Development of Anthropomorphic Robot Hand with Tactile Sensor: SKKU Hand II

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1. Introduction

Recently, robots have begun to perform various tasks on replacing the human in the daily life such as cleaning, entertainments etc. In order to accomplish the effective performance of intricate and precise tasks, robot hand must have special capabilities, such as decision making in given condition, autonomy in unknown situation and stable manipulation of object. It must also possess tactile information to be able to carry out complicated manipulative tasks in a natural environment. Consequently, the tactile sensor is required to support natural interaction between the robot and the environment.

Many researches on the tactile sensing and the anthropomorphic multi-fingered robot hand have been reported up to now. Dario *et al.* developed "Artificial tactile sensing system" for a robot finger (Dario & Buttazzo, 1987). The system is able to detect the contact force, the vibration and the variation of temperature like mechanoreceptor of the human by arranging PVDF films that possess piezoelectricity and pyroelectricity. Howe *et al.* developed a dynamic tactile sensor that can detect slippage by means of the change of stresses due to deformation of the contact with the object (Howe & Cutkosky, 1993). Maeno *et al.* presented a tactile sensor, called "artificial finger skin" based on PVDF (Fusjimoto et al., 1999; Yamano et al., 2003). The sensor capable of detecting the incipient slip was designed to possess the characteristics similar to that of the human finger. Hosoda *et al.* reported a soft fingertip with two layers made of different kinds of silicon rubbers (Hosoda et al., 2003). The Utah/MIT hand developed by Jacobsen *et al.* is driven by actuators that are located in a place remote from the robot hand frame and connected by tendon cables (Jacobsen et al., 1984; Jacobsen et al. 1988). Hirzinger *et al.* developed DLR-Hand II, which build the actuators into the hand. Each finger of robot hand is equipped with motors, 6-DOF fingertip force torque sensor and integrated electronics (Butterfass et al., 2001; Gao et al., 2003). Kawasaki *et al.* presented anthropomorphic robot hand called the Gifu hand III, which has a thumb and four fingers (Kawasaki et al., 2002; Kawasaki et al., 2002). The thumb has 4 joints with 4-DOF and each of the fingers has 4 joints with 3-DOF. Moreover, the distributed tactile sensor which is made of conductive ink is arranged about 859 sensing points on the palm and the fingers. Shimojo *et al.* utilized the pressure conductive rubber as a pressure sensitive material (Shimojo et al., 2004). They attached the sensor onto a four finger robot hand and a demonstrated its grasping operations with a column, sphere, etc. Although a number of researches have been done up to now, however, their motion of robot hands is unlike that of the human because the mechanism of robot hands is different from that of

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human in many aspects. A study on the grasping motion of the human hand noted that the metacarpal link of the thumb plays the key role in power grasping (Calais-Germain, 1993). Despite these differences, however, many researches have been investigated about the robot hand of gripper type, which is difficult to perform dexterous grasping and manipulation of object like the human hand. Furthermore, most developed robot hands are larger than human hands. In addition, more researches are still necessary to put the tactile sensor into the practical use, because there remain many problems such as the limitations in the hardware as well as the algorithms for signal processing, the lack of the reliability, accuracy, response speed, dynamic•static characteristic, economical efficiency (Nicholls & Lee, 1989; Lee & Nicholls, 1995).

Fig. 1. SKKU Hand II with tactile sensor

In this chapter, we propose an anthropomorphic robot hand called SKKU Hand II, which has a miniaturized tactile sensor applicable to the robot hand. Thumb is at an angle opposite to its other fingers, and the thumb and fingers are orthogonal, such that it can performs dexterous grasping and manipulation like the human hand. The hand is similar to the human hand in geometry and size because inessential degree-of-freedom is abbreviated during grasping. All parts of the SKKU Hand II were composed of independent modules from each finger to the electric board for control. Moreover, SKKU Hand II's fingertip tactile sensor is composed of two functional units: a PVDF-based slip sensor designed to detect slippage such as incipient slips between sensing elements and contact surfaces, and a thin flexible force sensor that can read the contact force of and geometrical information on the object using a pressure-variable resistor ink. Both of them are integrated into a tactile sensor. All the sensing system can be embedded into the fingertip by miniaturizing the sensor and signal processing units. The proposed system is able to communicate with PC or external devices to provide information for controlling the robot hand. Also, the actuators, driving circuits of SKKU Hand II and its entire sensing system are embedded in the hand, and each driving circuit communicates with others using CAN protocol.
This chapter is organized as follows. In sections II and III, kinematic design and mechanical design of SKKU Hand II are presented. The issues on the development of the PVDF texture sensor and thin flexible force sensor are discussed in sections IV and V. Also, system schematic of robot hand is described in section VI. In section VII, experimental procedures

for evaluation of the performance of the robot hand which has fingertip tactile sensors are mentioned. And finally the paper is concluded with summary in section VIII.

2. Kinematic design of SKKU hand II

To develop the SKKU Hand II, the design process started with the simulation to get optimal ratios of link lengths of finger (Kyriakopoulos et al., 1997; Wilkinson et al., 2003). We estimated an index of power grasping and fingertip grasping using kinetics model. Through the kinematic analysis and simulation, we decided that the ratio of length of link is 2-3-5 by Fibonacci sequence. Human hand is able to grasp objects by finger and thumb crossing each other to length way. The position of thumb and other finger is opposite to each other and thumb parallels other finger when gripper-type robot hand is grasping. However, in case of anthropomorphic robot hand, it grasps an object using the angle to direction of length of each finger for the power grasp and fingertip grasp. Especially, it has more powerful grasp by using the angle to direction of length of each finger in pinch grasp.

