JOURNAL OF KOREA MULTIMEDIA SOCIETY, VOL. 7, NO. 6, JUNE 2004(pp. 767-780)

PVDF Dynamic Tactile Event Sensor for Ubiquitous Computing

Taehee Kim[†], Mikeung Park[††]

ABSTRACT

Interaction requires dynamic relationship between objects. In ubiquitous computing environment, interaction between human and the environment is implied. Tactile interaction has so far been less addressed, while tactile sensation should be an important topic in the field of multimedia study. This paper describes development of a novel PVDF (Polyvinylidene Fluoride) dynamic tactile sensor and associated experiments. PVDF dynamic tactile sensors detect touch events applied to the sensor skin by low frequency components of the signal. Rubber skin-covered sensing material was mounted on the bones. Robust performance with low noise was figured out in our robotic experiment. Whereas most conventional sensors are interested in measurement, our dynamic tactile sensor is sensitive to change of state, which could be a key for economic understanding of happenings in the dynamic world. We note that dynamic sensing uses motion as a part of sensing modality We suggest that dynamic sensing be understood in technological terms in the perspective of interactive media and ubiquitous computing.

Keywords: PVDF Tactile Dynamic Sensor, ubiquitous computing environment, PVDF

1. INTRODUCTION

Tactile sensation has less been appreciated in the context of multimedia while tactile sensing plays a significant role in human sensation. Tactile sensing is characterized to be of dynamic since tactile signal requires motion or force. Thus, tactile sensing must be best understood in the context of dynamic world. Ubiquitous computing environmentm assumes dynamic world because it deals with changes and actions in the interaction between human and the environment.

Researchers have preferred to develop accurate sensors for the measurement of physical quantities. This is a natural consequence of the world model being expressed as a conventional scientific model, *e.g.* solid-geometric. A measured physical quantity is utilized for comparison with and/or updating of the world model. However, biological sensors tend to be sensitive to a change of physical quantity: change of smell; change of noise; change of scene of the visual space; change of force, etc. In addition, animals tend to introduce motions to obtain more information. For instance, a blind man uses a stick to parallel a normal human in many situations, by constructing a 3D spatial image using tactile sensing and motions[1]. In *active vision*[2], use of motions simplifies the task of extracting useful information from image sequences, such as using *optical flow*[3]. Sensors that detect changes in physical quantities, and the introduction of motions to sensing, may improve an autonomous systems in the sense that less computation is required.

In ubiquitous computing environment, where the surrounding might be thought as an organic autonomous system, sensing would play an sub-

---

※ Corresponding Author : Mikeung Park, Address : (626-840)Junam-Ri, Woongsang, Yangsan, Kyungnam, Korea, TEL : +82-55-380-9252, FAX : +82-55-390-9249, E-mail : park@ysu.ac.kr

Receipt date : Jan. 2, 2004, Approval date : March 18, 2004

[†] Associate Professor, School of Multimedia Eng. Youngsan Univ.
(E-mail : thkim@ysu.ac.kr)

[††] Associate Professor, School of Computer Information and Engineering, Youngsan Univ.

※ This work was supported by the Youngsan Univ. 2001.

stantial role for such system. Since the world is dynamic, conventional sensing biased to measurement might not be sufficient. Dynamic sensing[4] focuses on the use of motions to enhance sensing activity. Sophisticated sensors designed for precise measurement to be used by conventional autonomous systems usually require intensive computation and are often expensive. Instead of quantitative sensing, qualitative sensing incorporated with motions can provide appropriate information economically.

The development of the event sensors were motivated by the need of economic sensors for dynamic purposes *i.e.*, providing informations about the effect of the current motion of manipulators or devices. We developed an economic event signature sensor for part contact using piezoelectric PVDF (polyvinylidene fluoride) films. PVDF material is known to exhibit good sensitivity to many kinds of physical change of quantity, such as mechanical vibration and change of heat. However, it is not considered as a good choice for a measurement task unless much effort is exerted to provide constrained conditions, since they have considerable inherent capacitance, which results in differentiation of the signal, and induced noise. But, it can be turned into a suitable sensing device when qualitative sensing is much favoured. Because it has good sensitivity to change, sensitive event signature sensors can be built out of it.

This paper first reviews tactile sensors, particularly for dynamic purpose. Implementation of the sensor is next described. Then, the sensor developed is evaluated in a robotic context. Finally, the work is summarized and discussed. The implication of dynamic sensing in the context of interactive art and ubiquitous computing is addressed.

2. TACTILE SENSING FOR DYNAMIC PURPOSES

Human tactile sensing is so versatile and delicate that fine manipulation greatly relies on it, for instance in the assembly of a clockwork watch. Note that the clearances of assembly, *e.g.* 1/100 mm, exceed the dead-reckoning accuracy of almost all assembly arms, therefore some extra assistance is needed. Hence, it is useful to aim for something like human tactile sensing for devices such as assembly robots that are equipped with a fine part manipulation capability.

The terms “active” and “dynamic” sensing can cause confusion. Although both can be used to mean sensing involving motion, this paper distinguishes: 1) active sensing, as opposed to passive sensing, to mean sensing which actively emits energy with which to sense, such as infrared or sonar sensors; 2) dynamic sensing, as opposed to static sensing, to mean sensing which involves motion However, “active” can be used to mean both senses. Active Vision uses motion in order to help vision sensing[2]. Hillis[5] referred to tactile sensing incorporated with motion as “Active Tactile Sensing”. But, Active Sonar is commonly used to mean self-emitting ultrasonic sensing[6].

This paper is interested in tactile sensing for dynamic purposes, *i.e*, involving motions. In this section, tactile sensing for dynamic purposes in part manipulation is reviewed. Functional scope of the transducers of human tactile sensing is first described. Secondly, technologies for tactile sensing are reviewed. Then, approaches to tactile sensing for dynamic purpose is mentioned.

