

Development of Fingertip Tactile Sensor for Detecting Normal Force and Slip

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Abstract: In this paper, we present the finger tip tactile sensor which can detect contact normal force as well as slip. The developed sensor is made of two different materials, such as polyvinylidene fluoride(PVDF) that is known as piezoelectric polymer and pressure variable resistor ink. In order to detect slip to surface of object, a PVDF strip is arranged along the normal direction in the robot finger tip and the thumb tip. The surface electrode of the PVDF strip is fabricated using silk-screening technique with silver paste. Also a thin flexible force sensor is fabricated in the form of a matrix using pressure variable resistor ink in order to sense the static force. The developed tactile sensor is physically flexible and it can be deformed three-dimensionally to any shape so that it can be placed on anywhere on the curved surface. In addition, we developed a tactile sensing system by miniaturizing the charge amplifier, in order to amplify the small signal from the sensor, and the fast signal processing unit. The sensor system is evaluated experimentally and its effectiveness is validated.

Keywords: PVDF, Pressure variable resistor ink, Tactile sensor, Signal processing, Robot hand

1. Introduction

In the future, the robot can be performed various tasks to replace the human to every day life. Especially, when humanoid robot comes in contact with environments, it must be consider the safety of contact objects in the first place. Accordingly, the future robots are required capability that grasps an object without damaging and slipping during manipulation to determine the amount of contact force and contact shape of object. Therefore, tactile sensors are an important class of sensors to measure parameters of a contact interaction between the device and some physical stimuli.

Many researches about the tactile sensing have advanced with development of new tactile sensor for a guide that could provide the reliable and precise tactile information. Dario *et al.* developed ‘Artificial tactile sensing system’ for a robot finger [1]. The tactile sensing system detected the contact force, the vibration and the variation of temperature like mechanoreceptor of human by arranging PVDF films that possess piezoelectricity and pyroelectricity. Howe *et al.* developed dynamic tactile sensor that could detect slippage by means of change of stresses that are happened by deformation of sensing element when artificial skin contacted to the object [2]. Maeno *et al.* also detected incipient slip between artificial finger and object by fabricating ‘Artificial finger skin’ using PVDF [3]. The artificial finger skin is designed to have characteristics similar to that of a human finger. The finger skin has ridges on the surface in each of which a pair of PVDF film sheets are embedded. Also, in order to judge occurrence of incipient slip automatically they used multi-layered ANN. Koresar *et al.* realized tactile sensor of 8×8 taxel matrix directly by coupling a piezoelectric PVDF polymer thin film to an electrode matrix fabricated on a silicon integrated circuit [4]. Hosoda *et al.* developed soft

finger tip has two layers made of different kinds of silicon rubber basically imitating the human finger [5]. And several strain gauges and PVDF films are randomly distributed in both silicon layers. Kawasaki *et al.* developed distributed tactile sensor that has grid pattern electrodes [6]. These tactile sensor used conductive ink in which the electric resistance changes in proportion to the pressure on the top and bottom of a thin film and realized the stable grasp of object by arranging detecting points of 859 on the palm, the thumb, and each of the fingers. Shimojo *et al.* used pressure conductive rubber as a pressure-sensitive material [7]. The tactile sensor was adopted by stitching wire electrodes into pressure-conductive rubber. Then, they attached the sensor to a four-finger robot hand and grasped a column, sphere, and so on, and showed the experimental data on the transition of the contact points characterizing the grasping operation. However, in its present state, it is difficult to apply tactile sensors to robot hand directly with respect to the problems such as size of external hardware of sensor, development of algorithm for signal processing and so on. Therefore, a fragmentary detection ability only applied to robot yet. Also, although robot hand attached tactile sensors is used by researcher, it is difficult to grasp object actively and autonomously and to put to practical use because of some problems such as the reliability, accuracy, response speed, dynamic · static characteristic, economical efficiency.

