Ultrasonic Emission Tactile Sensor for Contact Localization and Characterization

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Abstract

This paper describes our primary study for a new type of tactile sensing devices which are based on instantaneous localization of acoustic emissions caused necessarily by touch and/or contact movement. We assume a sensor structure which consists of a flexible spherical fingertip-like body and a quadruple PVDF sound sensing matrix placed at a center of the body. The PVDF matrix works as a wide-band acoustic emission (AE) transducers which is capable to detect an arrival direction of a wave packet. Therefore it can resolve and localize multiple ultrasonic emissions at a sensor surface caused by a touch and slip. In order to realize this type of tactile sensor, the most important questions will be: 1) What kind of ultrasonic emission do appear by touch, and is it detectable ? 2) How can the multiple wave packets be resolved and localized ? To the first question, we show a theory of wave generation at collision, and examined it and the detectability by several experiments. For the second question, we are applying our newly developed sound localization algorithm for an auditory sensor. By assuming the use of this algorithm, and from several experiments under various contact and slip conditions, we show the following features and tactile information will become obtainable: 1) quick localization of touch and detouch, 2) sensation of texture under movement, 3) quick detection of precursor of slip.

1 Introduction

In tactile sensation, most of essential information arises in movement, i.e. detection of touch, slip sensing and its precursor, texture sensation while sliding motion, and so on. The design of a tactile sensor oriented to such dynamic information differs from static approaches such as 2-D pressure sensor arrays, optical contact imagers, and so on[1]. This is because 1) response of such a dynamic sensor is far more quicker [2], 2) it can make use of a contact movement as some kind of spatial to temporal conversion operation, therefore 3) reduction of the complexity of the sensor fabrication will become possible[3, 4]. This sort of approaches are also seen in some recently developed sensors in which various tactile information is obtained using elastomer as an information processing medium[6].

Acoustic emission[10] which arises necessarily by touch and slip is first introduced by Dornfeld for tactile sensation[7]. He clarified the importance of it for detecting onset of slip and motion.

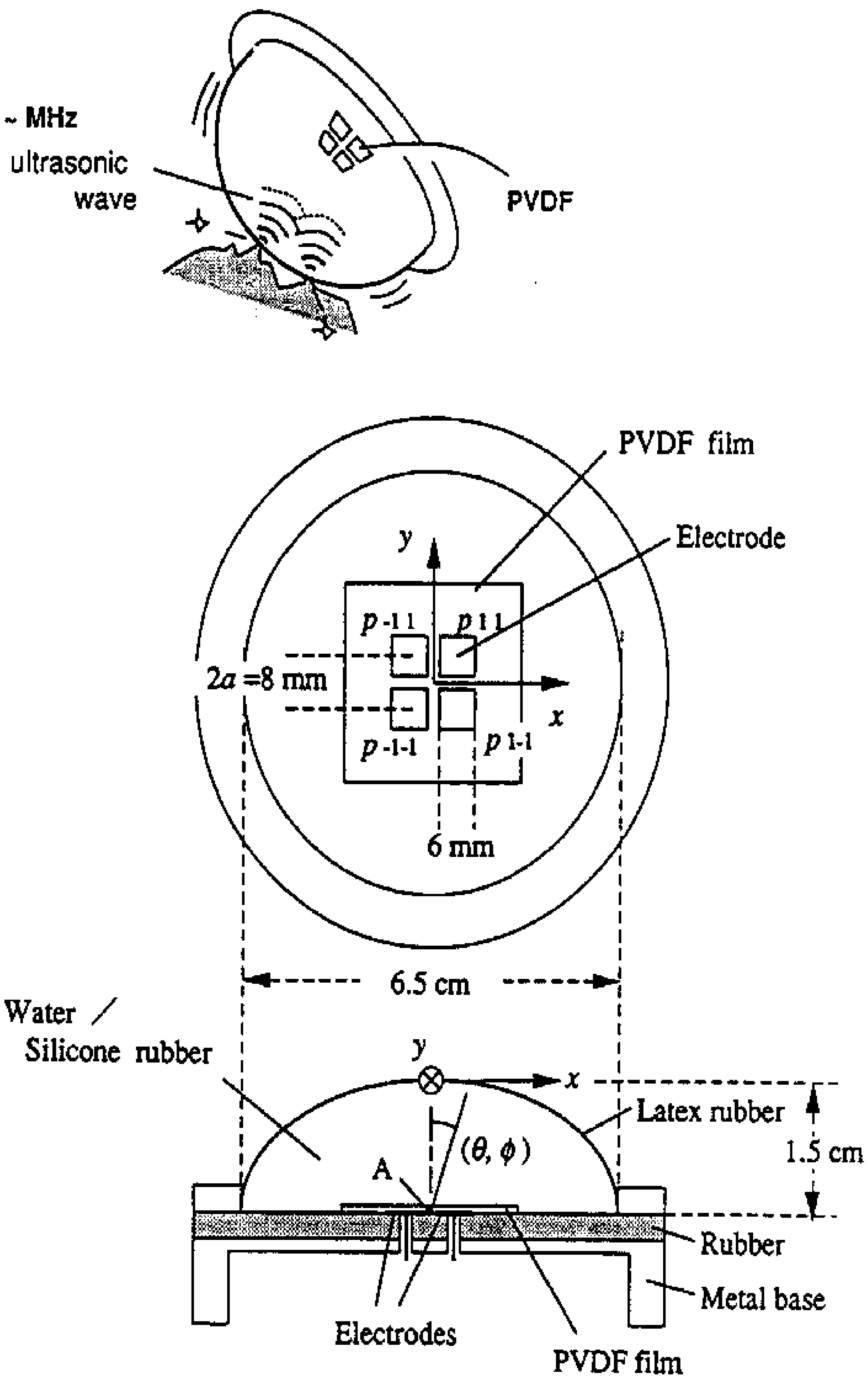

Fig.1 Structure of the sensor.

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But the another importance of it will be precise position information conveyed by the wide band signal of the ultrasonic emission.

In our new sensor structure shown in Fig.1, the quadruple PVDF matrix (four closely placed rectangular PVDF films) are intended to localize emission points by detecting incident directions of wide-band (wavelength smaller than a radius of the sensor sphere) ultrasonic waves. This structure will also enable us to gather overall contact information very quickly at only one position. Since it resides in the center, it will be the safest from damages.

To realize this, we must answer to two key questions, i.e. 1) What kind of ultrasonic emission do appear by touch, and is it really usable for our purpose? 2) Is it possible to resolve and localize the multiple wave packets? And how signal processing is suitable for our tactile sensing?

The goal of this paper is to answer these fundamental questions. For the first one, we show a theoretical analysis of wave generation by collision, and examined it and the practical detectability by several experiments. For the second question, we are applying our newly developed sound localization algorithm for an auditory sensor. By assuming the use of this algorithm, and from several experiments under various contact and slip conditions, we show the following tactile information will become obtainable: 1) quick localization of touch and detouch, 2) sensation of texture under movement, 3) quick detection of precursor of slip[5].