	Joint	Gear	Torque	Size [L× M][mm]	Weight [kg]
finger	J1	275:1	0.115	115×22.5	0.116
	J2	258:1	0.106		
Thumb	J3	275:1	0.285	139×28	0.242
	J4	275:1	0.285		
	J5	258:1	0.106		
	J6	64:1	0.0297		
Total	-		-	-	0.9

Table 1. Specification of SKKU Hand II

3. The mechanical design of SKKU HAND II

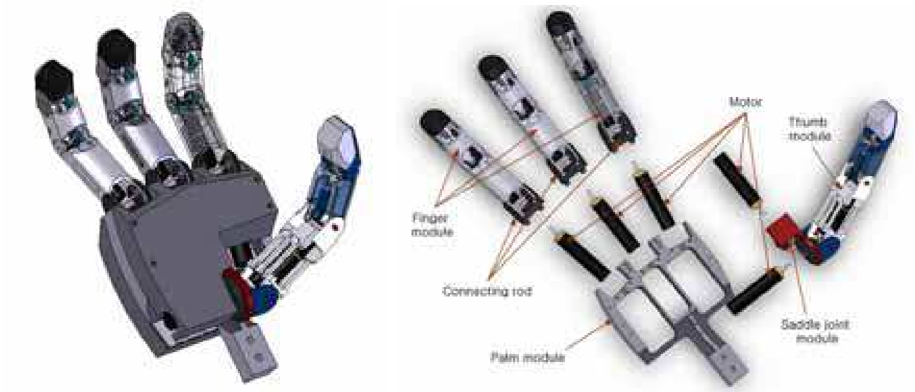


Fig. 2. The mechanical design of SKKU Hand II

As shown in Fig. 2, the SKKU Hand II is designed to be anthropomorphic in terms of geometry, size, and kinesis so that it performs power grasping and fingertip grasping as well as manipulations like the human hand. Especially, all of the parts consist of modules for easy development, maintenance and repair.

3.1 Finger module

As shown in Fig. 3, the SKKU Hand II has three fingers, and it is about 1.1 times bigger than a human hand. Each finger module has total 3-DOF, including coupled joint of the last two joints, and degree of freedom of finger of robot hand is smaller than that of human finger and the difference is due to the reduction of unnecessary degree of freedom for the ability of grasp and maximization of efficiency with size of robot hand very close to that of human hand. The actuator of finger module has two electric motors. And every motor is installed possibly close to palm module in order to consider weight balance and kinesis. And the last two joints, Distal phalange and Medial phalange joint, are mechanically coupled like a human finger by the pulley and timing belt. Also, it has some special space for being easy to install a variety sensors and the sensor processing circuit, in which for movement is more similar to human hand.

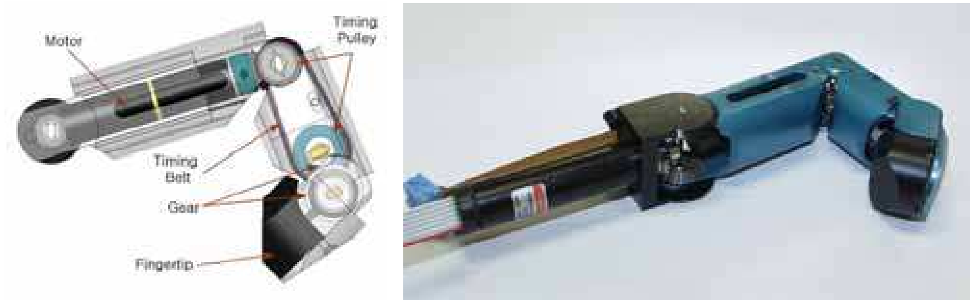


Fig. 3. Finger module

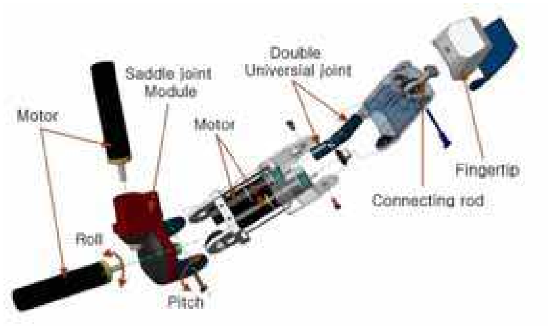


Fig. 4. Composition of thumb module

3.2 Thumb module

The thumb module has four DOF, and it is about 1.1 times bigger than a human thumb. The thumb has played a very important part in the anthropomorphic robot hand as well as human hand. The thumb can fulfil a complex work by means of saddle joint that is closest to the wrist. In general, the saddle joint of human has 3-DOF, and it is possible to manipulate any motion in the three-dimensional space because the motion of pitch, roll and yaw is performed simultaneously. The motion of pitch and roll is usually used to grasp the object, and the motion of yaw is used to circumvolve the object (precision grasp) motion like opening the cap of bottle. As depicted in Fig. 4 and 5, SKKU Hand II is realized with mechanism which imitates the role of saddle joint of human, but motion of yaw is neglected. The transmission of power is used with the bevel gear with 1:1 ratio, but distal phalange joint is composed of the double universal joint so that the position of motor stays close to palm module and for the independence of actuators.

Fig. 5. Thumb module

3.3 Fingertip module

The shape of human fingertip is not just round but polyhedral. The surface of the fingertip can be discriminated into five parts depending on the grasping modalities such as pinch grasp, fingertip grasp and power grasp. As shown in Fig. 6, the fingertip grasp uses a bottom of fingernail, the pitch grasp that hold a small and long object strongly and safely uses a side of fingertip. In the power grasp which is for wrapping an arbitrary object, the object is restricted using bottom of finger, thumb, and palm, and then object is fixed by bottom of fingertip at last. Consequently, the fingertip of SKKU Hand II is designed as a unique shape which can realize composite task like fingertip of human.