In this paper, we propose a miniaturized tactile sensing system that is possible not only to apply to real robot hand and finger but also to provide information for robot hand to grasp object accurately and safely. To realize this, the PVDF tactile sensor could detect information of slippage such as stick-slip for stabile grasping is developed by measuring dynamic response between sensing elements and contact surfaces using PVDF. Also, thin flexible force sensor that has a number of sensing elements can recognize shape information of contact object and contact force is developed

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by measuring static force by using pressure variable resistor ink. All of sensing system is able to embed by integrating sensor modules and miniaturized signal processing module into robot finger tip. The proposed system is able to communicate with PC or external devices and the acquired data can be provide information for control of robot finger.

This paper is organized as follows. In the next section 2, we introduce the basic principle of PVDF and pressure variable resistor ink. The issues on the development of the PVDF texture sensor and thin flexible force sensor is discussed in the section 3. In the section 4 and 5, the miniaturized signal processing unit is described and experimental procedures for evaluation of the performance of the sensor are mentioned. And finally the paper is concluded with summary in the section 6.

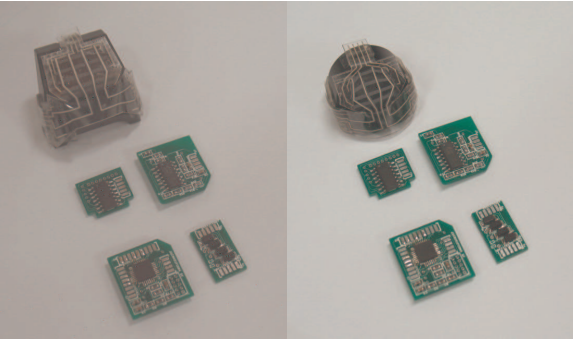


Fig. 1. Tactile sensing system.

2. Principle of sensing materials

2.1. Principle of PVDF

After Kawai discovered strong piezoelectricity in PVDF (polyvinylidene fluoride) in 1969, PVDF has been used in a lot of commercial products [10]. PVDF is a semicrystalline polymer with an approximate degree of crystallinity of 50%. The chemical structure of it contains the repeat unit of doubly fluorinated ethene $\text{CF}_2\text{-CH}_2$. The voltage output of PVDF is 10 times higher than piezo ceramics for the same force input. The reason for the strong piezoelectric activity is related to the large electronegativity of fluoride atoms in comparison to the carbon atoms, thus accommodating a large dipole moment.

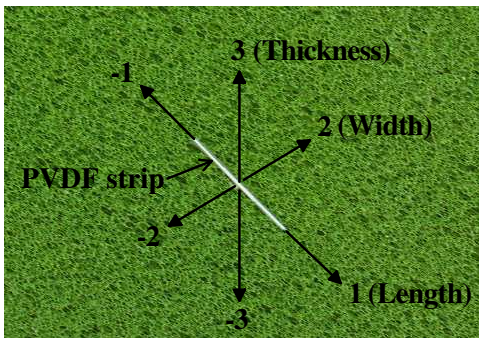


Fig. 2. Reference axes in PVDF strip

The piezoelectric coefficient of PVDF is shown as

$$d_{ij} = \begin{pmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{24} & 0 & 0 \\ d_{31} & d_{32} & d_{33} & 0 & 0 & 0 \end{pmatrix} \quad (1)$$

As shown in Fig. 2 the axes are defined in terms of the length direction (direction 1), normal to the length direction in the plane of the film (direction 2) and normal to the plane of the strip (direction 3).

The surface charge Q from the piezoelectric phenomena is proportional to the applied force F via an relation such as

$$D = \frac{Q}{A} = d_{3n}\sigma_n \quad (2)$$

where D is the charge density, A is the electrode area of the PVDF strip formed in the 3-3 plan, d_{3n} is piezoelectric strain coefficient for the axis of applied tensile force or compressive force, σ_{3n} is stress applied in the relevant direction. The d_{3n} piezoelectric strain coefficient is commonly expressed in $[\frac{\text{C}}{\text{N}/\text{m}^2}]$.