2.1 Human Tactile Sensing Transducers

There are various types of sensory receptors in the skin, which are non-uniformly distributed throughout the human tissue. Their known functions are briefly described as follows[7-9]:

- **Free nerve endings** can detect very slight pressure and are extremely sensitive. They are also responsible for temperature sensing.
- **Pacinian corpuscles** are the largest of the encapsulated endings. Due to the protection of its

large capsule from steady mechanical pressure, the nerve ending is sensitive only to changes in pressure. They also serve the kinesthetic sense.

- **Meissner's corpuscles** are found in hairless skins, responsible for the localized pressure sensing. These provide a high degree of spatial localization.
- **Ruffini end-organs** detect continuous deformation of the skin and deep tissues.
- **Hair end-organs** detect mechanical deflection of the hairs to which they are attached.

The tactile sensing of human beings provides important information in manipulating objects, especially when objects cannot be seen or more accuracy is required than other sensors can provide[10].

2.2 Technologies for Tactile Sensing

Human tactile sensing comprises touching, force, temperature, vibration, and feeling texture by slipping. While it is difficult to condense all these competences into a small package, or even to implement one competence well, current tactile sensors mimic some of these competences. Replicated human sensing competences for robots can be itemized as: simple contact; magnitude of force; 3-dimensional shape; slip; thermal properties; and so on[11].

Tactile sensing can be divided into two modes based on the properties of the object sensed: *extrinsic object properties* and *intrinsic object properties*[12]. Extrinsic properties comprise shape (edges, corners, faces...), texture, and hardness. Intrinsic factors are force, moment, and displacement, in addition to their time derivatives. Extrinsic properties are retained by the object, and hence are mostly static, although motions are required to sense texture for instance. On the other hand, intrinsic factors only appear dynamically in response to stimuli.

2.2.1 Extrinsic Tactile Sensors

Research on tactile sensing has been biased towards the extrinsic approach, where tactile sensing cells are spread over the contact surface, focusing on the problems of processing the projected images (*e.g.*, continuous force or binary) of the gripped object. Various technologies have been investigated for use as the sensitive cells of tactile array sensors. Functionally, these cells can be either binary or force sensors.

For example, Hillis[5]. in the early 80's, developed a tactile array sensor with each sensitive cell being a force sensor. Anisotropically conductive rubber (ACS) was used. Conductive rubber presses through a meshed separator on a printed circuit board so that the area of contact, hence the contact resistance, varies with the applied pressure. Dario and De Rossi[13] reported their work on the development of a human-skin-like tactile sensor. Their sensor comprises deep ("dermal") and shallow ("epidermal") sensing layers, based on the technology of ferroelectric polymers using PVDF transducers. The dermal layer was intended to mimic the role of the slowly adapting receptors of the human skin, which are sensitive to the spatial features of the indenting object, while the epidermal layer was implemented to cover a few sensing sites and particularly sensitive to dynamic contact stimuli, like the quickly adapting skin receptors[14].

Other techniques, such as capacitive, magnetic, and optical transduction, are well reviewed in [15,10], and [16].

2.2.2 Intrinsic Tactile Sensors

Compared to Extrinsic tactile sensors, research on intrinsic tactile sensors is scarce. Salisbury[17] analysed contact geometries in order to obtain high quality control of the force and motion states of the grasped object. Bicchi and Dario[18] reported their work on an intrinsic tactile sensor using seven strain gauges mounted on a finger bone in order to measure the force exerted on the finger during part manipulation. In their work, an ex-

Table 1. A comparison between extrinsic and intrinsic tactile sensors

Features	Type	
	Extrinsic	*Intrinsic*
Spatial resolution	Inherently	Theoretically infinite
Bandwidth	Limited	High
Contact force	Generally Inaccurate	Fast, linear, nonhysteretic
Frictional effects	At present, not sensed	Measured
Slippage detection	None	Possible
Sensor surface shape	Free	Only simple shapes
Sensor cover compliance	Allowed	It produces errors
Paratactile sensitivity	Possible	Impossible
Encumbrance	Many wires	Rather bulky, few wires

trinsic sensor was implemented on top of the intrinsic tactile sensor used in a complementary manner. While strain gauges are widely used for force measurement, Okada and Rembold[19] point out the difficulties in using strain gauges due to their fragility, sensitivity to temperature, and possible crosstalk for multiple-axis load cells. They proposed an optical technology to measure[1] force for an intrinsic tactile sensor.

Bicchi and Dario[18] identify advantages and disadvantages of the extrinsic and intrinsic approaches to tactile sensing, as reproduced in Table 1. However, there are a few points to be questioned. First, Bicchi and Dario describe extrinsic tactile sensors as unsuitable for slippage detection. But it would be possible for a force array tactile sensor to detect slippage by comprehending the change of the contact images. Furthermore, apart from array tactile sensors, a vibration tactile sensor, although still an extrinsic tactile sensor, can be made to detect slippage (*e.g.* [20] and [21]). It is possible for an intrinsic tactile sensor to sense slippage by interpreting the vibration detected by a force transducer (*e.g.* [22]). Second, on the encumbrance feature, extrinsic tactile sensors could have many wires if they are tactile arrays, while those with few transducers would not. Intrinsic tactile sensors can be bulky depending on the technology and the transducer type employed.

2.3 Use of Tactile Sensing with Motion

Beni *et al.*, proposed[2] for the situation where robot motion increases the functionality of sensors, obtaining more information than when used in a static manner. For instance, a single photo cell can be used with planar motion of a robot in order to obtain a full 2D image. Guarded moves[23] by their nature involve motions in sensing. For instance, when a robot places an object on an unknown part, exploratory moves would be required with appropriate sensing incorporated until any expected contact is met. A guarded move is a form of dynamic sensing which combines sensing and motion.