Fig. 6. The surface of fingertip depending on the grasping modalities

Fig. 7. Motor control board

3.4 Motor control board

Our anthropomorphic robot hand has the ten motor control boards. As shown in Fig. 7, each board size is 39.5 x 23.5(mm) and every board is able to control just one corresponding motor. All of this board is composed independently from each other, but they are connected by CAN protocol. Also main microprocessor of motor control board used PIC16F458 and the Motor control board includes the current sensor and counter chip to check the state of motor in real time. Each current sensor which can be utilized information of force feedback control with tactile sensor of fingertip is used to measure the torque of finger joint.

4. Tactile sensor of SKKU hand II

4.1 Integrated fingertip tactile sensor

The finger tip tactile sensor consists of two different sensing elements, which is a thin flexible force sensor for detecting the contact force and location and the PVDF sensor for incipient slip. The structure of the fingertip tactile sensor is shown in Fig. 8. Thin flexible force sensor which possesses 24 sensing elements is attached under the fingertip to detect static contact force. Also, the PVDF sensor which has two PVDF strips is located on the thin flexible force sensor to detect dynamic response such as slippage using the mechanical deformation of the silicone (Choi et al., 2005).

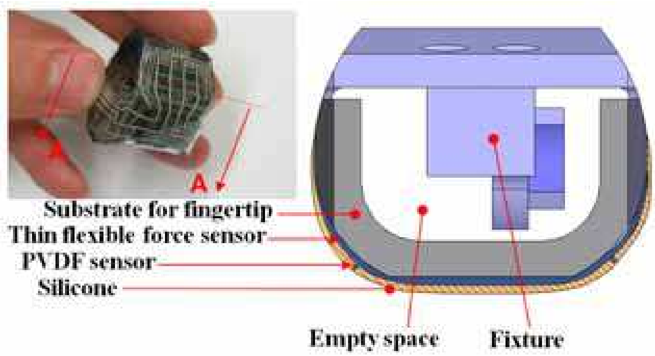


Fig. 8. Structure of fingertip tactile sensor

4.2 Principle of PVDF

Since Kawai discovered strong piezoelectricity in PVDF in 1969 (Kawai, 1969), PVDF has been used in a lot of commercial products. PVDF is a semicrystalline polymer with the 50% degree of crystallinity approximately. Its chemical structure contains the repetitive unit of doubly fluorinated ethene CF_2-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 (Kolesar et al., 1996; Fraden, 1997; Yu et al., 2002).

To derive fundamental equations for PVDF, as shown in Fig. 9, a frame is 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 PVDF strip (direction 3). The surface charge Q from the piezoelectric phenomena is proportional to the applied force F such as

$$D = \frac{Q}{A} = d_{3n}\sigma_n \tag{1}$$

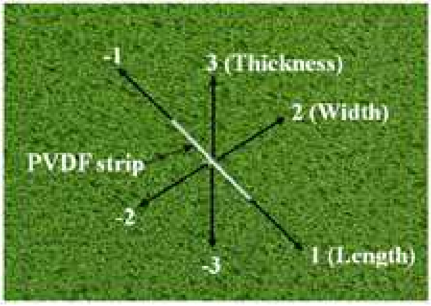


Fig. 9. Reference axes in PVDF strip

where D is the charge density, A denotes the electrode area of the PVDF strip formed in the 3-3 plane, d_{3n} is piezoelectric strain coefficient for the axis of the applied tensile force or compressive force, σ_{3n} is stress applied in the relevant direction. The piezoelectric strain coefficient d_{3n} is commonly expressed in $\left[\frac{C/m^2}{N/m^2}\right]$. 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 along the 1-1 and 2-2 directions, the output charge can be expressed as

$$\frac{Q}{A} = d_{33}\sigma_3 = d_{33}\left(\frac{F}{A_3}\right) \tag{2}$$

$$Q = d_{33}F \tag{3}$$

where d_{33} represents the piezoelectric strain coefficient along the 3-3 direction. Normally, the output charge is due to the combination of d_{31}, d_{32}, and 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 (Dargahi, 2000). It is because of the extreme thinness of the PVDF film, which is applied to develop the miniaturized high sensitivity PVDF sensor.

4.3 Principle of pressure variable resistor ink

In case that a constant load is applied to PVDF for an extended period of time, the response decreases and eventually becomes zero. Consequently, PVDF is adequate for sensing dynamic force, not the static one (Russell, 1990). In this research, pressure variable resistor ink (Creative Materials Inc.) is used to develop a force sensor. Pressure variable resistor ink is an electrically conductive ink, where its resistance decreases as the pressure goes up. Also, its minimum and maximum resistance can be adjusted by blending it with other conductive ink (Ashruf, 2002). As shown in Fig. 10 the force sensor is fabricated by sandwiching the ink between two polyester films with the pattern of electrodes. The fabricated force sensor can be modeled as a variable resistance such that its resistance decreases as the pressure increases as illustrated in Fig. 10.