2 Basic structure and key problems

The sensor structure is shown in Fig.1. A quadruple PVDF matrix are located at the center of a round soft fingertip. Denoting directions of touches and separations as $(\theta_i, \phi_i), (i = 1, \cdots, N)$ with respect to the center of the sphere where the PVDF matrix is placed, and supposing that waveforms of each emitted ultrasound observed there is $f_i(t)$, we can easily describe the outputs of each sensor as

$$p_{\xi\eta}(t) = \sum_i f_i(t + \xi\tau_{xi} + \eta\tau_{yi}) \quad (\xi, \eta = \pm 1) \tag{1}$$

Here, the direction information of the touching/separating points is involved in the temporal disparities

$$\tau_{xi} = \frac{a}{c}\sin\theta_i\cos\phi_i \tag{2}$$

$$\tau_{yi} = \frac{a}{c}\sin\theta_i\sin\phi_i \tag{3}$$

among four sensor outputs where c is the velocity of a longitudinal wave.

In order to recover each directional information, the necessary conditions will be as follows:

1. A wavelength of the ultrasound must be much smaller than the sensor radius so that it propagates as a wave. This requires

$$\lambda_{MAX} \equiv \frac{2\pi c}{\omega_{MIN}} \ll R \tag{4}$$

   where ω_{MIN} is the lowest frequency of the ultrasounds, λ_{MAX} is its wavelength, and R is a radius of the sensor sphere. If the sensor radius is 1cm, for example, $\omega_{MIN}/2\pi$ must be higher than 100kHz.

2. A temporal duration of the wave packets arising from multiple contacts must be smaller than the interval of each packet so that they can be separated as a single response. This requires

$$T_A \gg T_D \gg \frac{2\pi}{\omega_{MAX}} \tag{5}$$

   where ω_{MAX} is the highest frequency of the ultrasounds, T_D is a duration time of the wave packet, and T_A is an average interval of packets. If the bandwidth ω_{MAX} is 1MHz for example, T_D is a few micro second minimum, so T_A must be much longer than it, although this limit of T_A can be reduced to be comparable to T_D by using gradient based algorithm[8], as shown in the section of algorithm.

In the next section, we show theoretically that such a high frequency wideband ultrasound can be emitted by a touch, and its energy is strong enough to be detectable by PVDF through soft sensor body.

3 Acoustic Emission by Touch

In this section, we describe theoretically how an ultrasonic wave is emitted at the moment of touch. This analysis gives important results also to the second question as well as the first one. Now let an rigid object collide with a soft sensor, because a fundamental mechanism of acoustic emission in tactile sensing is seen in it. Since we are interested in only a small temporal and spatial neighbours around a collision point, we derive how ultra-sound is observed when a rigid convex quadratic surface collides with a flexible flat surface.

Suppose that a homogeneous rigid convex surface expressed as

$$z = a(x^2 + y^2)/2 \tag{6}$$

is contacting the flat sensor surface with initial velocity v_0 just at the moment $t = 0$, and that the displacement distribution by contact is expressed as

$$u(\mathbf{r},t) = \begin{cases} u_0(1-e^{-\alpha t}) - \frac{a}{2}|\mathbf{r}|^2 & (\text{for } t \geq t_0 \text{ and } |\mathbf{r}| < \sqrt{\frac{2u_0}{a}}) \\ 0 & (\text{otherwise}) \end{cases} \quad (7)$$

where α is time constant, $v_0 = \alpha u_0$, and $t_0 = -(1/\alpha)\log\{1 - a|\mathbf{r}|^2/(2u_0)\}$.

Because the temporal spectrum $P(\omega)$ of acoustic pressure $p(t)$ at the point A in Fig.2 caused by a surface displacement distribution u is given as

$$P(\omega) = -\frac{\omega^2\rho}{2\pi}\int_{\text{surface}} U(\mathbf{r},\omega)\frac{e^{(j\omega l/c)}}{l}dS \quad (8)$$

($U(\mathbf{r},\omega)$: the Fourier transform of $u(\mathbf{r},t)$, l: the distance between A and $\mathbf{r}$, and ρ: the density of elastic medium), the observed pressure under this contact model is expressed as

$$P(\omega) = \frac{\rho {v_0}^2 \exp(j\omega l/c)}{al}\left(\frac{2}{j\omega+2\alpha} - \frac{1}{j\omega+\alpha}\right) \quad (9)$$

$$p(t) = \begin{cases} \frac{\rho {v_0}^2}{al}(2e^{-2\alpha(t-l/c)} - e^{-\alpha(t-l/c)}) & (\text{ for } t > l/c) \\ 0 & (\text{otherwise}) \end{cases} \quad (10)$$

In this analysis, we assumed that l in the term $\exp(j\omega l/c)/l$ in Eq.(8) can be regarded as constant and absorption of ultra-sound was neglected. The attenuation through the body will be discussed in the section of experiments.

These equations mean that even if the touching object is smooth and convex, a discontinuity appears at the moment of contact, then effective amplitude of ultrasound can always be detected near the moment even after any high-pass filtering.

Here, we substitute typical value for each variable such as $v_0 = 30$[cm/s], $\rho = 10^3$[kg/m^3], $l = 10$[mm], $a = 1$[1/mm], then the high-pass filtered pressure $\hat{p}(t)$ just near $t = (l/c)+$, is estimated as

$$\hat{p}(\frac{l}{c}+) = \frac{\rho v_0^2}{al} = 9 \quad [\text{Pa}] \quad (11)$$

Another important property is that the duration T of $\hat{p}(t)$ is determined by the cut-off frequency $\omega_0 (\gg \alpha)$ of high-pass filtering as $T \approx 1/\omega_0$. Therefore if we observe a high-pass filtered signal with cut-off frequency $\omega/2\pi = 100$kHz, the duration for one collision is as short as 10μsec.

4 Signal processing

This section deals with the second problem about overlaps between consecutive arrivals of ultrasound packets.

