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# Two-dimensional Scanning Tactile Display using Ultrasound Radiation Pressure

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## Abstract

In this paper, we propose a new tactile display which produces spatio-temporal stress patterns on a 2-D plane. The first prototype of the display consists of an octagonal arrangement of ultrasound linear arrays. Each array has 40 pieces of PZT(lead zirconate titanate) transducer. The 320 channel driving circuit was designed to produce 1000 frames of 2-D stress patterns per second. The 2-D stress patterns can cover 1cm by 1cm area. Simulation studies were carried out to examine the adequacy of the proposed design. It showed that the octagonal arrangement can produce a well-focused force spot to be scanned in the display area. The results were satisfactory compared to other polygonal arrangement. Several initial results on the 2-D prototype are also discussed.


**CR Categories:** I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Virtual Reality;

**Keywords:** Tactile display, Ultrasound, Radiation pressure

## 1 Introduction

One of the difficulties in designing tactile displays is to find appropriate tactile stimuli and their synthesis. Even if it is possible to stimulate different kinds of mechanoreceptors selectively with particular methods (for example, intraneural microstimulation[1], functional electrical stimulation[2]), combining these stimuli to produce realistic tactile feeling is still a difficult challenge. In order to solve this problem, first of all, we should know the relationship between tactile perceptions and actual stress fields on the skin surface by precisely controlling the stress fields. We have proposed a tactile display which realizes stress field reproduction using acoustic radiation pressure [3][4]. In previous studies, we developed a prototype tactile display composed of a one-dimensional linear array and confirmed that the prototype display could produce various spatio-temporal patterns of tactile stimuli along an axis on the skin surface.

We are now developing a new tactile display which can create two dimensional patterns of radiation pressure by scanning a focal point of ultrasound. In this paper, we discuss several problems inherent in implementing 2-D scan using PZT transducers and propose an appropriate design of a 2-D scanning tactile display to solve these problems. The discussed problems and methods are described in Section 2. We carried out simulation studies to discuss the feasibility of the method and the design of the display. The feasibility of the method is discussed in Section 3. The implementation of the proposed system is shown in Section 4.

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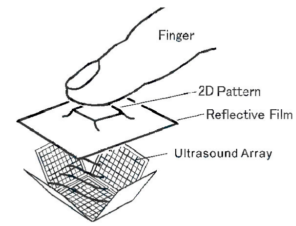


Figure 1: Concept of the two dimensional scanning tactile display. The display scans the focal point of ultrasound faster than human tactile perception to create two dimensional patterns of tactile stimuli.

## 2 Method

### 2.1 Tactile display using ultrasound

It was first shown by Dalecki et al.[5] that radiation pressure can provide sufficient force to produce tactile feeling. One obvious advantage of using ultrasound instead of conventional actuators is that both spatial resolution and temporal bandwidth are easily obtained. The intensity of the radiation pressure is proportional to the energy density of the ultrasound. Therefore if the ultrasound is focused on a point, it provides highly localized force. Though Dalecki controlled temporal intensity of ultrasound, the spatial distribution of radiation pressure did not vary because their aim was not to develop tactile displays but to investigate the threshold for tactile stimuli at a single point on the skin.

We have proposed a method to create spatiotemporal patterns of tactile stimuli with the radiation pressure. In our method, the focal point was steered on the skin surface at a higher speed than human tactile perception to create various spatiotemporal patterns of pressure. In our previous studies, we implemented this method with a one dimensional linear array. We confirmed that the spatial resolution of the display was 1 mm and the frequency characteristics were quite sufficient, up to 1 kHz, and that the display could produce various spatiotemporal patterns of tactile stimuli along an axis on the skin surface.

Expanding this method, we propose a 2-D scanning tactile display. Figure.1 shows the basic idea of the 2-D scanning tactile display. Ultrasound from PZT transducers converge to create a focal point. The focal point is steered on a 2-D plane. In order to avoid applying ultrasound directly on the skin, ultrasound reflective film is placed between the medium and the skin. The reflective film is made of polyurethane and silicone rubber, and is very thin and flexible.

### 2.2 Structure

Instead of using a simple 2-D array tiled with square ultrasound transducers, we propose an octagonal arrangement of linear arrays

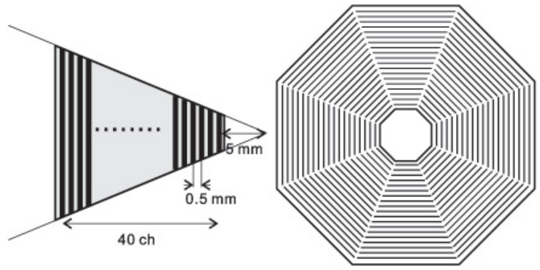


Figure 2: Octagonal arrangement of eight linear arrays. Left: A schematic drawing of a single linear arrays. Right: An arrangement of the eight units of the linear arrays.