When a PVDF strip is compressed by a probe on a rigid flat surface, assuming, that both the flat surface and the probe are friction-free, the film is free to expand in the 1-1 and 2-2 directions, the output charge can be expressed in Eqs. (4)

$$\frac{Q}{A} = d_{33}\sigma_3 = d_{33}\left(\frac{F}{A_3}\right) \quad (3)$$

$$Q = d_{33}F \quad (4)$$

where d_{33} is the piezoelectric strain coefficient in the 3-3 direction.

Normally, the output charge is due to a combination of d_{31} , d_{32} , d_{33} . It is important to remember that, for a given applied force, the output charge from the PVDF in the length or width direction much higher than that of thickness direction [11]. This is because of the extreme thinness of the PVDF film. Therefore, we can develop the miniaturized high sensitivity PVDF sensor using this principles.

2.2. Principle of pressure variable resistor ink

The piezoelectric method is not suited for static measurements because of the leakage current. If a constant load is applied to a piezoelectric sensor for an extended period of time, the response decreases and eventually becomes zero. Consequently, PVDF is suitable for dynamic force sensor better than static force sensor. In this research, pressure variable resistor ink (the product of Creative Materials incorporated) is used to develop distributed force sensor. Pressure variable resistor ink is an electrically conductive ink that decreases in resistance as pressure is increased. It can be blended with other conductive ink to alter the initial and final resistance of the material. Pressure variable ink is blended at a fixed rate is applied between two polyester films which a silver electrode is formed using silk-screening technique and sensing element finally is formed.

As shown in Fig. 3 force sensor is fabricated through insertion of ink between two polyester film that has electrode pattern. Each of polyester film and electrode is physically

flexible. The fabricated force sensor is possessed single sensing element and it can be modelled as a variable resistance that decreases in resistance as pressure is increased such as Fig. 3.

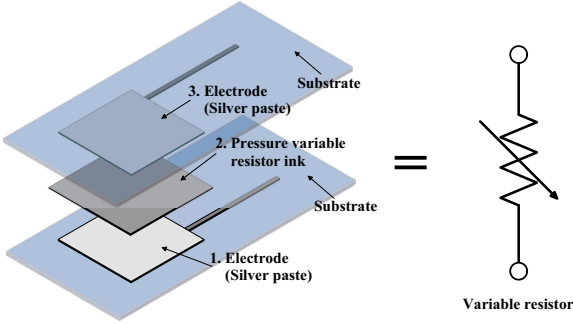


Fig. 3. Structure of force sensor that has one sensing element

The Fig. 4 explains the operational principle of fabricated force sensor. When the fixed input voltage is applied to sensor, force sensor can obtain a variation of output value that is amplified by voltage gain. The output equation from explained inverting amplifier is expressed in Eqs. (5)

$$V_{out} = -V_{cc} \frac{R_F}{R_s} = -V_{cc} R_F S_s \quad (5)$$

where R_s is resistance of force sensor, S_s is conductance that is defined as the reciprocal of resistance. Also, R_F is the op-amp's feedback resistance.

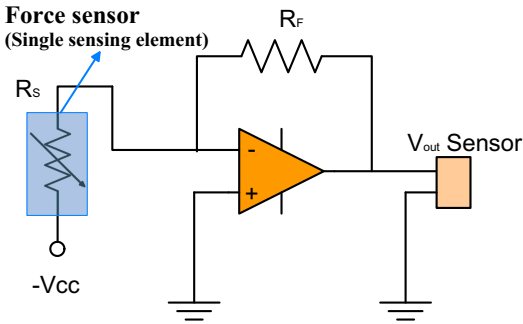


Fig. 4. Basic principle of operation of force sensor

3. Design of finger tip tactile sensor

3.1. PVDF texture sensor

In this chapter, we propose the miniaturized high sensitivity PVDF sensor which is attached to robot finger. After Polyvinylidene fluoride pellets of Aldrich Chemical Co., Inc. were arranged between polyimide films, these pellets are pressed at $230^\circ\text{C} \sim 240^\circ\text{C}$ for 25 minutes with an applied pressure of 10MPa using hot press machine. Then, PVDF film allowed to cool to room temperature about $1^\circ\text{C}/\text{sec}$.