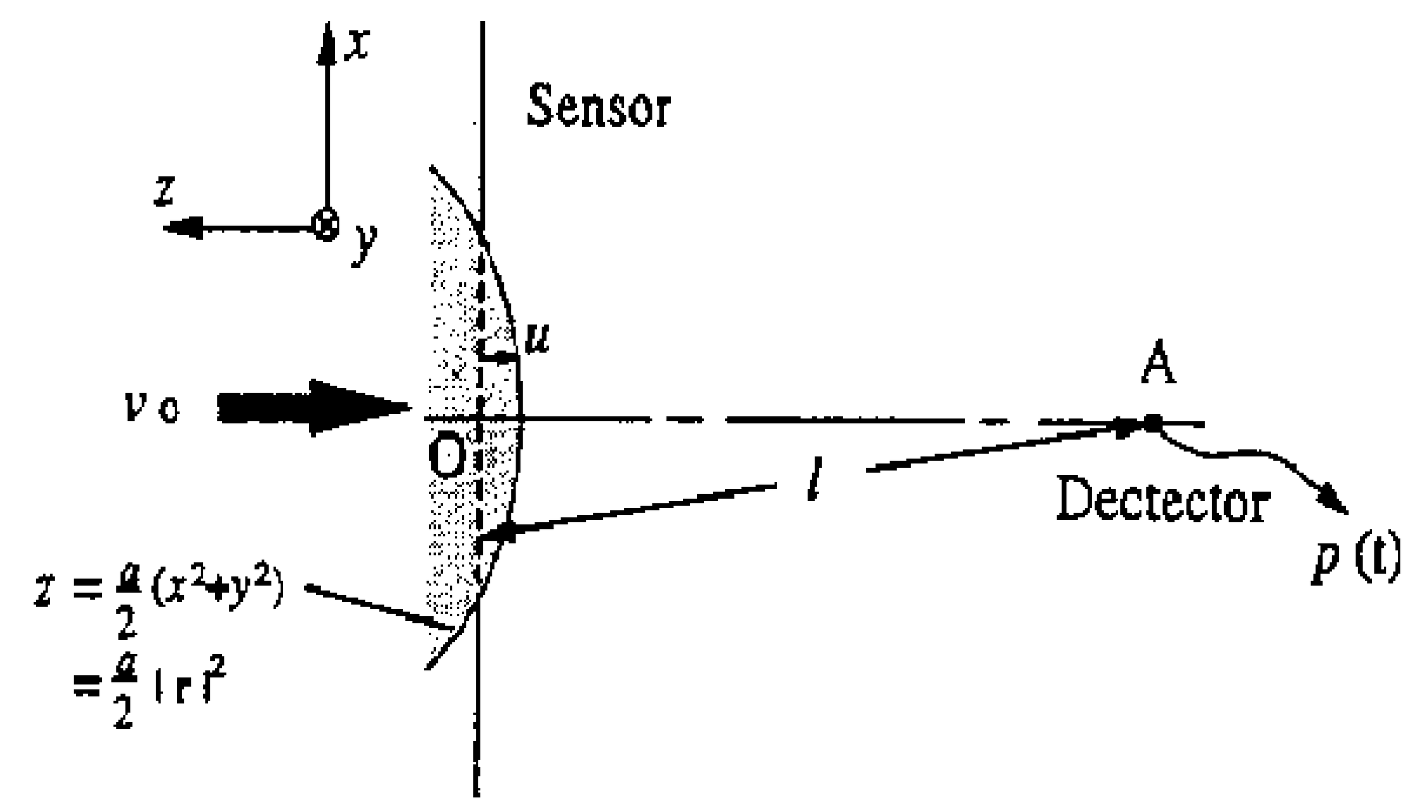

Fig.2 Smooth and convex surface colliding with the sensor.

The above analysis has shown that the emission time is very short ($\approx$ 10μsec when 100kHz high-pass filtering). So, if an algorithm permits some degrees of overlaps, the chance of harmful interference effects will become negligible, and almost all of the detector outputs caused by a single or dual touches can become resolvable.(See Fig.3) This is also the case when the sensor surface contacts dynamically with an object, because contacting points can be numerous but any of them continue touching and separating randomly instead of keeping stationary contacts.

For this purpose, we expect that a gradient based sound localization algorithm[8] can be successfully applied, which has been already used for our sensory robot head. The simple circuit can localize the emission source packet by packet from the short time data of four time-shifted detector outputs, and accumulate the results in real time operation. Besides when a serious overlap arises unfortunately, it detects the overlapping and does not give a result of localization.

We have not complete the sensor combined with this circuit yet. In this paper, we examine how good waveforms of signal are seen before entering this circuit. If we can observe a sequence of solitary packets when touch and each of the four PVDF outputs are a properly time-shifted signal to one another for any packet, the circuit will be successfully combined with the sensor device.

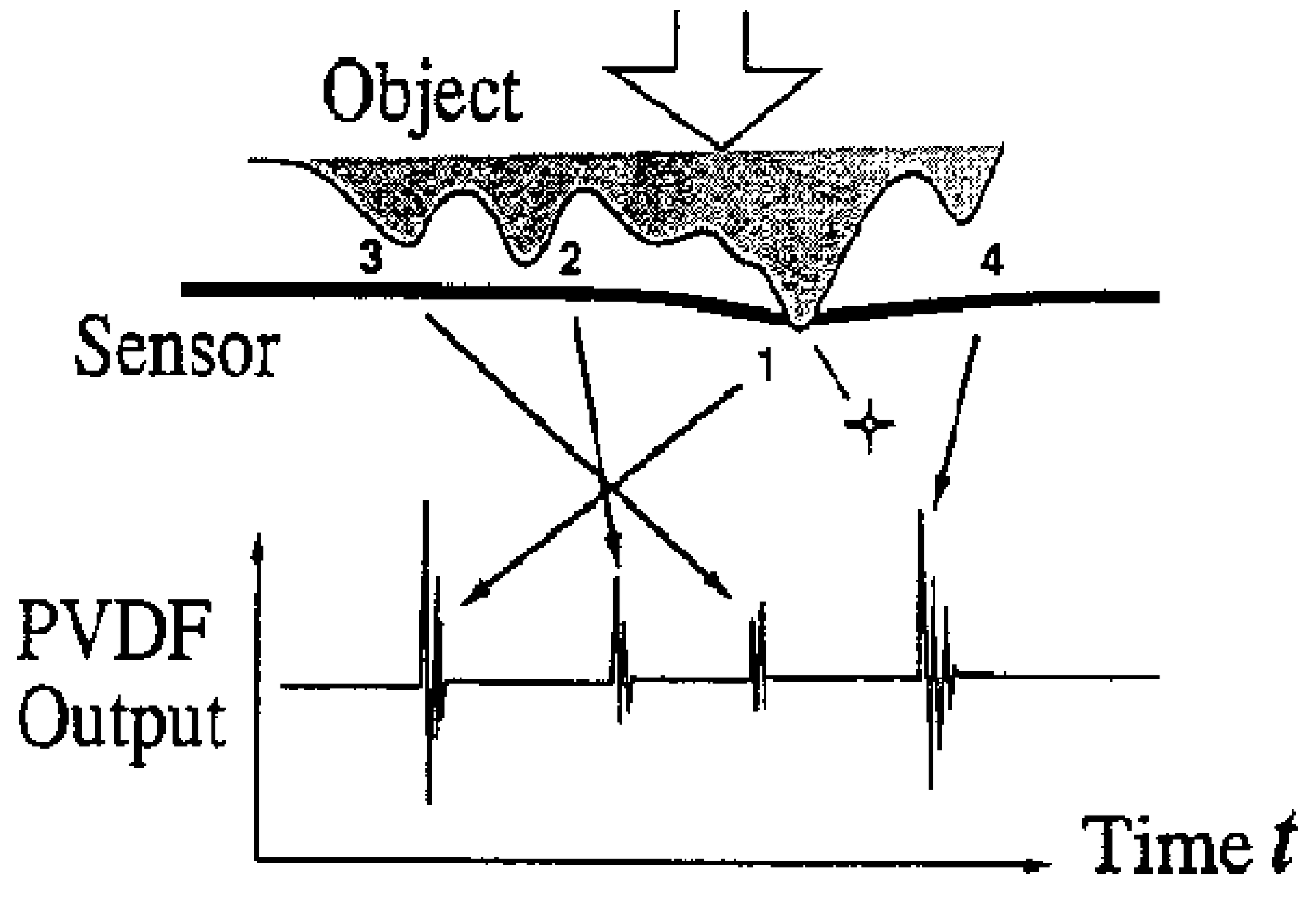

Fig.3 Touch with many points and the signal.

