of the applied

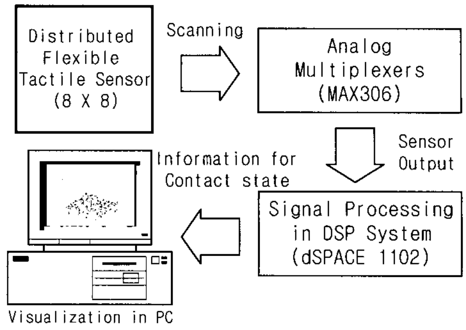


Fig. 9. Configuration of the signal processing system.

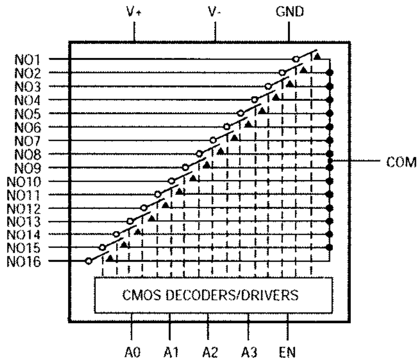


Fig. 10. Functional diagram of the MAX306 16 - channel multiplexer.

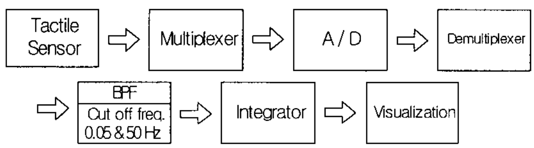


Fig. 11. Block diagram of the signal processing flow.

Table 2. Description of the load shapes used for the experiments.

Load shape	Dimensions(mm)
Bar	60.0(length)×5.0(width)
Doughnut	40(outer diameter)× 30(inner diameter)

forces in respect to the time($\partial F/\partial t$). The processed signals of the sensor output are visualized on a 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. Figure 12 shows the photograph of the distributed flexible tactile sensor system used for the sensing examples. Table 2 describes the load shapes applied to the sensing experiments.

The sensor response in the case of bar shape contact is shown in Fig. 13. According to the figure the bar shape force is applied to the 4th column tactels. In the figure, the non-contact region represents some force distributions 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 to the actual contact region.

The sensor response to a doughnut-shape contact is shown in Fig. 14. The figure represents the almost doughnut-shape force distribution. In the figure, the inner region of the doughnut-shape shows some force distribution due to the sensor structure.

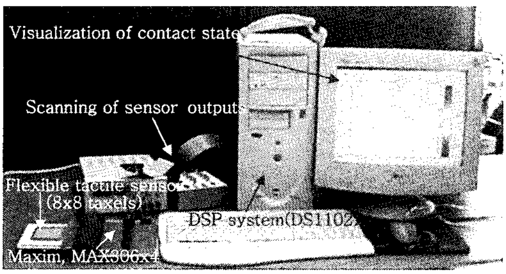
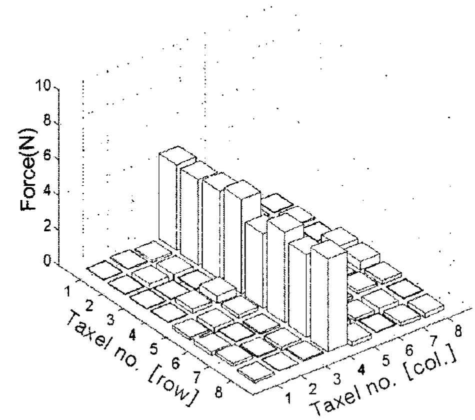
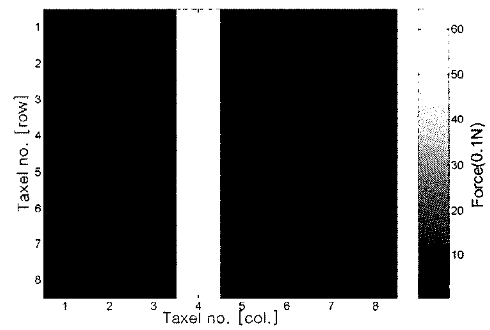


Fig. 12. Photograph of the array type flexible tactile sensor system.

This phenomenon will disappear by making the sensor with more flexible structure. The detected mean forces of the sensing examples are given in Table 3. According to the table, the detected force of the non-contact region in respect to the applied force is of 4.23% in case of the bar shape and of 6.88% in case of the doughnut-shape.



(a) 3-dimensional image

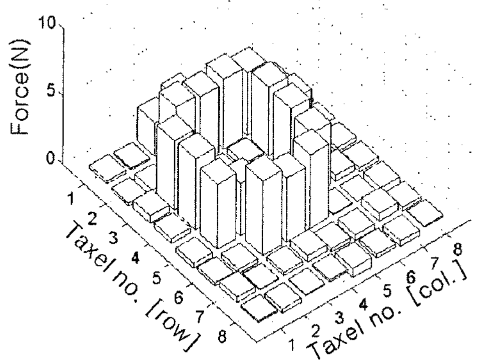


(b) 2-dimensional image

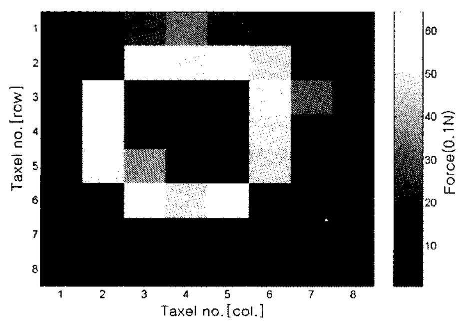
Fig. 13. Sensor response to bar shape contact.

Table 3. Detected mean force (unit: N).

Bar shape		Doughnut shape	
Contact Region	Non-contact Rgion	Contact Region	Non-contact Region
4.990	0.211	2.807	0.193



(a) 3-dimensional image



(b) 2-dimensional image

Fig. 14. Sensor response to the doughnut shape contact.

Finally, the proposed fabrication procedure is simple and easy, so the sensor can be made in the laboratory without using any special equipment. The tactile sensor array can be made easily according to the needs of its practical application with the taxels of arbitrary shape. Also, the stable signal-processing algorithm has been designed against the noisy and weak signals from the sensor. The sensor system shows a reasonable response to applied dynamic forces with various frequencies in real-time. The developed tactile sensor will be a very useful feature for dynamic contact or manipulation. The information of the dynamic contact state obtained through the signal processing system was visualized on a personal computer for the user interface. In the experiment, the two types of object were applied to the sensor, and we can see that the sensor has reasonable performances.

6. Conclusion

The objective of this research is to fabricate and evaluate the performance of the flexible tactile sensor array realized by PVDF film with a thickness of 28 μm. To obtain the more flexible structure and reliable output characteristics, we made the new sensor by using FPC techniques.

The output of the developed flexible tactile sensor with 8×8 taxels with the size of 5mm$\times$5mm, varies linearly according to the applied forces. Moreover, the dynamic response of the sensor that shows almost constant gain in broad bandwidth is enough for a practical application. The signal processing system was designed for the detection of the contact state and the graphical representation and it has been verified that the sensor has adequate capabilities for the detection of shape and force distributions of the manipulated objects.

Acknowledgments

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