Development of a Tactile Sensor Array with Flexible Structure Using Piezoelectric Film

Kee-Ho Yu*, Tae-Gyu Kwon, Myung-Jong Yun, Seong-Cheol Lee
School of Mechanical and Aerospace Systems Engineering
(Automobile Hi-Technology Research Center)
Chonbuk National University, Chonju, Chonbuk 561-756, Korea

This research is the development of a flexible tactile sensor array for service robots using PVDF(polyvinylidene fluoride) film for the detection of a contact state in real time. The prototype of the tactile sensor which has 8×8 array using PVDF film was fabricated. In the fabrication procedure, the electrode patterns and the common electrode of the thin conductive tape were attached to both sides of the 28μm thickness PVDF film using conductive adhesive. The sensor was 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 were sensed and processed in the DSP system in which the signals are digitized and filtered. Finally, the signals were integrated for taking the force profile. The processed signals of the output of the sensor were visualized in a personal computer, and the shape and force distribution of the contact object were obtained. The reasonable performance for the detection of the contact state was verified through the sensing examples.

Key Words: Tactile Sensor Array, Flexible Structure Piezoelectric Film(PVDF), Sensor Fabrication, Signal Processing, Contact State

1. Introduction

In near future, it is expected that robots will play an important role in social welfare, medical treatment, services in home or office, and so on, coexisting with human 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 a robot which can attenuate the impact to guarantee the safety. For this feature, technologies such as mechanism, control algorithm and sensing strategy must be considered and developed cooperatively.

Confining our interest to the sensing strategy, tactile sensor is an essential device 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 ; 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),

* Corresponding Author,
E-mail : yu@chonbuk.ac.kr
TEL : +82-63-270-2471; **FAX** : +82-63-270-2472
School of Mechanical and Aerospace Systems Engineering (Automobile Hi-Technology Research Center) Chonbuk National University, Chonju, Chonbuk 561-756, Korea. (Manuscript **Received** May 26, 2001; **Revised** April 9, 2002)

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 piezoelectric film in robotic sensors. Dario and Rossi (1985) have developed a skin-like sensor based on PVDF (polyvinylidene fluoride) film. This sensor contains two force-sensing layers and has 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 the slip is detected by a piece of piezoelectric film moulded into the head. So far, the authors certified that the 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). Besides, some researches (Cheong et al., 1999 ; Shin et al., 2001) that use the piezoelectric materials as a sensor or actuator of mechanical systems were introduced.

In this paper, a flexible tactile sensor array for service robots using PVDF film for the detection of the contact state is introduced. The 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 sensitive to a tactile stimulus in relatively wide spatial range. The processed signals of the output of the sensor are visualized in personal computer, and the shape and the force distribution of the contact object are also obtained. The reasonable performance for the detection of the contact state is verified through 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 elements 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. Structure of Sensor and Fabrication

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

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

where g_{3n} is an appropriate piezoelectric coefficient for the axis of applied stress or strain. The first subscript refers to the electrical axis and the second one refers to the mechanical axis. Also X_n is the 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 Fig. 1 and the parameters of the PVDF film (AMP Co., USA) used for the fabrication are described in Table 1.

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

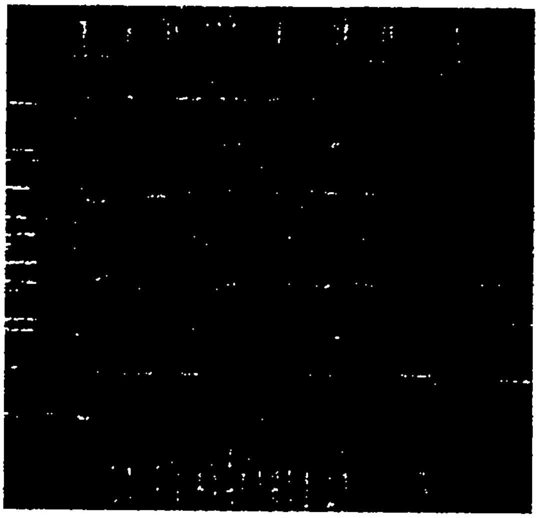
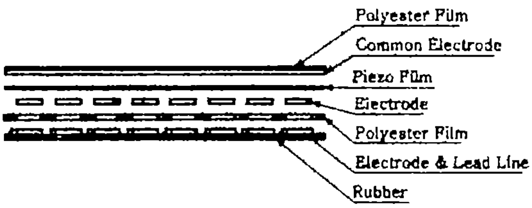