5 Experiments

5.1 Structure of the sensor

The structure of the experimental sensor is shown in Fig.1. The PVDF matrix is made of a film by forming four electrodes on one side by an etching process. Another side is wired directly to an electrical ground (metal base). The PVDF film was attached with electrode side down on the metal base which was covered with thin ultrasound absorbing rubber. By this structure, we can obtain a good electrical shield. The absorbing rubber layer can get rid of not only acoustic noises from the mount like a robot hand. but also the reflection behind the PVDF.

A possible choice of material of the sensor body is restricted. Many kinds of soft rubber-like material suitable for a tactile sensor are rather absorber of ultrasound. In the paper, we examined first the use of thin rubber skin filled with water because the attenuation of ultrasonic is negligible in it. Another candidate which is shown in the final experiments is made of special silicone rubber for an ultrasonic lens of medical use (Shi-Etsu Chemical Corp).

5.2 Detectability: spectral contents of ultrasounds

Experimental set-up using water - rubber skin model is shown in Fig.5(a). A round pin with 3.0mm diameter attached to a plastic plate was used as an impulsive contact generator to the sensor surface. The speed of pin just before the collision is 60 cm/s. Fig.5 (b) and (c) show waveforms of PVDF output at A_1 and A_2 respectively. These shows that a touch causes ultrasonic wave within very short period after the contact moment. Fig.6 shows spectra of the sensor output. A spectrum as seen in upper figure (a) agreeing with the theoretical analysis is most frequently observed. A spectrum like lower figure (b) with more intensive high frequency component was seen, although it was very rare, when a flat surface touches.

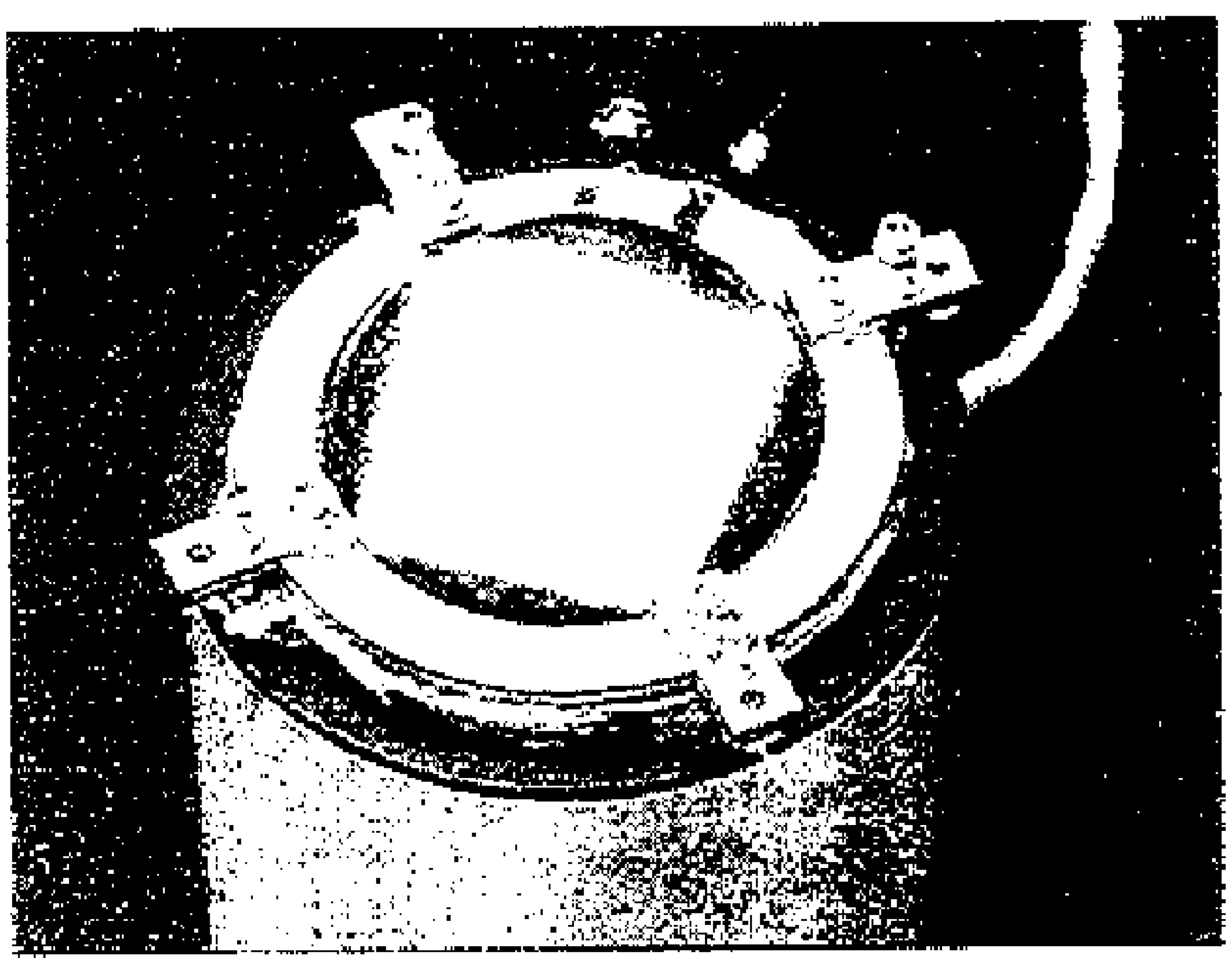

Fig.4 Photograph of the sensor. (Water - rubber skin model.)