The thickness of fabricated films has a value between $50\mu\text{m}$ and $70\mu\text{m}$. Then, the surface electrodes, which are both sides, are fabricated using silk-screening technique with silver paste. By this method, the fabrication process was became more simple and fabrication cost was decreased. The thickness of silver electrode is $5\mu\text{m}$, and it can stand heat of 200°C . In order to exhibit high piezoelectricity in the fabricated films, we polarized the fabricated PVDF film by applying the strong electric field using the high voltage supply after the electrodes of copper were attached on either side of the film. Poling was carried out at 170°C with an applied voltage of 3kV and load of 5N. With the voltage applied, the film was placed on a glass substrate with mechanical constrain and held at 170°C for 30 h, then allowed to cool to coolant before the applied voltage was removed. The PVDF films were polarized is characterized by piezoelectricity. As shown in Fig. 5, PVDF sensor has single PVDF sensing element, and used film of $100\mu\text{m}$ thickness to increase the sensitivity. PVDF strip, width 0.8mm and length 10.0mm, has sensing element of $0.4\text{mm} \times 4\text{mm}$ size.

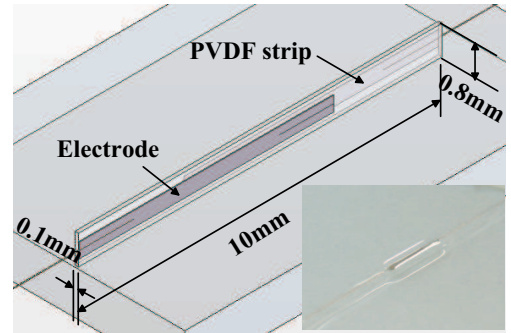


Fig. 5. Schematic of PVDF sensor and photograph

3.2. Thin flexible force sensor

According as the sensing elements become much increased, the sensor needs many wirings. Also, if we want to receive from a large number of sensing elements independently, design of sensor becomes complicated and size of each detection element is decrescent because of wiring. Moreover, a number of input and output ports required microcontroller to process data, and the load of hardware becomes more increased. To develop force sensor of high resolution from the above mentioned requirements, matrix method of grid type is used in this research. The two polyester films were oriented together so that their traces formed a grid, with the pressure variable resistor ink layers facing each other. Each cross section of the grid formed a sensing element of force sensor. As shown in Fig. 6 and Fig. 7, the size of sensing element is $0.5\text{mm} \times 0.5\text{mm}$ and a force sensor has total 24 sensing elements. If tactile sensors independently receive the output signal from the each of sensing element, totally 48 signal line is required and serious problem will be cause in the limited space. However, as matrix method of grid type was applied in the force sensor, it is possible to detect 24 sensing elements only 8 input voltage lines and 4 output

signal lines. Hence, it provides to simplify spatial resolution and integration of operation circuit.

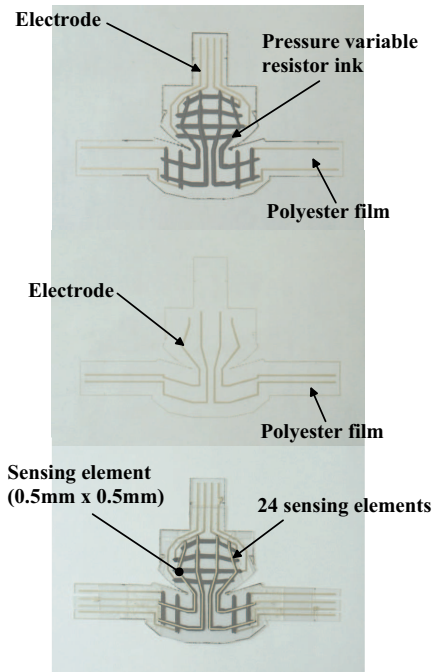


Fig. 6. Finger tip force sensor

4. Fabrication of tactile sensing system

In this chapter, we introduce the miniaturized tactile sensing system to process data is transmitted from a number of sensing elements. After signals is measured from the sensing elements of tactile sensor is amplified and is transformed into digital data in the A/D converter that is included in the microcontroller, the data is collected is transmitted user interface on PC by an RS232 serial communication or input port of an external device(Fig. 8).