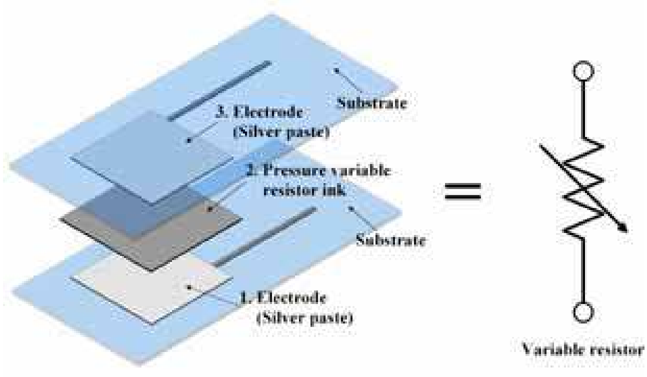


Fig. 10. Configuration of the force sensor

Fig. 11 explains the simple circuits utilized in the force sensor. When the fixed input voltage is applied to the sensor, it can read the change of the output value amplified by the voltage gain. Thus, the output is written by

$$V_{out} = -V_{cc}\frac{R_F}{R_S} = -V_{cc}R_F S_S \quad (4)$$

where R_S is resistance of force sensor, S_S denotes the conductance, that is, the reciprocal of resistance. Also, R_F is the op-amp's feedback resistance.

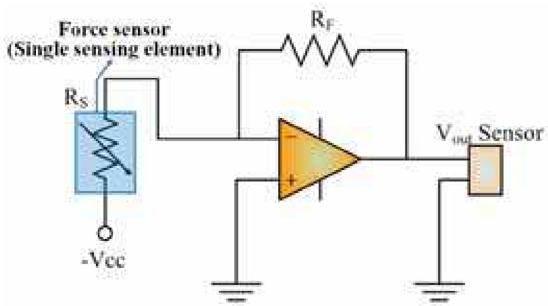


Fig. 11. Basic circuit of the force sensor

4.4 Slip sensor using PVDF

In this section, we explain the manufacturing and design of a miniaturized PVDF sensor with high sensitivity. After Polyvinylidene fluoride pellets (Aldrich Chemical Co.) is put between polyimide films, these pellets are pressed at 230°C ~ 240°C for 25 minutes with the pressure of 10MPa using a hot press machine. Then, PVDF film is allowed to cool down in the ambient temperature with the cooling speed about 1°C/sec. The thickness of fabricated films has a value between 50 and 70 µm. Then, the surface electrodes on both sides are fabricated using silk-screening technique with silver paste. By this method, a cost-effective and simple fabrication process is secured. The thickness of the electrode is about 5 µm, which can stand the temperature of 200°C. In order to exhibit high piezoelectricity in the fabricated films, the fabricated PVDF film is polarized by applying the strong electric field using the high voltage supply. Polarization is carried out at 170°C with the applied voltage of 3kV and load of 5N. The film is placed on a glass substrate while mechanically constrained and held at 170°C for 1 hour, then allowed to cool down before the applied voltage is removed. As shown in Fig. 12, the PVDF sensor consists of single PVDF strip with the thickness of 100 μm, 0.8mm width and 100mm length, where the sensing element has the size of $0.4mm \times 0.4mm$.

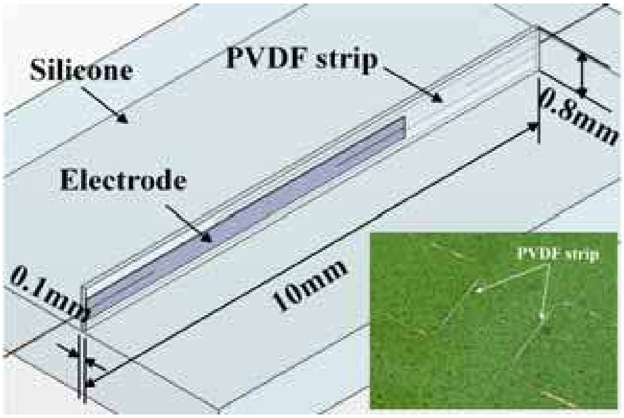
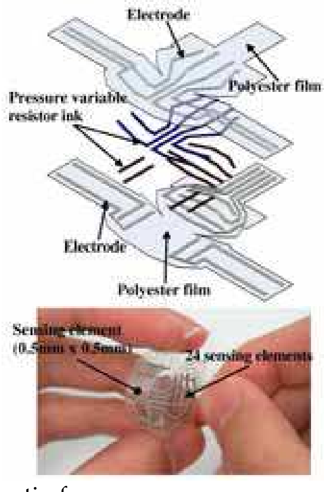


Fig. 12. Schematic of PVDF sensor and photograph

4.5 Thin flexible force sensor

In general, complexity of wirings increases largely depending on the density of the tactile sensor. To develop a force sensor with high resolution, the electrode pattern of the grid type is adopted in this research. The two polyester films are aligned as a grid while the pressure variable resistor ink layers face each other. Thus, each cross section of the grid forms single sensing element of the force sensor. As shown in Figs. 13 and 14, the size of each sensing



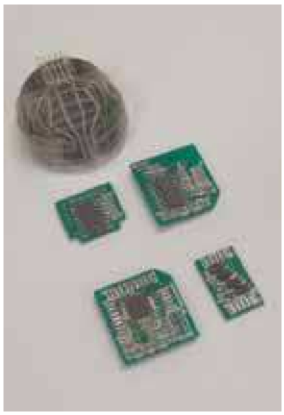


Fig. 13. Fingertip force sensor

element is $0.5mm \times 0.5mm$ and the total number of sensing elements goes up to 24. If the tactile sensor reads the output signal from the each sensing element respectively, total 48 signal lines are required. However, in the current approach, it is possible to read 24 sensing elements only with 8 input voltage lines and 4 output signal lines although the timing circuit is required.