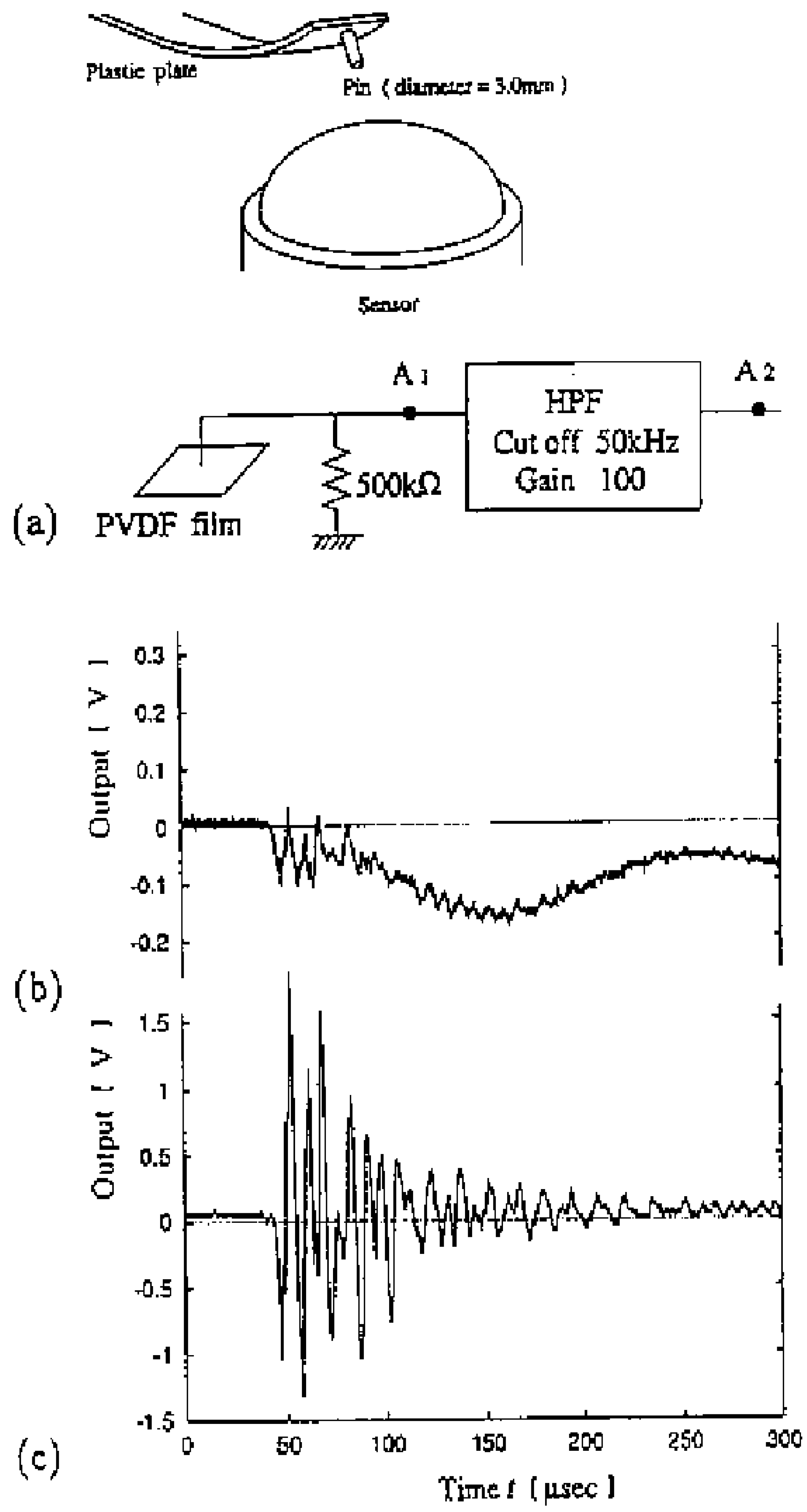

Fig.5 PVDF outputs caused by a touch on the sensor. (a): Experimental setup. (b): Waveform at A_1. (c): Wave form at A_2 after high-pass filtering.

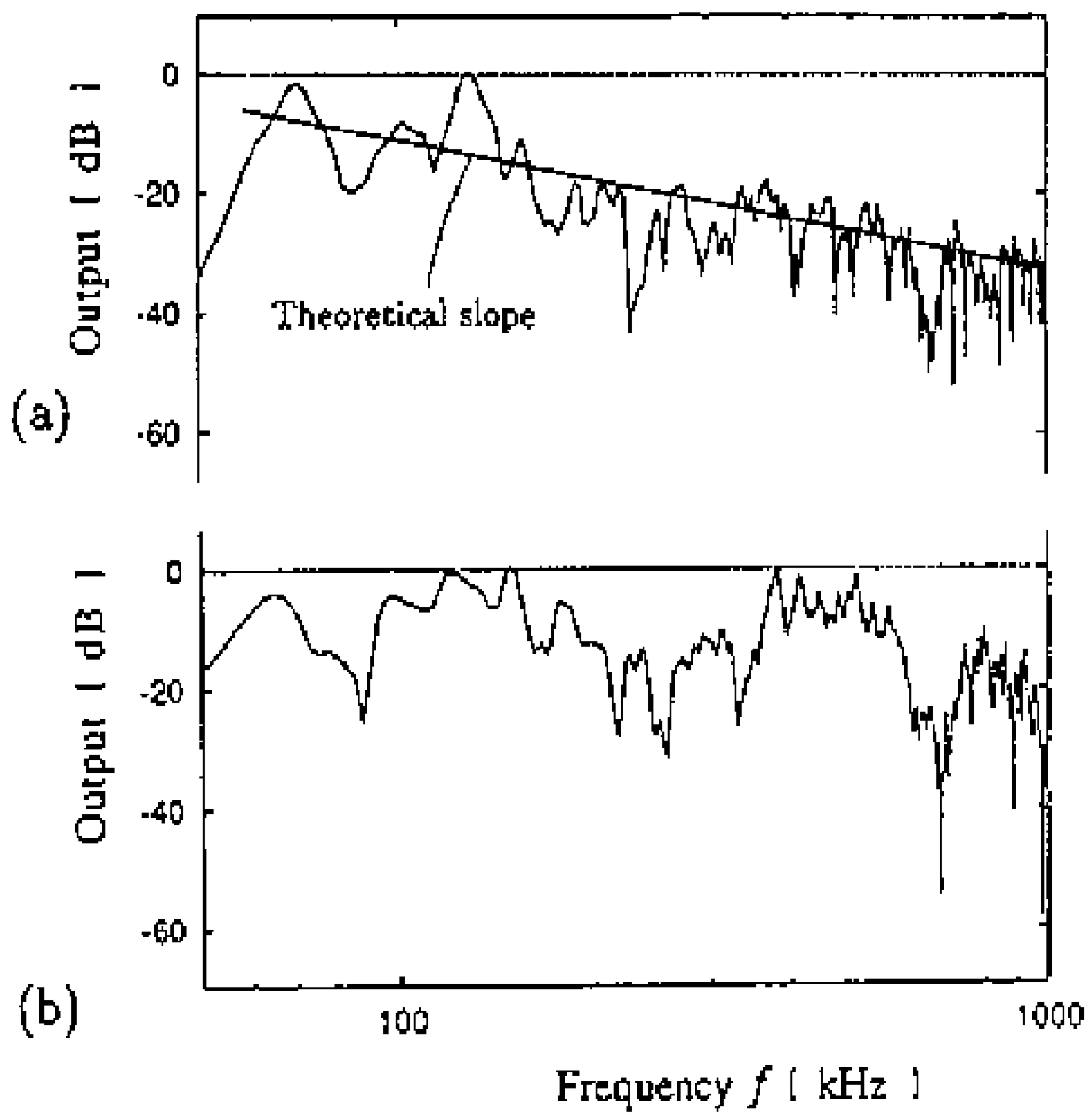

Fig.6 Spectra of PVDF outputs by touches.