Since tactile sensors retrieve only information about the contacted part of the gripped object, and the active area of the sensor is often small compared to the size of the gripped object, so the information received may not be sufficient to recognize the object. Examination of multiple contact images involving motions is referred to as *Active Tactile Sensing*[2][24,5,1]. Sensing of texture of an

---

[1] Note that event sensing would only require the sensitivity to change, which is technologically less demanding than accurate measurement.

[2] The term, *Active Tactile Sensing* here should be distinguished from active sensing where the sensor actively applies emitted energy such as a light beam as a part of the sensing activity, as identified at the beginning of this section.

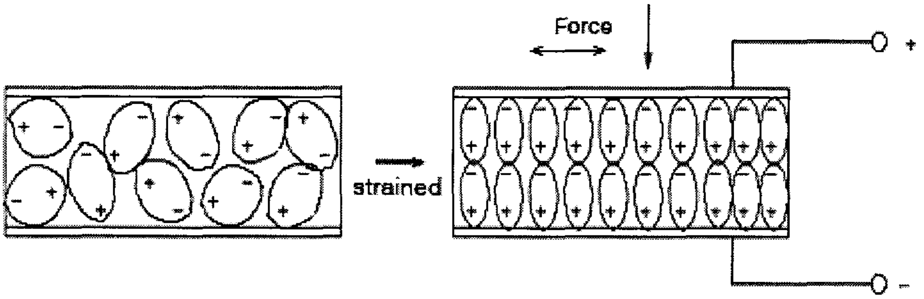

Fig. 1. Polarization

object would also require robot motion. One of the features of the PVDF tactile sensor developed by Dario and De Rossi[13], is to obtain the surface texture of an object using some control method shown in [14].

In dynamic tactile sensing, an understanding of the information that can be obtained from the impact of the object is often necessary, where impulsive forces may dominate all other forces[25]. For instance, Soderquist and Wernersson used measured acceleration in order to find the point of application of the impacting force, as well as its line of action, which had a positional accuracy of roughly 6% of the dimension of a body[26].

3. CHARACTERISTICS OF THE PVDF FILM AS A SENSORY TRANSDUCER

PVDF has been recognised as a useful sensory transducers, particularly for tactile purposes[27,28]. The piezoelectric effect is electric polarization produced by mechanical strain in certain crystals, the polarization being proportional to the amount of mechanical strain. Conversely, an electrical polarization will induce a mechanical strain in piezoelectric crystals. As piezo material, PVDF films are used throughout the event signature sensor implementation.

The PVDF film is a highly polarizing material, which is a long chain of semi-crystalline polymer of repeated units. PVDF remains unpolarized as long as no force is applied. Once an external force has been applied to the film resulting in compressive or tensile strain, the film develops a proportional open circuit voltage (see Fig. 1). Exposure to a reciprocating force results in a corresponding alternating electrical signal. The frequency response ranges widely from 0.005 Hz to gigahertz. The film is sensitive to vibration, at least 50 times more than common microphones.

The piezo film also acts as a pyroelectric transducer, it can be used to detect thermal radiation. When thermal energy is absorbed, the film expands with increasing temperature. This results in a detectable deformation and a corresponding charge is output. The reverse effect occurs on cooling of the film. Suitably designed sensors can be used for detecting heat radiation including infrared radiation. The film has been successful in many applications, such as vibration sensors in general, force sensors, accelerometers, compact switches, ultrasonic applications, infra-red applications, pyroelectric applications, and so on[29].

PVDF transducers are often used as vibration detectors in robotics applications. Son *et al.* employed four PVDF films in one finger tip with different frequency component amplification parameters for the films to detect the instant when the gripped part is just about to slip[30]. Shinoda and Ando used a PVDF transducer matrix to characterize and localize any touch directly on an elastic hemisphere body with transducers built in, by detecting the ultrasonic waves produced by touching[31]. Patterson and Nevill, Jr. used PVDF film to detect object texture by employing exploratory sliding motions[32]. The PVDF extrinsic tactile sensor developed by Dario and De Rossi[13] could detect object shape, texture, hardness, and temperature[14].

PVDF transducers have also been used for matrix tactile array sensors. For instance, Grahn and Astle have built 12 PVDF-based tactile sensor cells where each cell measures the normal force exerted on it[33]. By means of ultrasonic pulse-echo ranging, each sensor cell measures the change in thickness of a compliant, elastic pad whose surface is deformed by the gripped object with a spatial resolution of 0.5 mm.

4. DEVELOPMENT OF THE PVDF EVENT SIGNATURE SENSOR

Our tactile sensors are built and tested in robotic context. This section describes first, the manner that PVDF films are used for the PVDF event signature sensor developed, then the development of the interface electronics, and the construction of the physical sensor body.

4.1 The Way the Sensor Works

The PVDF film works such that once an external force has been applied to the film, which results in compressive or tensile strain, the film develops a proportionate open circuit voltage. Since the film responds to strain applied on it, bending of the film causes the film to generate a voltage which corresponds to the bending action as shown in Fig. 2[34]. Charge developed vanishes at a rate determined by the electrical time constant of the interface circuit. An input resistance of 10 MΩ was used to increase the time constant.

4.2 Building an Interface

Like other piezo materials, PVDF films require very high input resistance (mega *Ω*s) because they cannot afford much current. The use of a high input resistance allowed a technically difficult side effect, the *triboelectric effect* (i.e. electricity generated by friction) to cause interference. A wire between the transducer and the input resistance can generate some electric charge by friction which results from knocking or bending the wire. Although this charge is tiny, due to the high input resistance, it can be captured by the interface. The pattern and the strength of this false signal is similar to one generated by normal sensing action.