Fig. 1 Photograph of tactile sensor

The structure of the tactile sensor is shown in Fig. 2. In the fabrication procedure of the sensor, the electrode patterns and common electrode of the thin conductive tape are attached to 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 Fig. 3. The size of the tactile element is 5×5 mm, but this can be downsized for practical needs, and the shape of the tactile element can be designed arbitrarily according to the needs of a practical application. The lead lines are attached to the electrode patterns for sensing the contact force applied to 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 robot parts with various configuration.



(a) Side view of sensor

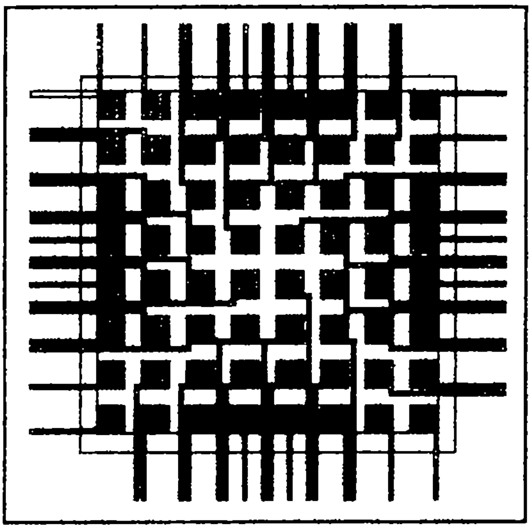
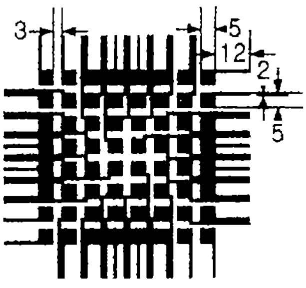

(b) Top view of sensor

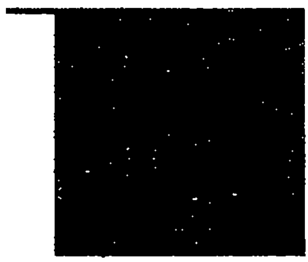
Fig. 2 Structure of tactile sensor

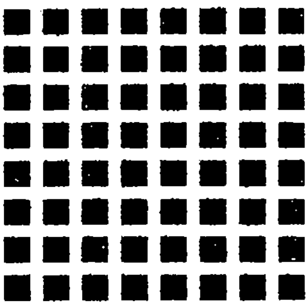
3. Output Characteristics of Sensor

In order to investigate the characteristics of



(a) Electrode and lead line


(b) Common electrode


(c) Electrode

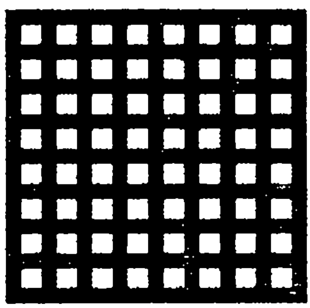

(d) Polyester film

Fig. 3 Patterns of layers used for fabrication

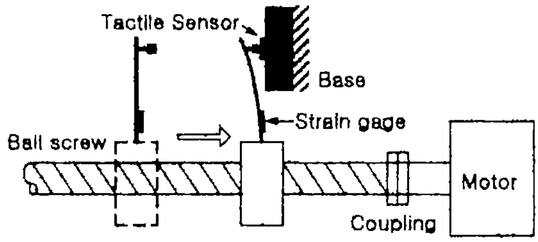


Fig. 4 Experiments for sensor calibration

the sensor, the sensor outputs to arbitrary forces are measured using cantilever beam with translational motion.