5.3 Position sensitivity: Contact position vs. temporal shift

In this subsection, we will observe the signal difference between PVDF elements, varying the position of contact. Fig.7(a) and (b) show results when contact points were $(x, y) = (0,0)$[mm] and $(2.5,0)$[mm] respectively. (The $x - y$ coordinates are shown in Fig.1) In Fig.7(a), the waveforms of $p_{11}+p_{1-1}$ and $p_{-11}+p_{-1-1}$ concur well with each other, but in Fig.7(b), there appears a clear temporal shift between $p_{11}+p_{1-1}$ and $p_{-11}+p_{-1-1}$. These results mean that the waveform of each unit of matrix is well modeled by Eq.(1) before the reflected waves arrive. Although the waveforms shows some disorder after the reflection arrival, no serious problems will be caused if we use our localization algorithm[8], because it localize the contact point choosing only well-ordered periods of data automatically.

Fig.7(c) is when $(x, y)=(5,0)$[mm]. To clarify quantitative relation between the contact position and temporal shift, we will compare in Fig.7(d) the real contact positions with the calculated positions by Eq.(2) and (3) using the temporal data within 30 μsec after the collision moments. These results prove that a precise contact position is obtainable from the signal of our sensor.

5.4 Resolvability: Touch with plural points

What signal will be detected when an object touches the sensor with plural points? Fig.8(a) shows the total output of four elements when a plate with three pins touches on the sensor. In this waveform, three impulses are recognized separately. Although we selected a special case the three pulses are seen within a very short period of 2 msec for illustration, but in most cases each packet was far more separated from one another. Fig.8(b),(c) and (d) shows each packet with magnified time scale. Also in these packets, a signal of an element of the matrix is a delayed one of that of another. Fig.8(e) illustrates real contact positions vs. calculated positions from the three packets in the same way described in above subsection. These show good agreements of the estimated positions with actual contact points.

5.5 Ultrasonic emission by slip

Up to now, we discussed the ultrasonic emission by touch. But it is known that the emission is generated in slip and its onset [7]. In this subsection, we will show what kind of emission is observed when a flat surface slipping on the sensor. When the condition between the sensor and an object was relatively adhesive[9](the surface of the sensor and an object were clean with no oil or dust), large emissions was observed.

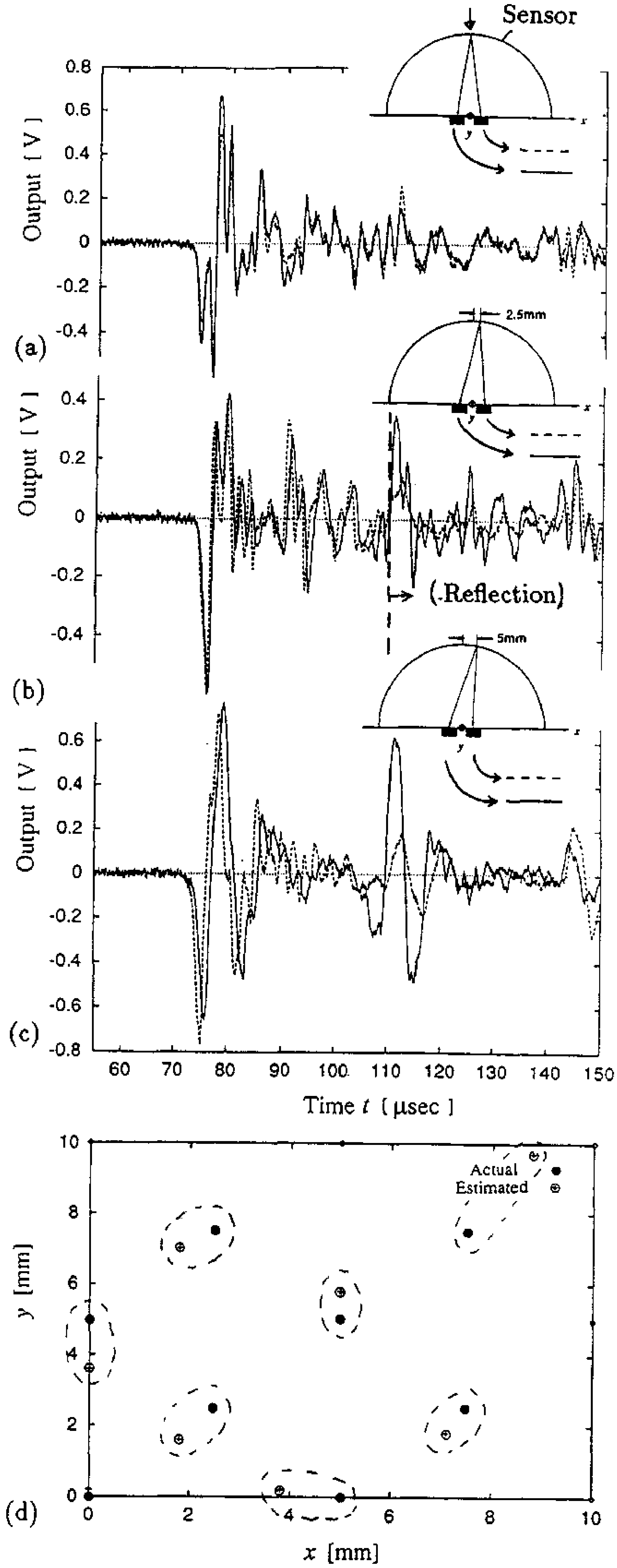

Fig.7 Experimental results. (a): Waveforms caused by a touch at $(x, y) = (0,0)$[mm], (b): at (2.5,0)[mm] and (c): at (5,0)[mm]. (d): Determination of contact positions from the sensor outputs.