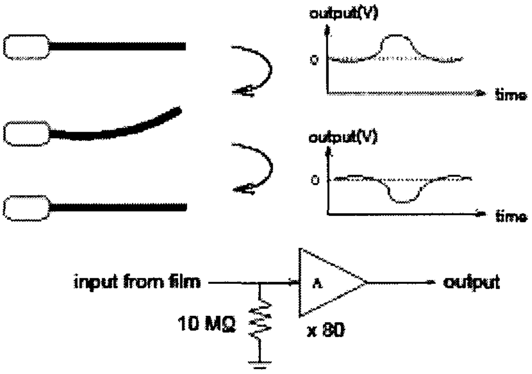

Fig. 2. Bending experiment of the PVDF film

There are two possible solutions to eliminate the triboelectric effect. One is to use a non-triboelectric cable, which is available commercially, but is expensive. The other solution is to keep the length of the wire as short as possible and ensure no significant friction is introduced to the wire. The latter is adopted.

A pre-amplifier is employed for each robot finger with plain twisted wires of length at most 5 to 10 cm. The circuit diagram of the pre-amplifier is depicted in Fig. 3. A 1 nF capacitor is placed in parallel with the 10 MΩ resistor to form a low pass filter. This low pass filter crudely filters out any strong relatively high frequency components (higher than a frequency ≈ 16 Hz), in order to prevent the main amplifier from saturation, which will result in loss of information.

The outputs of the pre-amplifier are fed to the main amplifier, through 5 meter long microphone coaxial wires. The much lower input resistance here eliminates any possibility of the triboelectric

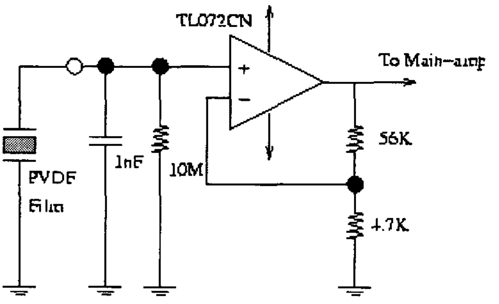

Fig. 3. Circuit diagram for the pre-amplifier

effect. The main amplifier has a band pass filter, which passes the signal frequency components around 0.4 Hz. The cut-off frequency has been chosen such that given the simplicity of the circuit as a first order filter, maximal sensitivity could be obtained, and the output settles at zero as soon as possible after a detection of an event so as to be ready for the next event. The circuit diagram of the main amplifier can be seen in the Fig. 4, and its simulated frequency response follows in the Fig. 5.

The analog signal from the electronic interface is processed by a PC. The PC samples data via two channels of an A/D converter, at a rate of 20 Hz. Signals from the two channels can vary between ±5 volts and are thresholded at ±0.5 volt to provide binary signals. A typical graph of these signals can be seen in Fig. 6.

4.3 Physical Construction

This section provides descriptions of the physical construction of the fingers for robotic manipulator with PVDF films. Two types of film placement are described and the use of compliant material is discussed. Film placement and the compliant materials including the skin used are closely related to the sensing performance.

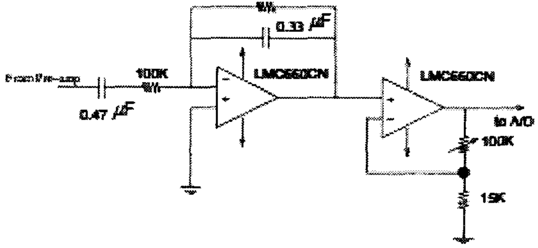

Fig. 4. Circuit diagram for the main amplifier

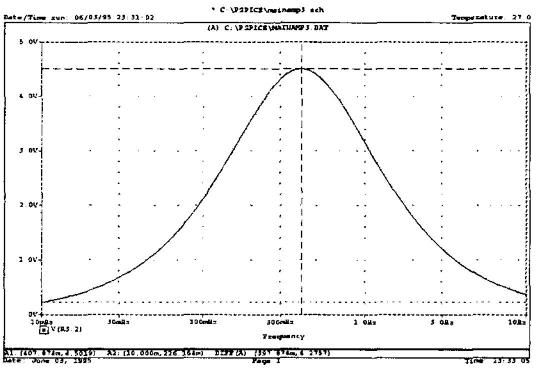

Fig. 5. The frequency response of the main amplifier

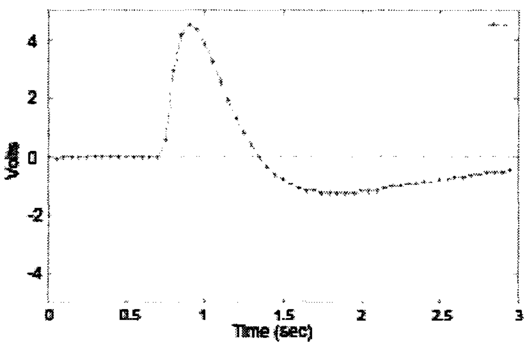

Fig. 6. A sample signal from the sensor

4.3.1 Film Placement

Two types of variations in film configuration are proposed so far: flat type and round type, as shown in Fig. 7[3]. The films used are LDT1-028K's[4], with the dimension of 40mm×15mm.

The round type has a good sensitivity to both vertical force and horizontal force. The flat type has poorer sensitivity than the round type, but better sensitivity than the round type on vertical force. Detailed experimental results of the

---

3) Not shown in the figure are the skins finally mounted on top of the PVDF films.

4) Piezo Film Sensors - Europe, Merrion Avenue, Stanmore, Middlesex HA7 4RS, U.K.