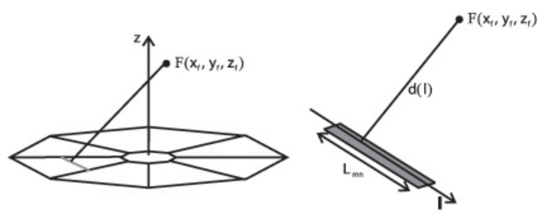


Figure 3: Parameters in Eq. (1). Left: A PZT piece on the octagonal arrangement of the linear array components. Right: The $n$th PZT piece on $m$th array component ($m = 1,2, \cdots, 8$, $n = 1,2, \cdots, 40$).

(shown in Fig. 2). Each linear array consists of 40 pieces of PZT transducers. Therefore a 320 channel driving circuit is required.

The reason why we avoid using a 2-D array tiled with small square ultrasound transducers is the complexity of its structure and related driving circuit. The main factor of the difficulties in fabricating a 2-D array is the interconnection to the large number of individual PZT pieces on the array. Though several methods using multilayer interconnection technique have been proposed[6], they are still not commercial products.

Hand wiring is one way for the interconnection of a 2-D array. However, the required number of PZT pieces for our device is quite large and hand wiring is not efficient. In previous studies, we confirmed that the output radiation pressure from a PZT piece (1.5 cm$^2$) saturated at 0.64 gf when the input energy was 60 W. To produce sufficiently perceivable force (a few gram), the radiation area should be about 10 cm$^2$. The frequency of the ultrasound should be 3 MHz for sufficient spatial resolution. In this case, the length of the side of the square PZT piece is about 0.5 mm because it should be less than the wavelength of the ultrasound. Then, in order to produce sufficient force, the required number of the PZT pieces is estimated at about 4000. To wire 4000 PZT pieces by hand is possible but not efficient.

In addition to the difficulties of fabricating the transducer array, the complexity of the driving circuit is also a problem. Though row and column drivers for matrix electrodes, like those used for driving LCD displays, are widely available, these are not suitable for our purpose. Such drivers activate each electrode sequentially by selecting each crossing of the row and column of a matrix array. Consequently, the required input energy per frame for a single piece of PZT should be delivered in quite short time.

Suppose we have a 2-D array comprised of $N$ pieces of square PZT transducers and drive it with a matrix electrode which applies voltage to the PZT pieces sequentially from the first piece to the $N$th piece. The frame period is $T$ [s]. In this case, each piece receives the input energy during $T/N$ [s] within one frame. If the required input energy per frame for each piece is $E$ [J], $NE$ [J] should be delivered to each piece within $T/N$ [s]. That means the required input voltage must be $\sqrt{N}$ times larger compared to the case in which each PZT piece is driven continuously.

If the number of the PZT piece is 3600, the input voltage must be 60 times larger than that of the case of continuous driving. In previous studies, we confirmed that the PZT we used saturated when the input voltage was around 45 V. Therefore even if we increase the input voltage to 2 kV, the PZT can not produce excessive ultrasound. Therefore, the 2-D tiled array cannot be driven with the row and column drivers. Each PZT piece should be driven not sequentially but simultaneously. Consequently, it is unavoidable that the complexity of the driving circuit increases if the number of PZT piece is huge.

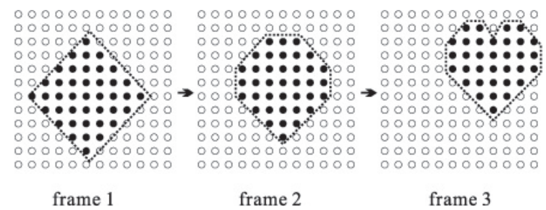


Figure 4: Method for producing spatio-temporal patterns of tactile stimuli. Several points are selected as stimulation points and the display produces the radiation pressure on the points. The frame rate is 1 kHz.