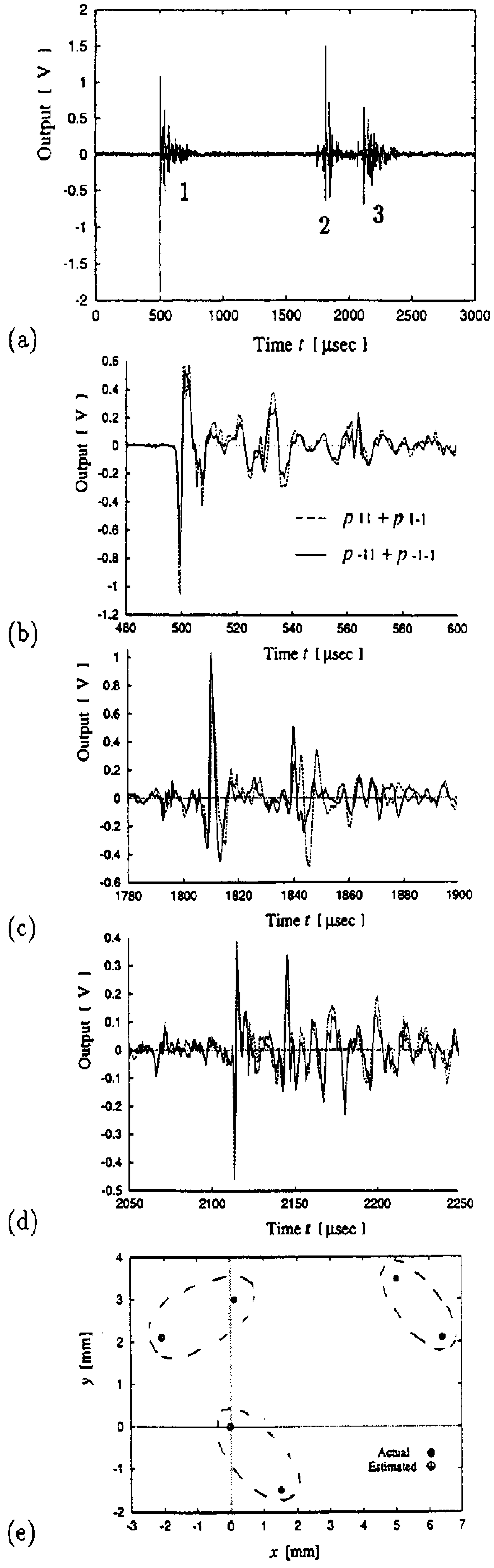

Fig.8 Experimental results of a touch with three points. (a): Waveform including three packets. (b): The first packet. (c): The second packet. (d): The third packet. (e): Determination of contact positions.

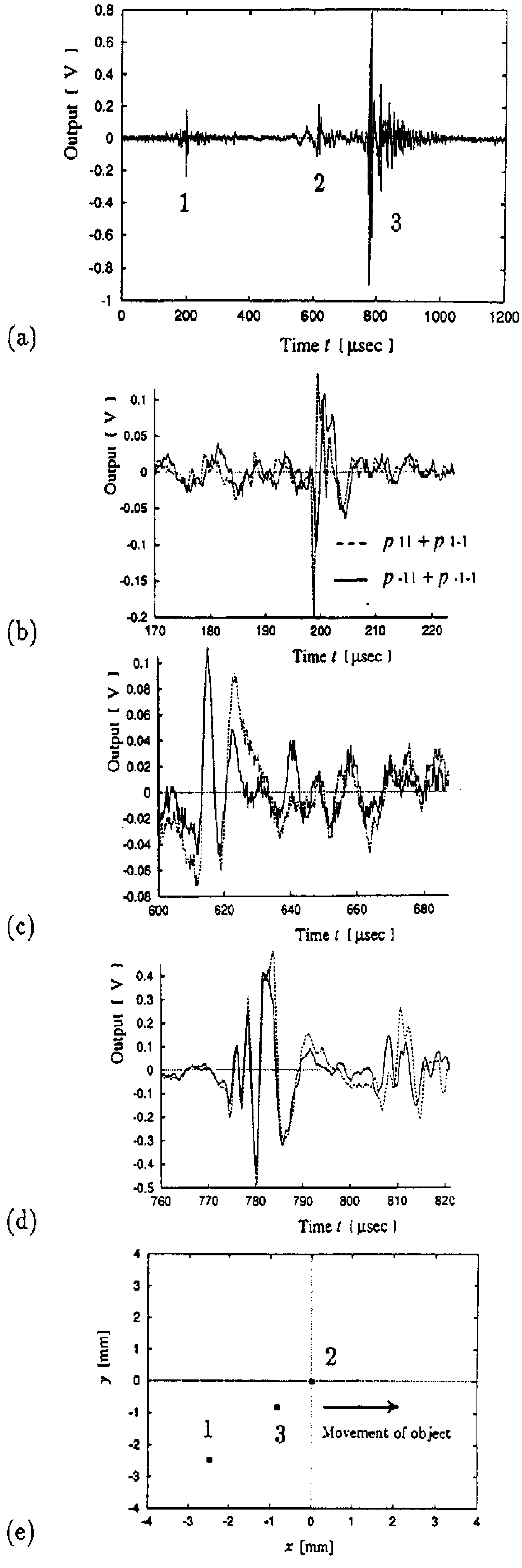

Fig.9 Experimental results of a slip detection. (a): Waveform while slipping. (b): The first packet. (c): The second packet. (d): The third packet. (e): Localization of the slips.

Fig.9(a) shows three pulse-like waves detected while a plane object slipped on the top of the surface along x axis. Note that for all the three packets, a waveform of an element of the matrix has a similar shape to that of another but have a temporal shift as shown in Fig.9(b),(c) and (d). This verifies that each packet can be considered to originate from a small area of the surface. Fig.9(e) shows the calculated positions from the packets.

5.6 The results of a silicone model

Our primary study has been carried out by a water - rubber skin model. But it is desirable that a practical sensor should be made of some solid material. Fig.10 shows the results of a silicone model in which the water is replaced with special pure silicone rubber (Shin-Etsu Chemical Corp.). This material is soft but carry ultrasound over MHz well, and the acoustic impedance of it is near to that of human body as well. Thus it is used for a medical ultrasonic lens.

The experimental setup was the same as that of the water model. The two kinds of waveforms are the PVDF outputs when the pin touches the sensor just at the points $(x,y) = (0,0)$ and $(x,y) = (-5,0)$. Effective amplitudes of signals comparable to that of the rubber skin model were observed, and proper temporal shifts are seen. Experiments have not exhausted yet, but it seems that any serious problems will not arise in silicone sensor.