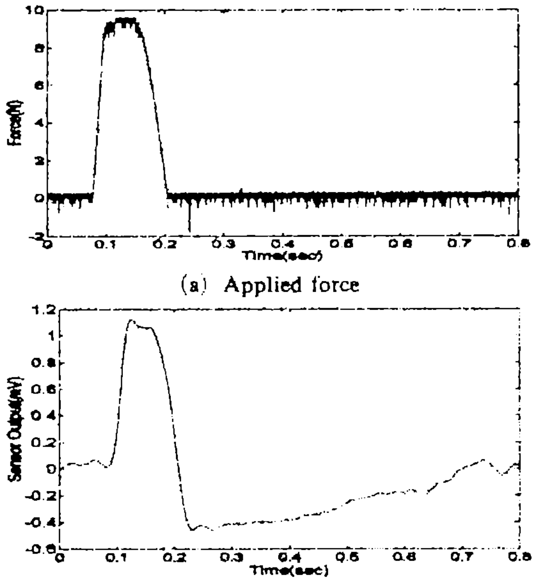
Figure 4 shows the experiments for sensor calibration in which the outputs of the strain gages (CAS Co. AE-11-S30N-120-EL) attached to the cantilever beam and the tactile sensor are compared for the calibration. The strain to the applied force is obtained as

$$\epsilon=\frac{6Fl}{Ebh^2} \tag{2}$$

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 were sensed and processed in the DSP system (dSPACE 1102) and personal computer. The time response characteristics are shown in Fig. 5, which also shows the relationship between the applied force and the output of the sensor when a square wave force was 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 10 ms. 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 Fig. 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 Fig. 6, the output of the sensor is linear with a negligible deviation. Each tactile element in the sensor represented the linear response (0.1377 N/mV)



(a) Applied force

(b) Output of sensor

Fig. 5 Output of sensor due to an applied force

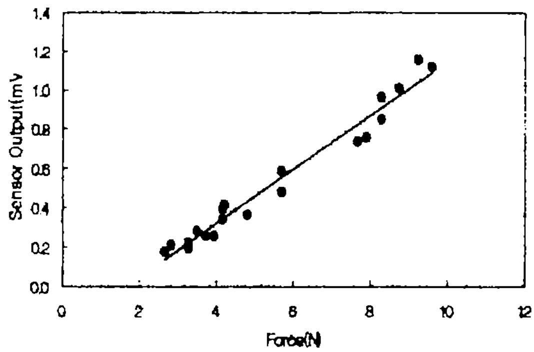


Fig. 6 Output characteristics of sensor

for the applied forces spanning 1.3 N to 10 N. The output of the sensor is approximated by

$$Y=0.14X-0.23 \tag{3}$$

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

The sensor output due to the applied sinusoidal forces with some varying frequencies from 1 Hz to 100 Hz 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

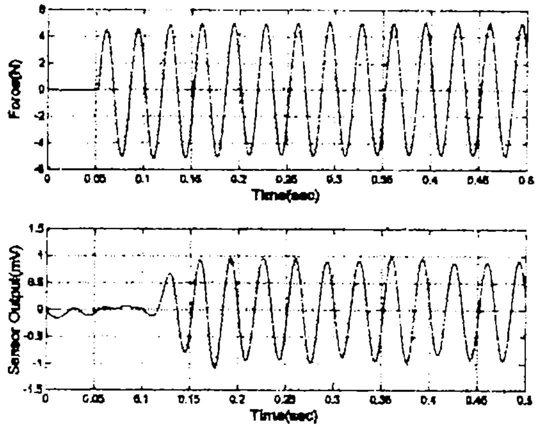


Fig. 7 An example of sensor output by sinusoidal force (frequency : 30 Hz, amplitude : 4 N)