4.1. Amplifiers

The amplifier is consists of two types, PVDF sensor amplifier and force sensor operation amplifier. Because the output of PVDF depends on an instant variation, it is electrically charged for a relatively short time. Therefore PVDF tactile sensor is responsive only to a changing stress rather than to a steady level of it. Considered these problems, we designed PVDF sensor amplifier. PVDF sensor amplifier basically is used to convert to voltage signals from the PVDF strip which generate very low charges. The size of developed PVDF sensor amplifier is 18mm × 14mm and it has input and output port of 2-channel respectively. The circuit of PVDF sensor amplifier is consists of Charge amplifier, non-inverting amplifier and 60 Hz notch filter.

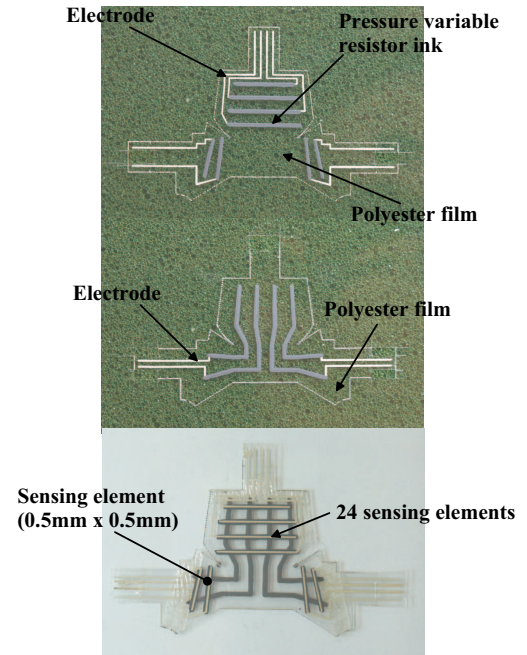


Fig. 7. Thumb tip force sensor

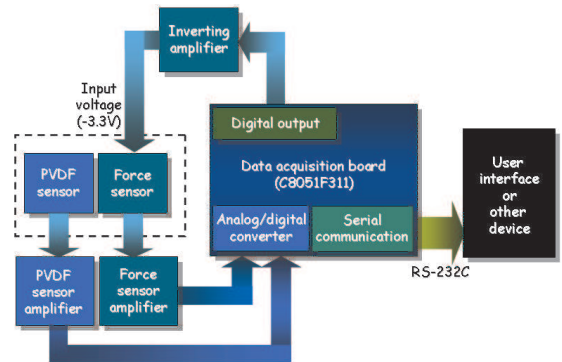


Fig. 8. Schematic of tactile sensing system

Unlike PVDF sensor amplifier, force sensor amplifier is employed to operate force sensor because it sends output voltage by variation of voltage gain with amplifier. The force sensor amplifier is shown in Fig. 9. It has input, output port of 4-channels and is miniaturized to embed finger tip and thumb tip of robot hand.

4.2. Signal processing board

The circuit was designed on the single board for data acquisition, control, communication. Data acquisition and communication is performed by using microcontroller(Silicone laboratory, C8051F311), signal processing board is able to transmit data to user interface on PC by an RS232 serial communication or input port of an external device by SM-Bus.