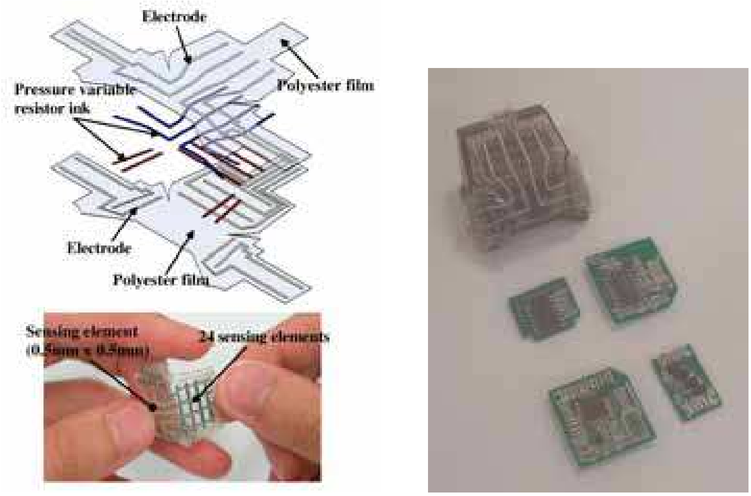


Fig. 14. Thumb tip force sensor

5. Hardware for signal processing

In this section, we introduce the miniaturized electronic hardware to be utilized for signal processing. As shown in Fig. 15, after being read from the sensing elements, the signals are

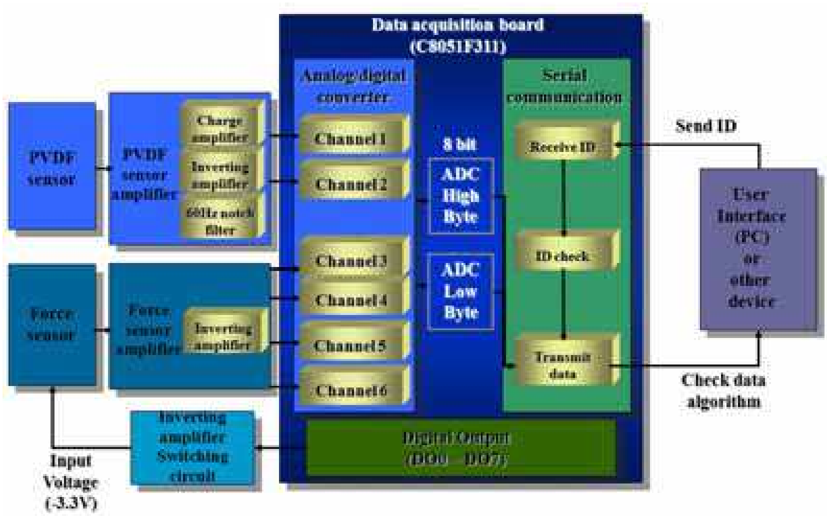


Fig. 15. Schematic of tactile sensing system

amplified and transformed into digital data with the A/D converter which is included in the microcontroller. Then the collected data is transmitted to the PC via an RS232 serial communication or input port of the external device.

5.1 Amplifiers

Two signal amplifiers have been developed in this research. One of them is for the PVDF sensor and the other for the force sensor. Because the output of PVDF depends on an instant variation of the load, it is electrically charged for a relatively short time. Therefore PVDF sensor gives the output voltage only in response to changing load rather than static one. The amplifier for PVDF sensor is basically used to convert the minute charge output from the PVDF strip into the voltage signal. The circuit for the PVDF sensor amplifier with the size of 18mm × 14mm, consists of charge amplifier, non-inverting amplifier and 60 Hz notch filter. Different from the PVDF sensor amplifier, the force sensor amplifier just amplifies the output voltage of the sensor using an op-amp.

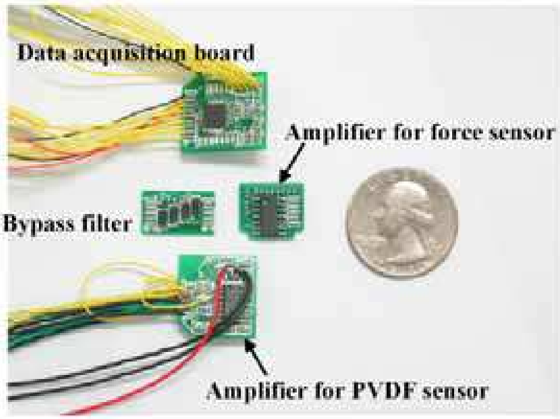


Fig. 16. Photograph of tactile sensing system

5.2 Signal processing unit

The circuit for the signal processing is designed on single board for data acquisition, control, communication. Data acquisition and communication are performed by using micro-controller (C8051F311). The signal processing board is able to transmit data to the PC via RS-232 or SMBus. The microprocessor in the signal processing unit is able to receive output signals from each sensing element by periodical scanning. Therefore, 8 digital output ports of a signal processing board become the input voltages of the force sensor, 4 A/D convert ports receive the output signal of the force sensor. Also, 2 A/D converter ports of the signal processing board receive the amplified output signal of the PVDF sensor. The scanning circuit of the force sensor is shown in Fig. 17.

In the circuit, the digital output lines of the microcontroller are changed to the active state and the microcontroller receives the outputs of the sensing elements via the AD converter. Therefore, the proposed configuration of the force sensor can effectively control all the sensing elements by using the minimum number of input and output signal lines.