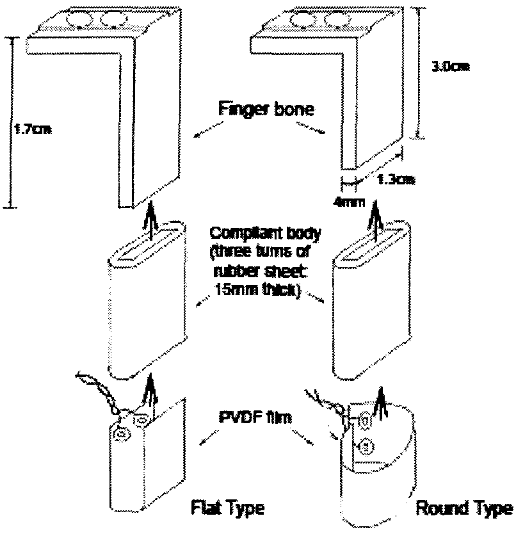

Fig. 7. Two variations in the PVDF film configuration

experiment of the sensing capability will follow in later sections.

4.3.2 Compliant Materials for the Dynamic Tactile Sensor

The kind of compliant material used for the finger body, including the skin, is an important factor in determining the performance of tactile sensors[35,10,36]. Depending on the softness of the compliant material, sensitivity, resolution (in the case of a matrix tactile sensor), *etc*, are restricted. Durability of the material, particularly for the skin, is one of the important factors for practical application of the sensors.

In designing our tactile sensor, the degree of softness of the compliant material which is placed in between the film and the metal bone must be considered in conjunction with the gripping force of the gripper. First, it should remain compliant even when a desired gripping force is applied in order to provide the desired sensitivity, since the sensitivity is related to the degree of deformation of the film. Second, it needs to be firm enough not to cause to much inaccuracy in part position.

Rubber sheet cut from rubber kitchen gloves is a good material in many respects. It can be wrapped onto a finger bone as many times as required to provide a desired compliance. It is a good material for artificial finger skin since it has appropriate friction and durability, after all it is intended to be used in human grasping. As the inner compliant material, a patch of rubber sheet was wrapped around the finger bone to 1.5 mm thickness (three turns), to which a PVDF film was fixed. The width of fingers are approximately 1.7 cm after they are finished with the rubber skin. Unnecessary gaps were filled with silicon rubber. Silicon rubber was also used as an adhesive in addition to instant super glue.

5. SENSOR EVALUATION EXPERIMENTS AND THE RESULTS

This section describes the procedures and results of the experiments to evaluate the performance of two types of the dynamic tactile sensor implemented (the round and the flat types) implemented when used for guarded moves. The purpose of the sensitivity experiments is to investigate the limitations due to the sensitivity (i.e. how fast the robot should move in order to guarantee reliable sensing). The sensitivity is tested at various robot speeds for both horizontal placing and vertical placing. In addition, the sensitivity to a torque on gripping a contact surface is also tested.

The sensitivity of the dynamic tactile sensor is specified in terms of the minimum speed of the robot necessary to generate a strong enough signal to reliably detect the contact of rigid objects. An electric parallel gripper with adjustable gripping force was mounted on a ADEPT1 robot and used for the experiments. Each finger has one film built in. A pentagonal 1 mm thick polished aluminium plate is used as the gripped object. Vertical placing is illustrated in Fig. 8 (left). Horizontal placing is performed with the wrist bent by 90 degrees moving the robot also downwards, as illustrated

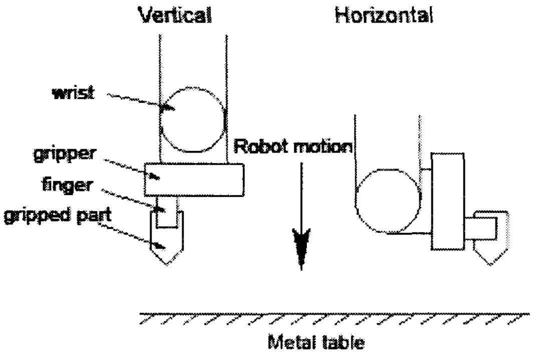

Fig. 8. Experiment on vertical placing and horizontal placing

in Fig. 8 (right).

Table 2 summarizes the sensitivity, *i.e.*, the minimum robot speed required (in mm per second) to cause a strong enough sensor signal to be reliably detected. The increment was approximately 10 per cent of the speed, and each speed specified in the table was the minimum speed where at least 5 consecutive tries were successful. The gripping force is measured to be approximately 2500 gram force. As the robot speeds in the table decrease, and the energy of impact decreases, there comes a point where the sensors quite abruptly cease to detect the impacts.

The sensitivity of the round type fingers is more uniform in response to forces from different directions than that of the flat type fingers. However, given the simplicity of the interface electronics, the flat type fingers show a high sensitivity on vertical placing at the cost of a relatively poorer sensitivity on horizontal placing.

The ADEPT robot has some degree of compliance at its wrist joint compared to the other extremely stiff joints. This compliance diminishes the sensitivity on horizontal placing[5]. Without this compliance, horizontal placing is expected to cause the sensors to be as responsive as in the case of vertical placing. It is easier to bend the film along its long side than its short side when it is rolled into a cylindrical shape. For the round type, the tangential force is exerted along the long side of the film, and the good sensitivity compensates for the compliance of the wrist. At the lowest possible speed for sensing, 0.1 mm per second, the robot exerts approximately 102 gram force to the object[6]. This is the highest possible delicacy in using the sensor given its sensitivity.