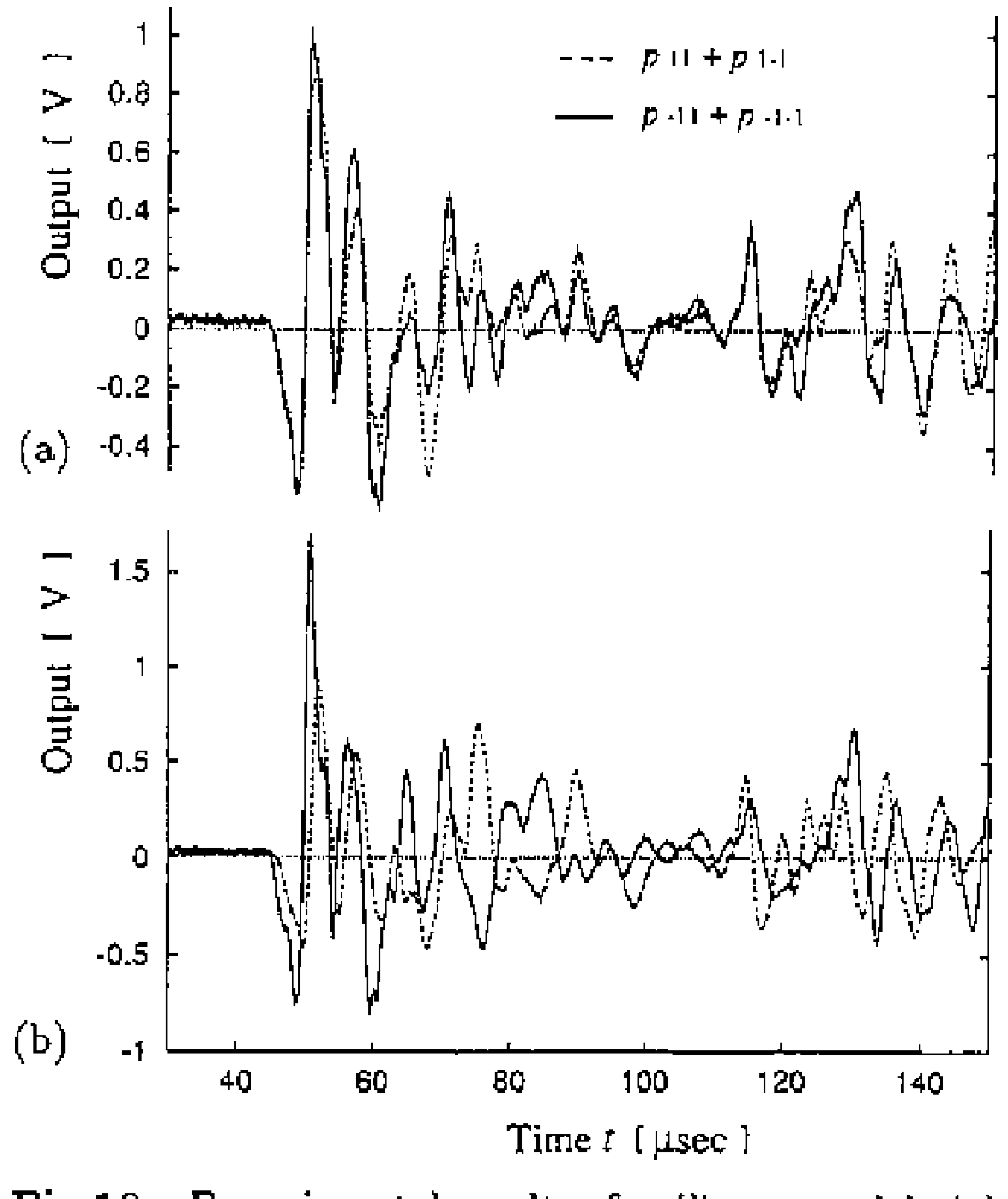

Fig.10 Experimental results of a silicone model. (a): Waveforms by a touch at $(x,y) = (0,0)$[mm], and (b): at (5,0)[mm].

6 Future work and possible applications

Based on the success of this primary research, we are planning to complete the tactile sensor combined with the emission source localization circuit in near future. The sensor will be able to sense such tactile informations as illustrated in Fig.11.

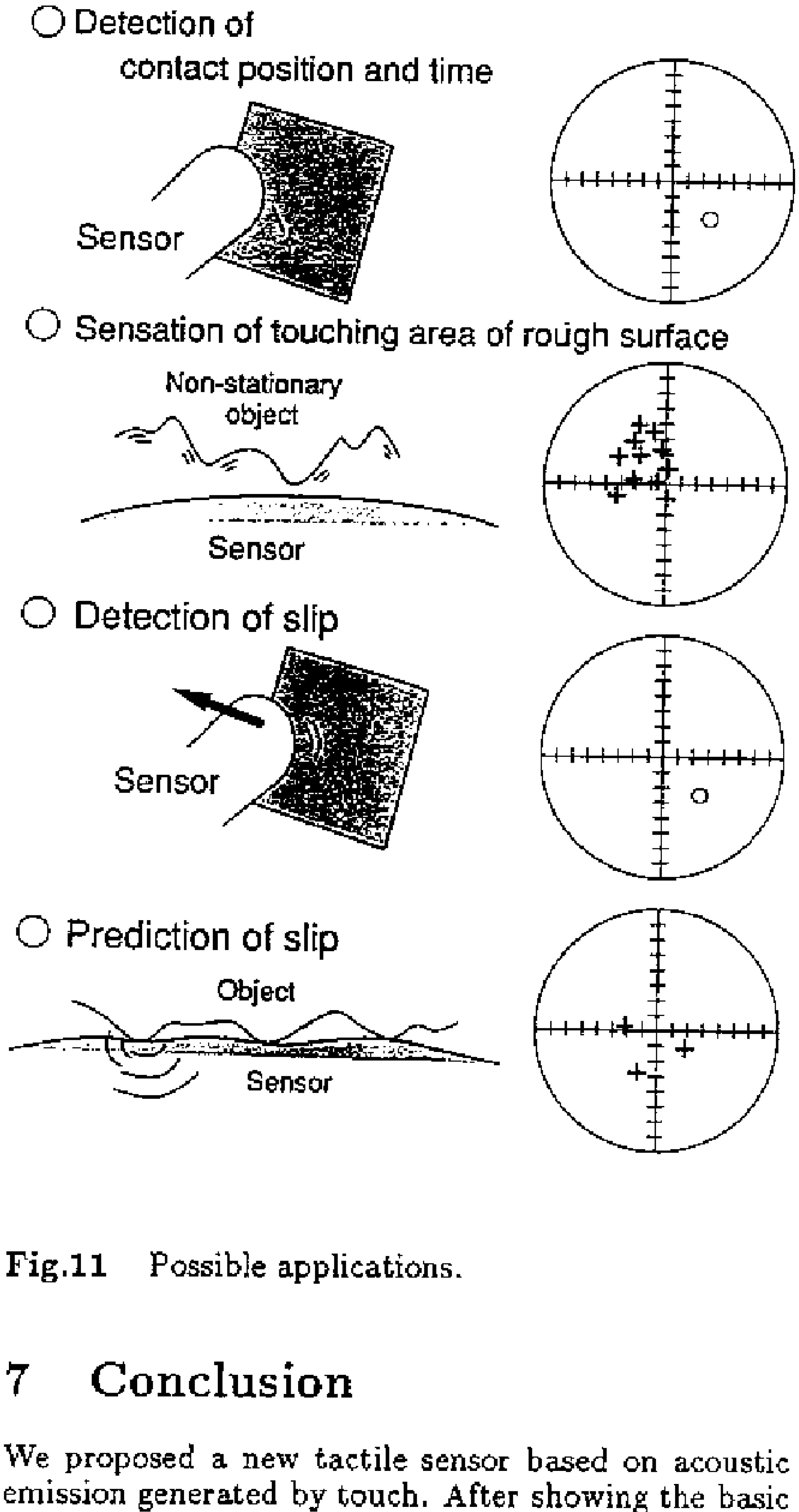

Fig.11 Possible applications.

7 Conclusion

We proposed a new tactile sensor based on acoustic emission generated by touch. After showing the basic principle of our sensor, we confirmed the key points for realizing it theoretically and experimentally that

1. High frequency ultra-sound caused by touch is practically detectable. And the observed waves keeps precise position information.

2. The duration of the emission is very short.
3. Effective amplitude of ultra-sound by slip can be observed when the contact condition is adhesive.

The experiments were carried out by both water-skin model and silicone model. Completing the sensor combined with our emission source localization circuit, such tactile information will be obtainable as 1) quick localization of touch and detouch, 2) sensation of texture under movement and 3) quick detection of precursor of slip.

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