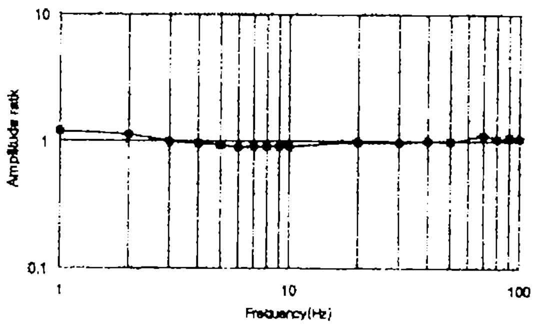


Fig. 8 Frequency response of sensor

example, the output of the sensor by the sinusoidal force of 30 Hz is shown in Fig. 7. The sensor output shows the time delay of about 60 ms due to the signal processing. Figure 8 shows the frequency response of the sensor with respect to the sinusoidal forces with varying frequencies from 1Hz to 100Hz. We can see that the sensor has an almost constant gain through the broad range of frequencies.

4. Signal Processing

4.1 Configuration of signal processing system

The outputs of the sensor were scanned sequentially by the analog multiplexers (Maxim, MAX 306) and processed in the DSP system (dSPACE 1102). The obtained information about the contact state was visualized in personal computer.

4.2 Signal processing

In order to manipulate the output signals of the 8×8 array, four 16-channel analog multiplexers were used. The signals of the 64 tactile elements were scanned sequentially with the sampling rate of 1.6 ms. The signals from the sensor according to the applied forces were digitalized and filtered for noise rejection, and then amplified. In the filtering operation, the DC offset was rejected by the high-pass filter with the cutoff frequency of 0.5 Hz. The noise due to the AC power source and the high frequency noise were eliminated by the notch filter with the cutoff frequency of 60 Hz and the low-pass filter with the cutoff frequency of 100 Hz respectively. Finally, the signals were 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 were visualized in personal computer, and 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 was 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 Fig. 9. 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 compared with those in the true

Table 2 Load shapes and detected mean forces

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

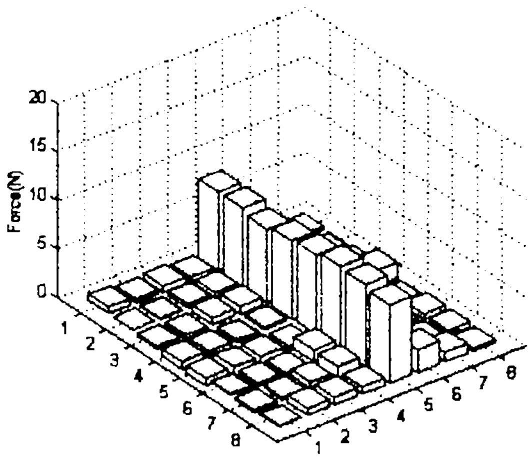


Fig. 9 Sensor response in case of bar-shape contact

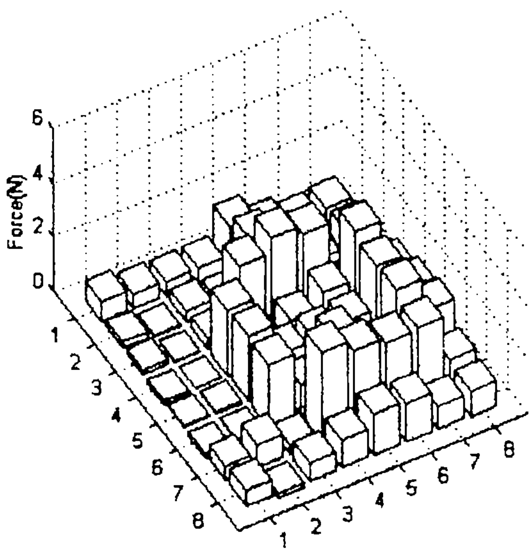


Fig. 10 Sensor response in case of doughnut-shape contact

region due to the applied forces.