Table 2. Minimum robot speed required for reliable sensing mm per second

	Minimum robot speed required (mm per second)	
	Round type	Flat type
vertical	1.2	0.1
horizontal placing	1.3	2

The sensitivity to the torque exerted on the fingers was also investigated. Fig. 9 shows the two different kinds of torque applied. Torque parallel to the sensitive surfaces of the finger is named *lateral torque* (left of the fig), and torque vertical to the sensitive finger surfaces is named *vertical*

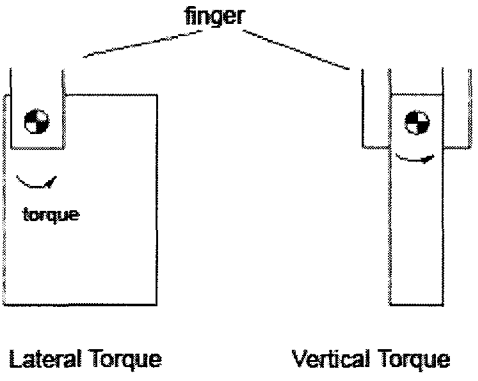

Fig. 9. Lateral torque and vertical torque

---

[5] Compliance will add to the distance travelled to build up the sensing force, and thus the time of build up. Since sensitivity is here defined in terms of *minimum* speed, extra compliance will require the speed to be raised in proportion. At typical high working speeds of sensor operation (e.g., 10 mm/s compared to 1 mm/s here), an extra compliance of even as much as 1 mm (at typically 2 Kg force) will only have a small effect on sensor output.

[6] The force was measured using a 6-axis force/torque sensor sitting on a stable table while the robot issues a guarded move on the sensor.

torque (right of the fig). The minimum robot speeds required in mm per second at which the sensors respond reliably, for the round type fingers and flat type fingers are summarized in the Table 3. The procedure followed in arriving at the results in the table was for the speed for each trial be raised until in a least five successive trials, a response always occurred. The object was gripped 3.5 cm away from its collision location. The lateral torque causes much less deformation of the sensor body than the vertical torque, due to the finger construction. This limits the scope of the general application of the sensors developed. More research is required on finger construction. For example, a gripper with three fingers could reduce the sensitivity variation over different torque directions.

The sensors developed are shown in the Fig. 10 (top-left: round type; top-right: flat type; bottom-left: round type with a fingernail; bottom-right: fingers for the left hand).

Table 3. Minimum robot speed required for torque event sensing in mm per second

	Minimum robot speed required (mm per second)	
	Round type	Flat type
lateral torque	8	10
vertical torque	1.3	0.4

6. CONCLUSIONS

The competences demonstrated so far by the dynamic tactile sensor developed can also be demonstrated by other sensors such as force/torque sensors and possibly some other tactile sensors. However, these sensors have drawbacks of being expensive and tend to be bulky. The sensors developed here have, in general, advantages over those sensors in that:

- The manufacturing process is not difficult.
- They are cheap, and hence less of a loss if damaged.
- The sensors make almost direct contact with the object with only minimal intermediate material, such as skin.

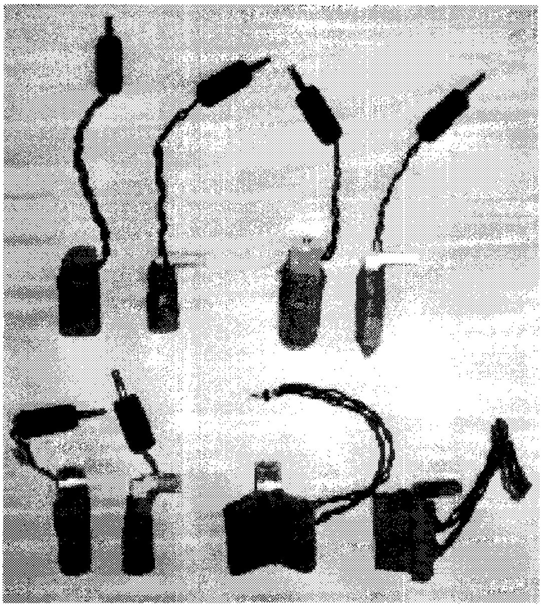

Fig. 10. Sets of fingers with the embedded sensors

- Although mounted on the fingers and making a direct contact with an object, they are less sensitive to the gripping force as they detect only the changes in force.
- The fingers can be shaped in various forms since PVDF films are flexible.
- They have a wide band of signal detection of force strength.
- They are very sensitive and as a result, the skin can be thick and hard for durability and accuracy.

However, possible disadvantages could also be itemized as:

- Because the sensor body has some compliance in order to allow the PVDF to deform, although it can be small, there is always some position error introduced in part contact.
- Although detection of changes of force in part contact is considered to be important, information about the absolute force would be still required for certain tasks, to which the sensor we developed

is not well suited.

The simple electronic interface used in the experiments is good enough for the applications listed above. However, sensitivity can be greatly increased, if desired, by employing more sophisticated electronics.

In practice, the material remained deformed after being used for a long period, although no noticeable degradation of the sensitivity was observed. However, unless the robot is programmed not to consider precise finger positions, it may cause problems where finger position is crucial. The rubber sheet is not perfect for the skin, but our experiment shows it to be fairly good. It can also be easily replaced when worn out. In addition to the rubber sheet used, durable fabrics and even flexible metal sheet can be explored in an attempt to improve skin characteristics.