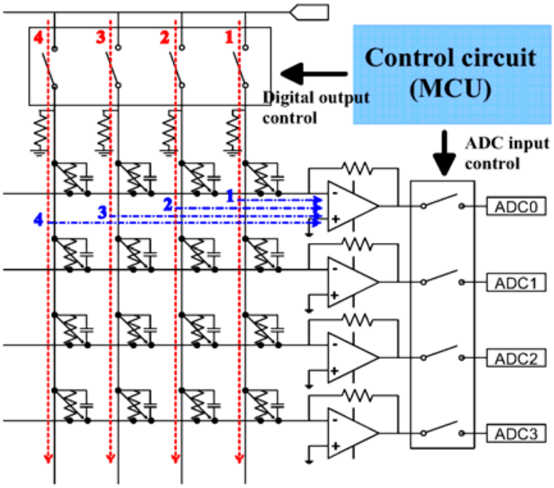


Fig. 17. Thin flexible force sensor scanning circuit

6. Control of the SKKU hand II

The SKKU Hand II is able to control and communicate with motor control boards through CAN communication method. As shown in Fig. 18, motors are controlled by each independent motor control board respectively. If main control receives a message for control of finger from other application, this message is sent to each motor control board by the main controller. Then motor controllers control the motors of each finger using PID control. Force feedback control can be interpreted in the main controller using output signal of thin

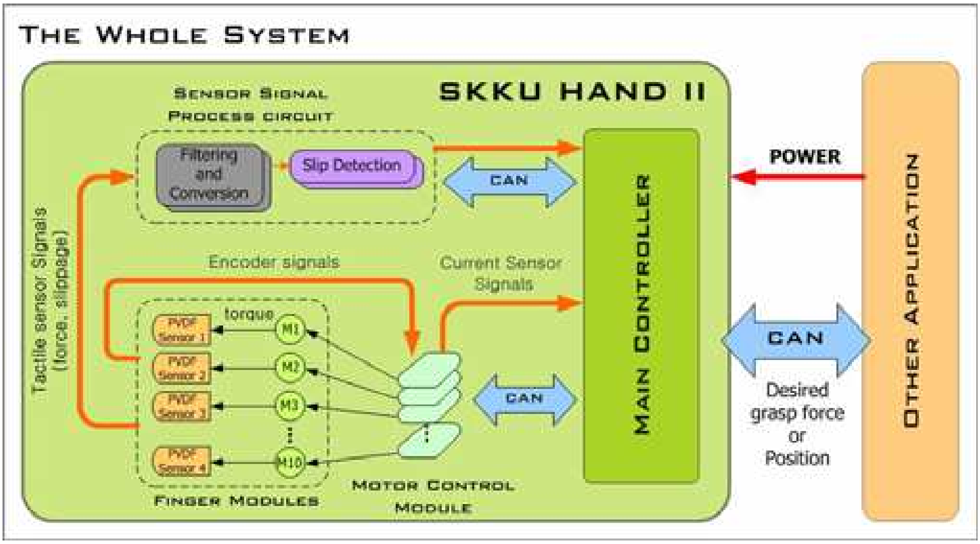


Fig. 18. System schematic of SKKU Hand II

flexible force sensor, PVDF slip sensor which is embedded each fingertip and current sensor which is integrated motor controller, and then, feedback parameters is sent to motor control module.

7. Experiments

In the first experiments, the sensor was touched and rubbed after installing on the fingertip. As shown in Fig. 19, it is noted that there exists the sharp change of signals, which implies that stick-slip occurred between the sensor and the contact surface. Also, the weight of 100g was rolled on the PVDF sensor. As shown in Fig. 20, the effect of stick-slip was not found and the smoother patterns of the signal compared to Fig. 19, was observed. When the weight of 100g rolled on the sensing element the output indicated about 1.2V constantly. Consequently, it is concluded that the characteristic of response can be discriminated depending on the surface characteristics of the object and the contact method, although calibrations are still needed.

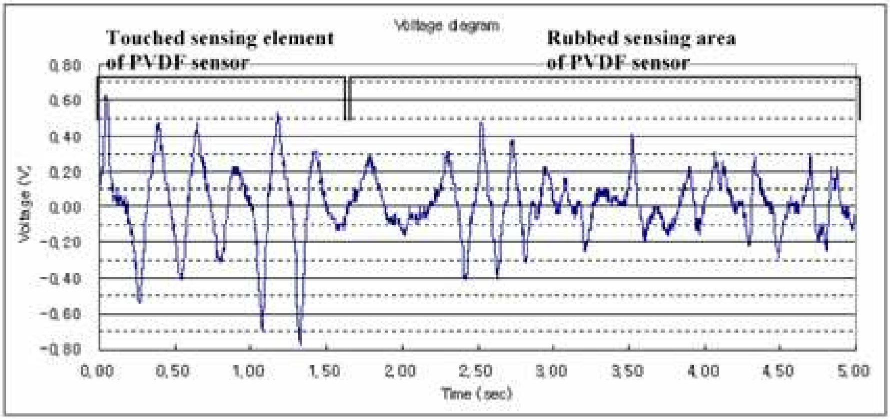


Fig. 19. Signal output from touching and rubbing.