Thin flexible force sensor is fabricated by using matrix method of grid type. The microprocessor can receive output signal from a number of sensing elements by scanning to acquire the measured data at regular time interval. Therefore, 8 digital output ports of signal processing board become input voltage of force sensor, 4 A/D convert ports is received

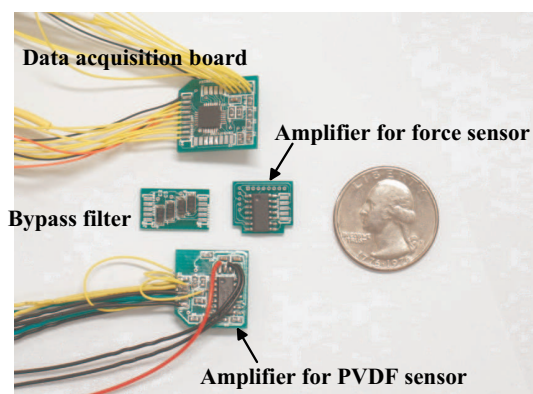


Fig. 9. Photograph of tactile sensing system

output signal of force sensor. Also, 2 A/D converter ports of signal processing board is received the amplified output signal of PVDF sensor. The scanning circuit of force sensor is shown in Fig. 10. The part which variable resistor and capacitor is connected in parallel is sensing element. The digital output lines of microcontroller serially is changed “High” and a microcontroller is received the output signals of sensing elements by operating AD converter. Therefore, matrix method effectively is able to control the number of sensing elements by using minimum input voltage and output signal line.

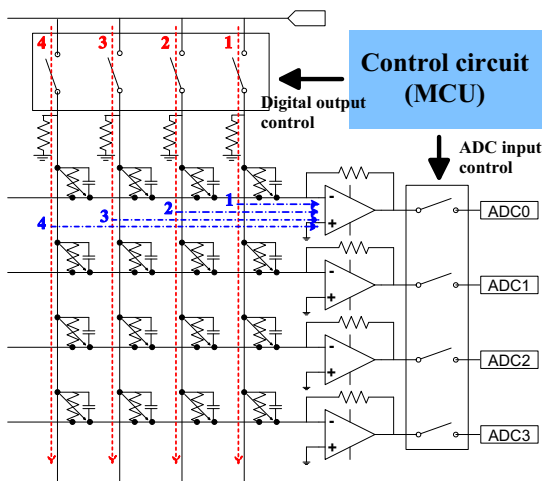


Fig. 10. Thin flexible force sensor scanning circuit

The sensing data that is acquired from the microcontroller provide three-dimensional data to user through user interface on PC or is able to supply measured information with external device for precise control and operation.

5. Experiment

PVDF sensor was miniaturized to attach finger tip and thumb tip of robot hand. The graph of Fig. 11 shows the characteristic of response when the PVDF sensor was touched and rubbed by object or finger tip. Fig. 11 shows

sudden change of gradient. It means that stick-slip occurred between the sensor and contact surface. Fig. 12 shows the characteristic of response when the weight of 100g rolled on the sensing element of PVDF sensor. Unlike Fig. 11 an effect of stick-slip seldom or never exists. So, a change of gradient is slow and when the weight of 100g rolls on the sensing element indicates about 1.2V constant value. Therefore, according to surface characteristic of contacted object and contact method, we are able to confirm that the characteristic of response is different.

Furthermore, thin flexible force sensor of matrix array is fabricated to attach finger tip and thumb tip of robot hand. Fig. 13 shows characteristic of response from the fabricated force sensor. When we applied to the weight of 100g and 200g, the output voltage of 2V and 4.25V was obtained respectively. As shown in graphs, the sensing element of force sensor indicate the output voltage without delay. The noise occurred on the graph is contact noise and it could be conspicuously decreased by using developed bypass filter.

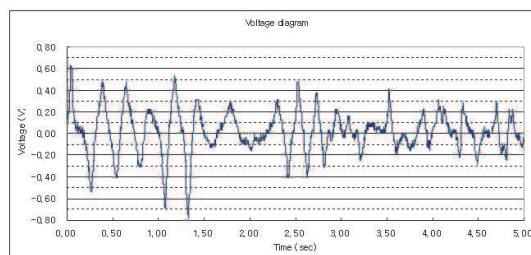


Fig. 11. When the PVDF sensor was touched and rubbed by object or finger tip.