Although sensor developed is a skin mounted sensor, *i.e.*, similar to other extrinsic tactile sensors, it is in fact an intrinsic tactile sensor, since it provides information about the force acting on the finger[7]. The sensors are skin acceleration sensors like the one developed by Howe and Cutkosky[21], with different physical construction, material, and frequency characteristics. Their sensor has 20 mm of soft foam rubber filled between the hard plastic core and the rubber skin. The 5 mm in diameter and 6 mm high accelerometer is mounted on the inner surface of the skin. Their skin acceleration sensor is a quartz crystal, built for slip and texture detection, hence is responsive to a higher frequency components (up to approximately 1000 Hz) than the sensors described in this paper. Howe *et. al.* used the skin acceleration sensors, in addition to force torque sensors, to analyse sensory phenomena during grasp and load/unload processes[37]. The acceleration sensors were used to indicate phase changes during the process. Our sensor can be used for similar purposes and yet could provide more robust and noise-less information since the low frequency band of the signal used by it is focused on where less noise can interfere with the signal.

The tensor cells[38] are an interesting use of PVDF material to construct sensors. The transducer is embedded in a compliant material (which may limit the sensitivity of the transducer by absorbing some force), which is different from the sensor developed that is mounted on the skin. Interpretation of the signal from the six transducers (PVDF films) fixed to the surfaces of the cube is required in order to figure out the force direction.

Force sensitive resistors are another good choice for contact force sensing, as Borovac *et al.* demonstrated[39]. Their sensor can be used for such tasks as peg-in-hole. They used soft sensor covers which introduce significant passive compliance during manipulation, whereas the sensor developed here is less compliant in order to prevent excessive positional error. Because the sensors using force sensitive resistors measure absolute force, minor changes in contact force are not well distinguished when significant gripping force is applied. However, the sensor developed here is less sensitive to the gripping force, since it only focuses on the change in deformation.

There are possible future extensions, such as:

- Profile understanding: Based on the characteristics of the force pattern provided by the sensors, investigation into profile understanding engines is desirable.
- Seeking compliant materials for the skin: This shares with other tactile sensor research on the investigation of compliant materials.
- Active application of vibration[8] would help our sensor to overcome the limitation of not being able to sense constant force.

---

[7] See Section 2.2, for the description of extrinsic and intrinsic tactile sensors.

[8] Lee and Asada introduced sinusoidal vibration to robot motions in order to obtain rich and robust information from a force sensor under significant uncertainty[40].

Study of the problems of soft materials for fingers (*e.g.*[36]) is essential in order to provide a fundamental basis of tactile sensor implementation. Study of the utility of information from impacts (*e.g.*[25,26]) is also essential, particularly when there is compliant material introduced in the contact (*e.g.*[41,42]).

We claim that our work produced an economic tactile sensors and suggest a novel application, *i.e.* exploiting dynamic sensing. Dynamic sensing is here suggested to be a topic that require more attention in designing an autonomous system in dynamic environment such as ubiquitous computing environment. Motion must be considered to be another sensing modality since it could help sensors do more work. This could propose another perspective in which interactive media is understood. Use of motions as sensing modality which helps intrinsic sensing would need more study in particular in philosophical terms.

7. REFERENCES

[1] Peter K. Allen, *Robotic Object Recognition Using Vision and Touch*, MIT Press, 1992.

[2] J. Aloimonos and A. Bandyopadhyay, "Active vision", *Proceedings of the* 1st *International Conference on Computer Vision*, pp. 35-54, 1987.

[3] David Marr, *Vision*. W. H. Freeman & company, 1982.

[4] G. Beni, S. Hackwood, L.A. Hornak, and J.L. Jackel, "newblock Dynamic sensing for robots: an analysis and implementation", *Robotics Research*, vol.2 pp51-61, 1983.

[5] William D. Hillis, "Active touch sensing", *A.I. Memo* vol. 629, MIT, April 1981.

[6] H. Akbarally and L. Kleeman, "A sonar sensor for accurate 3D target localization and classification", *Proceedings of IEEE International Conference on Robotics and Automation, pp.*3003 - 3008, 1995.

[7] J.S. Albus, *Brains, Behavior, and Robotics,* Byte Books, McGraw Hill, 1981.

[8] Bruce Bridgeman, *The Biology of Behavior and Mind*. John Wiley & Sons, Inc., 1988.

[9] Letty Moss-Salentijn, "The human tactile systems", In H.R. Nicholls, editor, *Advanced Tactile Sensign for Robotics*, chapter 7, pp. 123-150. World Scientific, 1992.

[10] R. Andrew Russell, *Robot Tactile Sensing,* Prentice Hall, 1990.

[11] Howard R. Nicholls, "Introduction to tactile sensing", In Howard R. Nicholls, editor, *Advanced Tactile Sensing for Robotics,* chapter 1, pp. 1-11. World Scientific, 1992.

[12] L.D. Harmon, "Tactile sensing for robots", In G. Beni and S. Hackwood, editors, *Recent Advances in Robotics*, chapter 10, pp. 389-424. John Wiley Sons, Inc., 1992.

[13] Paolo Dario and Danilo De Rossi, "Tactile sensors and the gripping challenge", *IEEE Spectrum,* 8:46-51, August 1985.

[14] Paolo Dario and Giorgio Buttazzo, "An anthropomorphic robot finger for investigating artificial tactile perception", *The International Journal of Robotics Research*, 6(3):25-48, 1987.

[15] Howard R. Nicholls, "Tactile sensor designs", In Howard R. Nicholls, editor, *Advanced Tactile Sensing for Robotics*, chapter 2, pp. 13-48. World Scientific, 1992.

[16] R.D. Howe and M.R. Cutkosky, "Touch sensing for robotic manipulation and recognition", In O. Khatib, J. Craig, and T. Lozano-Pérez, editors, *The Robotics Review 2,* pp. 57-112. The MIT Press, 1992.

[17] J.K. Salisbury, "Interpretation of contact geometries from force measurement", In *Proceedings of the* 1st *International Symposium on Robotics Research*, pp. 566-577. MIT Press, 1984.