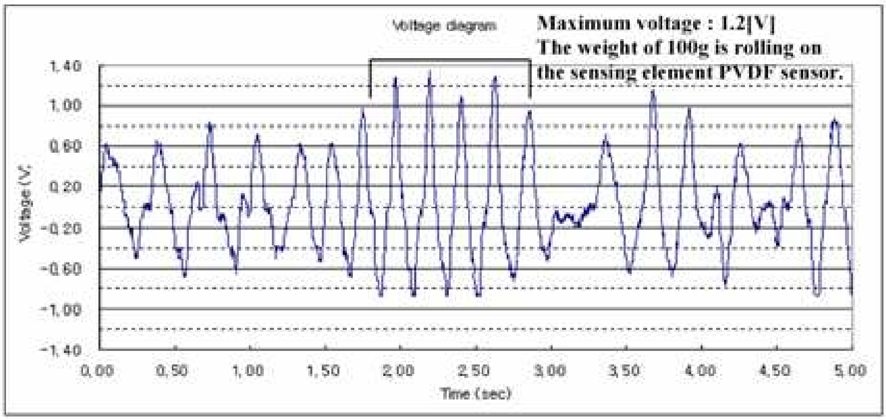


Fig. 20. Signal output from rolling of 100g weight

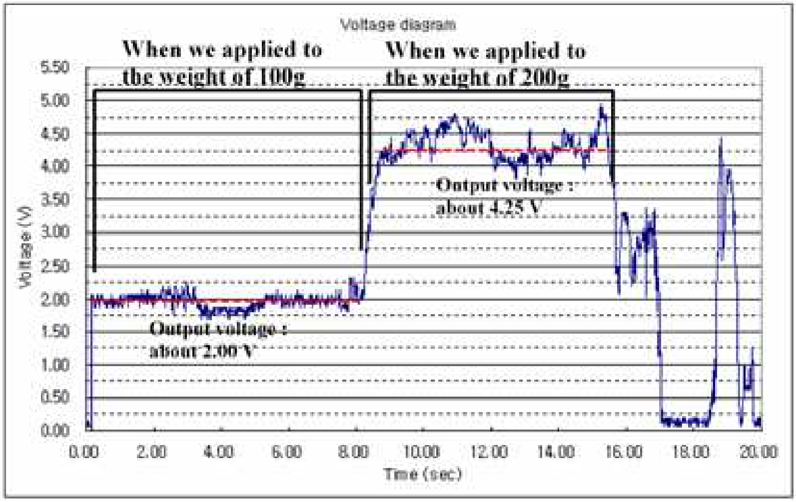


Fig. 21. The response of PVDF sensor, when we applied to the weight of 100g and 200g

In the second, the force sensor was tested. Static loads with the weight of 100g and 200g were applied, and the responses were obtained. As shown in Fig. 21, the output voltages of 2V and 4.25V were obtained for each weight. It is noted that the output has linear relation with the weight. Also, as shown in Fig. 22, user interface on the PC shows the data when the weight of 100g is rolled on the sensing elements of PVDF sensor and force sensor. Fig. 23 shows the contact information when we pressed the sensor in the fingertip. Before the

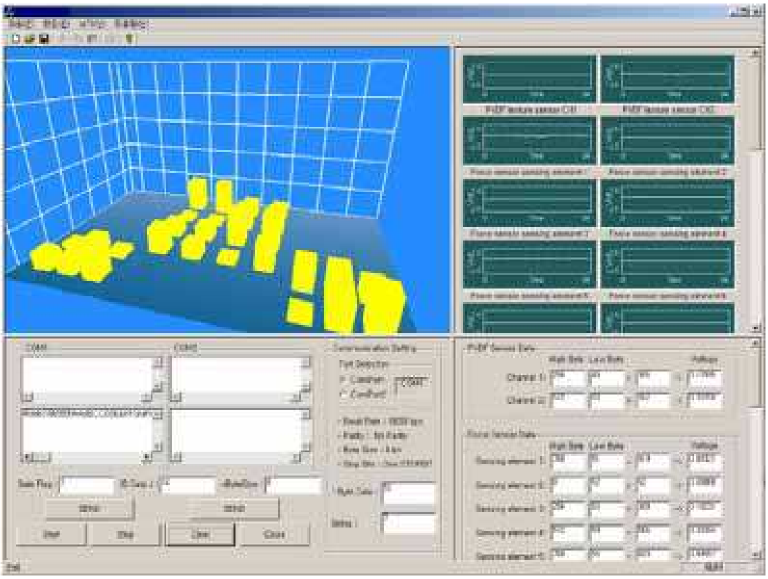


Fig. 22. The responses of PVDF sensor and force sensor, when the weight of 100g is rolled on the sensing elements

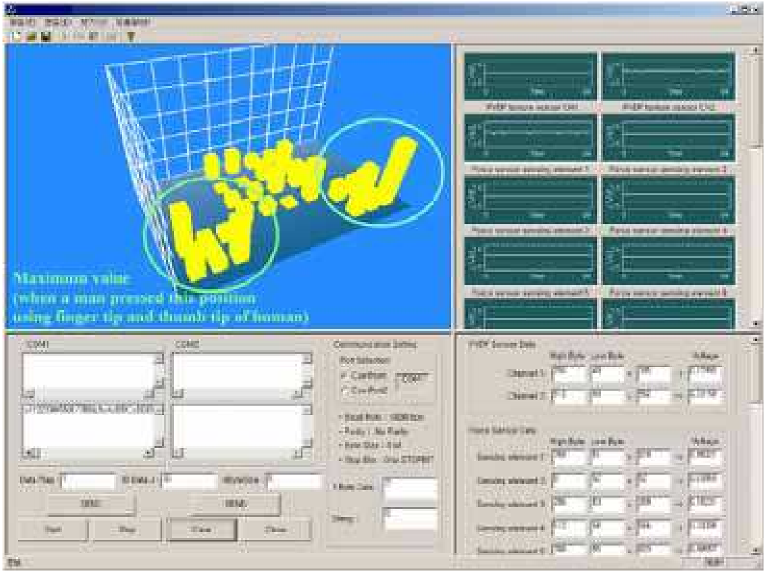


Fig. 23. The response of PVDF sensor and force sensor, when we pressed sensors using fingertip and thumb tip of human

integrated tactile sensor was attached to the robot hand, the SKKU Hand II was tested by grasping a bottle. As shown in Fig. 24, it is possible to confirm that the developed robot hand can grasp the bottle stably. Finally, the overall sensing system was tested by attaching it to the robot hand. We conformed the contact information through the user interface on the PC as shown in Fig. 25. It shows the contact information when we pressed the sensor in the fingertip. According to display of the user interface, the output distribution changes and the PVDF sensor responded to the stimuli sensitivity. In addition, Fig. 25 shows the contact information when robot hand grasped the bottle using the power grasping. According to the contact condition between sensing elements and contact surfaces of bottle, each fingertip sensor shows corresponding response. Therefore, it is possible to confirm that the each fingertip tactile sensor can detect the static force, location of contact and slippage.