The sensor response in the case of a doughnut-shape contact is shown in Fig. 10. The figure represents the almost doughnut shape force -istribution. In the figure the inner region of the doughnut shape shows some force distribution due to the sensor structure. This phenomenon will disappear 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 was to fabricate and evaluate the performance of an 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 the 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. In the practical applications, the time delay of 60 ms due to the signal processing should be resolved. To overcome the time delay in real time applications, implementation of the parallel processing unit to the local sensor array for the fast local processing of the sensor signals could be considered.

References

Beebe, D. J., Hsieh, A. S., Denton, D. D. and Radwin, R. G., 1995, "A Silicon Force Sensor for Robotic Manipulation," *7th Int. Conf. on Advanced Robotics*, pp. 889~894.

Brown, M. K., 1985, "Feature Extraction Techniques for Recognizing Solid Objects with an Ultrasonic Range Sensor," *IEEE J. Robotics Automat*. Vol. RA-1, pp. 191~205.

Cheong, C. C., Kim, J. H. and Lee J. K., 1999, "Piezoelectric Smart Structures for Noise Reduction in a Cabin," *KSME International Journal*, Vol. 13, No. 6, pp. 451~458.

Dario, P. and DeRossi, D., 1985, "Tactile Sensors and the Gripping Challenge," *IEEE Spectrum*, pp. 46~52.

DeRossi, D., Lazzeri, L., Domenici, C., Nannini, A. and Basser, P., 1989, "Tactile Sensing by an Electromechano-Chemical Skin," *Sensors and Actuators*, Vol. 17, pp. 107~111.

Fearing, R. S., 1987, "Some Experiments with Tactile Sensing During Grasping," *Proc. IEEE Int. Conf. Robotics and Automation*, pp. 1637~1643.

Hackwood, S., Beni, G., Hornak, L. A., Wolfe, R. and Neson, T. J., 1985, "A Torque-Sensitive Tactile Sensor Array for Robotics," *Int. J. Robotics Res.*, Vol. 2, pp. 46~50.

Hok, B., Tenerz, L. and Gustafson, K., 1989, "Fiber-Optic Sensors : A Micro-Mechanical Approach," *Sensors and Actuators*, Vol. 17, pp. 157~166.

Howe R. D., 1994, "Tactile Sensing and the Control of Robotic Manipulation," *Advanced Robotics*, Vol. 8, No. 3, pp. 245~261.

Johnston, D., Zhang, P., Hollerbach, J. and Jacobsen, S., 1996, "A Full Tactile Sensing Suite for Dexterous Robot Hands and Use in Contact Force Control," *IEEE Int. Conf. on Robotics and Automation*, pp. 3222~3227.

Kolesar, Jr., E. S., Reston, R. R., Ford, D. G. and Fitch, Jr., R. C., 1992, "Multiplexed Piezoelectric Polymer Tactile Sensor," *J. Robotic System*, Vol. 9, pp. 37~63.

Lee, M. H. and Nicholls, H. R., 1999, "Tactile Sensing for Mechatronics-a state of the art survey," *Mechatronics* 9, pp. 1~31.

Shin, J. W., Lee, K. Y. and Kwon, S. M., 2001, "Eccentric Crack in a Piezoelectric Strip Under Electro-Mechanical Loading," *KSME International Journal*, Vol. 15, No. 1, pp. 21~25.

Son, J. S. and Howe, R. D., 1996, "Tactile Sensing and Stiffness Control with Multifingered Hands," *IEEE Int. Conf. on Robotics and Automation*, pp. 3228~3233.

Yamada, Y. and Cutkosky, M. R., 1994, "Tactile Sensor with Three-Axis Force and Vibration Sensing Functions and Its Application to Detect Rotational Slip," *IEEE Int. Conf. on Robotics and Automation*, pp. 3550~3557.

Yu, K. H., Yun, M. J., Kwon, T. K. and Lee, S. C., 2001, "Fabrication and Characteristic Evaluation of a Flexible Tactile Sensor Using PVDF," *Journal of the Korean Society of Precision Engineering*, Vol. 18, No. 7, pp. 161~166 (in Korean).