[18] A. Bicchi and P. Dario, "Intrinsic tactile sensing for artificial hands", In *Proceedings of the* 4th *International Symposium on Robotics Research*, pp. 83-90, Santa Cruz, Au-

gust 1987. MIT Press.

[19] Tokuji Okada and Ulrich Rembold, "A tactile sensor based on a suspension-shell mechanism for dexterous fingers", *IEEE Transactions on Robotics and Automation*, 8(1): 126-131, 1992.

[20] J.S. Son, E.A. Monteverde and R.D. Howe, "A tactile sensor for localizing transient events in manipulation", *Proceedings of IEEE International Conference on Robotics and Automation*, pp. 471-476, 1994.

[21] R.D. Howe and M.R. Cutkosky, "Sensing skin acceleration for slip and texture perception", *Proceedings of IEEE International Conference on Robotics and Automation*, pp. 145-150, 1989.

[22] B. Eberman and J.K. Salisbury Jr., "Application of change detection to dynamic contact sensing", *The International Journal of Robotics Research*, 13(5):369-394, 1994.

[23] Peter M. Will and David D. Grossman, "An experimental system for computer controlled mechanical assembly", *IEEE Transactions on Computers*, c-24(9):879-888, September 1975.

[24] H.R. Nicholls and M.H. Lee, "A survey of robot tactile sensing technology", *The International Journal of Robotics Research*, 8(3): 3-30, 1989.

[25] Yu Wang and Matthew Mason, "Modelling impact dynamics for robotic operation", *Proceedings of IEEE International Conference on Robotics*, pp. 78-685, 1987.

[26] Bertil Söderquist and Åke Wernersson, "Information for assembly from impacts", *Proceedings of IEEE International Conference on Robotics*, pp. 2012-2017, 1992.

[27] P. Dario, C. Domenici, R. Bardelli, D.~De Rossi, and P.C. Pinotti, "Piezoelectric polymers: New sensor materials for robotic applications", *Proceedings of* 13th *Symposium on Industrial Robotics*, pp. 14.34-14.49, 1983.

[28] Stephen McClelland, "An overview of sensor development", *Sensor Review*, vol.9 no.2 pp. 105-109, 1989.

[29] "Piezo Film Sensors" - Europe, Merrion Avenue, Stanmore, Middlesex, HA7 4RS, U.K. Technical Notes, 1987.

[30] J.S. Son, E.A. Monteverde, and R.D. Howe, "A tactile sensor for localizing transient events in manipulation", *Proceedings of IEEE International Conference on Robotics and Automation*, pp. 471-476, 1994.

[31] H. Shinoda and S. Ando, "Ultrasonic emission tactile sensor for contact localization and characterization", *Proceedings of IEEE International Conference on Robotics and Automation*, pp. 2536-2543, 1994.

[32] R.W. Patterson and G.E. Nevill Jr., "The induced vibration touch sensor - a new dynamic touch sensing concept", *Robotica*, vol.4 pp. 27-31, 1986.

[33] A.R. Grahn and L. Astle, "Robotic ultrasonic force sensor arrays", *Proceedings of* 14th *Symposium on Industrial Robotics*, pp. 21.1-21.18, 1984.

[34] Taehee Kim, "The development of vibration sensors as event signature sensors in assembly", *DAI Technical Paper* 14, Department of Artificial Intelligence, University of Edinburgh, 1992.

[35] Ronald S. Fearing, "Planner elasticity for tactile sensing", Howard R. Nicholls, editor, *Advanced Tactile Sensing for Robotics*, chapter 4, pp. 75-93. World Scientific, 1992.

[36] K.B. Shimoga and A.A. Goldenberg, "Soft materials for robotic fingers", *Proceedings of IEEE International Conference on Robotics and Automation*, pp. 1300-1305, 1992.

[37] R.D. Howe, N. Popp, P. Akella, I. Kao, and M.R. Cutkosky, "Grasping, manipulation, and control with tactile sensing", *Proceedings of IEEE International Conference on Robotics and Automation*, pp. 1258-1263, 1990.

[38] H. Shinoda, N. Morimoto, and S. Ando, "Tac-

tile sensing using tensor cell", *Proceedings of IEEE International Conference on Robotics and Automation*, pp. 825-830, 1995.

[39] B. Borovac, M. Nikolić, and L Nagy, "A new type of force sensor for contact tasks", *Proceedings of IEEE International Conference on Robotics and Automation*, pp. 1791-1796, 1994.

[40] Sooyong Lee and Haruhiko Asada, "Assembly of parts with irregular surfaces using active force sensing", *Proceedings of IEEE International Conference on Robotics and Automation*, pp. 2639-2644, 1994.

[41] A. Bicchi, J.K. Salisbury, and D.L. Brock, "Contact sensing from force measurement", *A.I. Memo* 1262, MIT, October 1990.

[42] R.S. Fearing and J.M. Hollerbach, "Basic solid mechanics for tactile sensing", *The International Journal of Robotics Research*, 4(3): 40-54, 1985.

Taehee Kim

1990 B.Sc. Ajou University
1996 Ph.D. in A.I., University of Edinburgh
1997~1999 Senior researcher, KORDIC (KISTI)
1999~Co-Professor, Multimedia Eng., Youngsan University
Research Field : Intelligent Robot, Ubiquitous Computing, Science and Art

Mikeung Park

1981 B.Sc. Busan National University
1992 Ph.D Purdue University (Mathematics)
1992~1995 Adjunct Assistant Professor, University of Missouri, St. Louis
1995~1996 Visiting scholar, University of Warwick
1997. 3~1998. 2 Post doctor, ETRI
1998. 3~Associate Professor, School of Computer Information and Engineering, Youngsan University
Research area : Computer Graphics, Ubiquitous Computing, Digital Contents