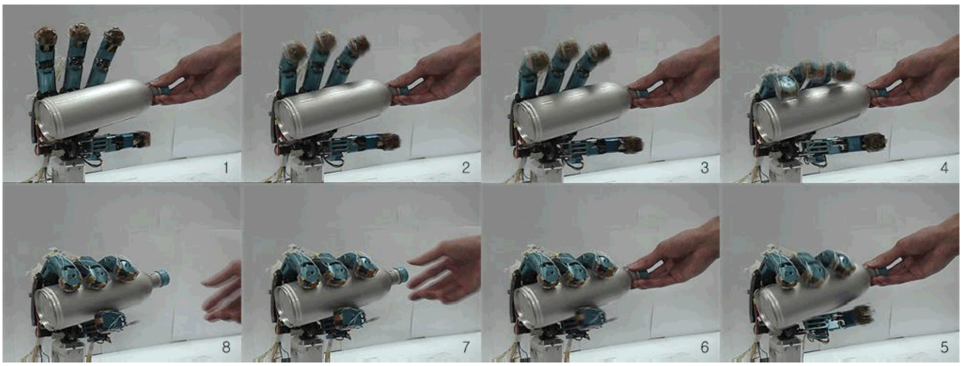


Fig. 24. Movement of SKKU Hand II

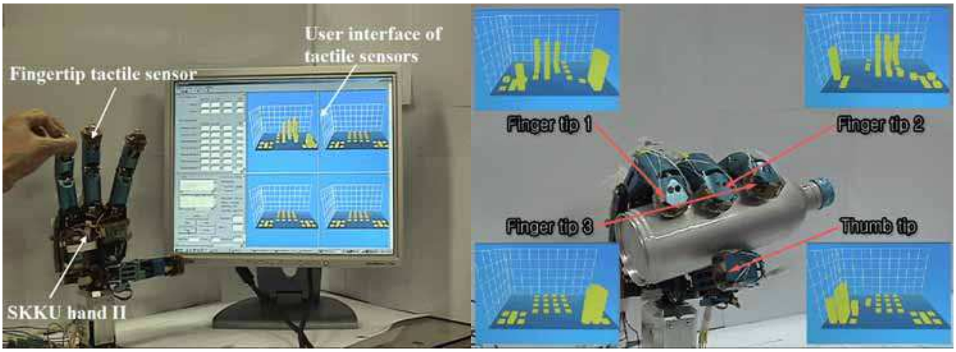


Fig. 25. Experiments of SKKU Hand II with fingertip tactile sensors

8. Conclusion

In this research, an anthropomorphic robot hand with tactile sensing system called SKKU Hand II was developed. Different from the previous gripper-type robot hands, the thumb of SKKU Hand II is designed as one part of the palm and provides the mobility of the palm. The robot hand is actuated by built-in DC motors, and fingertip tactile sensors are attached to its fingertips. A tactile sensor which can detects contact normal forces as well as slip is made of two organic materials, such as polyvinylidene fluoride (PVDF) that is known as piezoelectric polymer, and pressure variable resistor ink. Also, the 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 order to detect incipient slip, a PVDF strip is arranged along the direction normal to the surface of the finger of the robot hand. Also, a thin flexible sensor to sense the static force as well as the contact location is fabricated into an arrayed type using pressure variable resistor ink. The driving circuits and sensing systems for the SKKU Hand II were miniaturized as small as to be integrated into the robot hand. The SKKU Hand II which integrated fingertip tactile sensors is validated through preliminary experiments. According to experiments on this research, it is possible to confirm that the each fingertip tactile sensor can detect the static force, location of contact and slippage. In the next research, we will control the robot hand for dexterous grasping and manipulation using the force feedback from the fingertip tactile sensors and evaluation will be performed.

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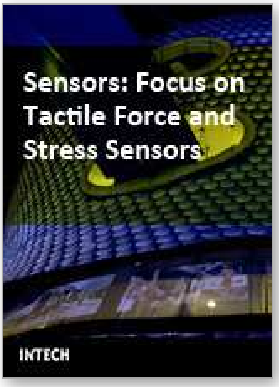

Sensors: Focus on Tactile Force and Stress Sensors
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This book describes some devices that are commonly identified as tactile or force sensors. This is achieved with different degrees of detail, in a unique and actual resource, through the description of different approaches to this type of sensors. Understanding the design and the working principles of the sensors described here requires a multidisciplinary background of electrical engineering, mechanical engineering, physics, biology, etc. An attempt has been made to place side by side the most pertinent information in order to reach a more productive reading not only for professionals dedicated to the design of tactile sensors, but also for all other sensor users, as for example, in the field of robotics. The latest technologies presented in this book are more focused on information readout and processing: as new materials, micro and sub-micro sensors are available, wireless transmission and processing of the sensorial information, as well as some innovative methodologies for obtaining and interpreting tactile information are also strongly evolving.

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