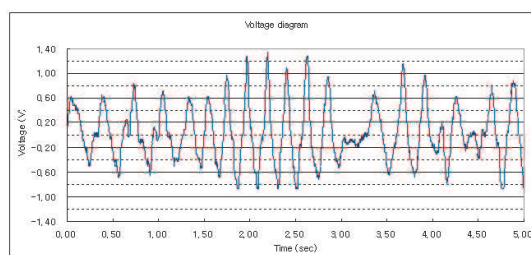


Fig. 12. When the weight of 100g rolled on the sensing element of PVDF sensor

Finally, PVDF sensor and force sensor was attached the developed sensing system. Then, we confirmed contact information through user interface on PC. Fig 14 shows the contact information when we pressed sensors in finger tip and thumb tip of human. The finger tip and thumb tip is situated the indicated areas and the maximum value displays in this area. Therefore, we could confirm that the developed force sensor enables a measurement of static force as well as local force detection through experiments. Also, the variation of dynamic force applied in this sensing elements can detect using PVDF sensor.

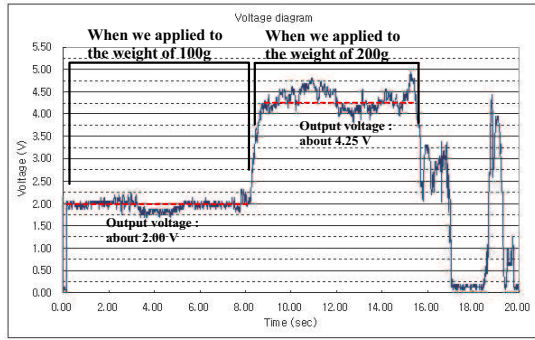


Fig. 13. When we applied to the weight of 100g and 200g.

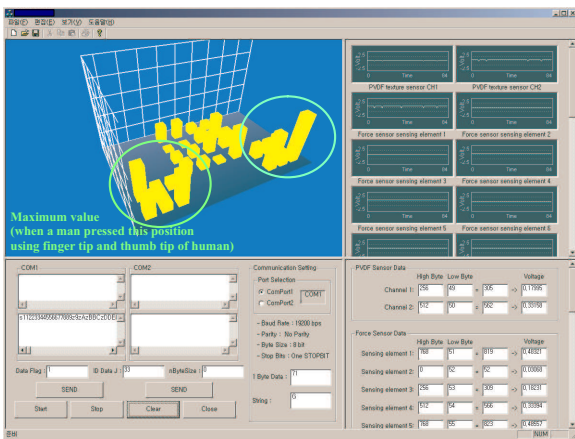


Fig. 14. When we pressed sensors in finger tip and thumb tip of human.

6. Conclusion

In this research, a tactile sensor which can detect contact normal forces as well as slip was developed. The developed sensor is made of two different materials, such as polyvinylidene fluoride (PVDF) that is known as piezoelectric polymer, and pressure variable resistor ink. In order to detect slip between sensor and object, a PVDF strip is arranged along the normal direction. Also, a thin flexible force sensor is fabricated in the form of a matrix using pressure variable resistor ink in order to sense the static force. The matrix method effectively enabled to control the number of sensing elements by using minimum input voltage and output signal line. Also, the developed sensing system was miniaturized to integrate system into robot finger. The developed tactile sensor is physically flexible and it can be deformed three-dimensionally to any shape so that it can be placed on anywhere on the curved surface. The sensing data that was acquired from the microcontroller provided three-dimensional data to user through user interface on PC or was able to supply measured information with external device for precise control and operation. In the future, we will couple up the tactile sensing system to the robot hand to evaluate the effectiveness of this tactile sensing system.

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