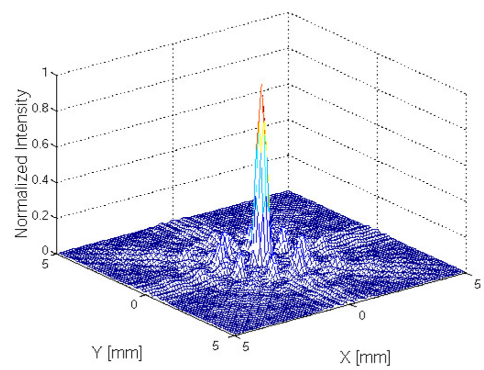


Figure 5: Simulation results for the octagonal arrangement. X axis and Y axis represent XY coordinates ranging from -5 mm to 5 mm. Z axis represents the normalized intensity of the radiation pressure.

### 2.3 Controlling 2-D spatio-temporal patterns

In order to produce spatio-temporal patterns of tactile stimuli, the focal point is scanned over a 2-D plane. The phase of ultrasound from each transducer is controlled so that it converges at a single focal point. Each PZT piece is recognized as a line source. Depending on the position of the focal point $F(x_f, y_f, z_f,)$, the phase of ultrasound from nth PZT piece on mth array at the focal point is determined as,

$$\phi_{mn}(x_f, y_f, z_f) = \arg\left(\int_0^{L_{mn}} e^{(j \cdot 2\pi \frac{d(l)}{\lambda})} dl\right) \quad (1)$$

where $\phi_{mn(x_f,y_f,z_f)}$is the phase, $L_{mn}$ is the length of the piece, $\lambda$ is the wave length of the ultrasound and $d(l)$ is the distance from a point $l$ on the piece to the focal point (see Fig. 3). The $n$th PZT piece on mth array is driven so that the phase is delayed by $\phi_{mn}$ in order to set the phase at the focal point to 0.

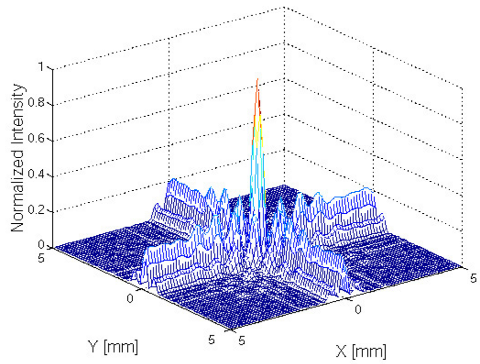


Figure 6: Simulation results for the square arrangement. X axis and Y axis represent XY coordinates ranging from -5 mm to 5 mm. Z axis represents the normalized intensity of the radiation pressure.

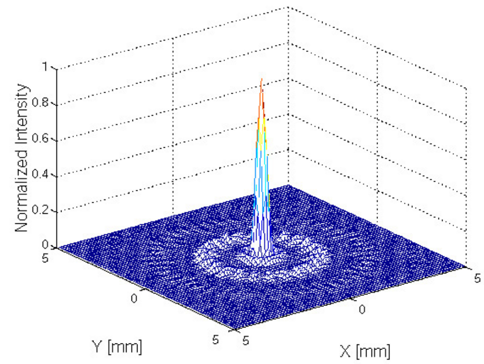


Figure 7: Simulation results for the dodecagonal arrangement. X, Y, and Z axis are the same as Fig. 5. The intensity at the second peaks is lower than that in Fig. 5.

The spatial pattern of tactile stimuli is created by producing several focal points on the display surface so that they fill up the pattern. The desirable distance between the focal points is estimated as follows. When a sinusoidal pattern of normal stress distribution is applied onto the surface of an elastic half-space, the amplitude of the sinusoidal stress distribution at the depth $z$ is given as[7]

$$P = P_0(1+|k_x|z)e^{-|k_x|z} \tag{2}$$

where $P$ is the amplitude of the sinusoidal pattern of normal stress distribution, which is perpendicular to xy plane, at the depth $z$. $P_0$ is the amplitude of the applied sinusoidal stress distribution. $k_x$ is the spatial frequency of the applied stress distribution. $z$ is the depth from the surface. In accordance with Eq. (2), it is considered to be difficult to transmit a stress pattern, whose spatial frequency is higher than $k/\text{mm}$, to $k$ mm under the surface of the elastic body. In our previous studies[3], we confirmed that the diameter of the focal point was 1 mm. And the thickness of the epidermis is generally about 1 mm. Therefore, if we want to produce a particular pattern by filling the area with the focal points, the largest distance between the points is estimated as 1 mm. Note that, in order to simplify the discussion, this estimation is roughly done by assuming the depth of the epidermis as 1 mm. From this estimation, 100 points are considered to be sufficient for covering a 1 cm by 1 cm area.

The radiation pressure is exerted on several focal points on the display surface within 1ms. The total amount of acoustic energy for 1ms is distributed to selected stimulation points. For example, if the number of the selected points is two and the ultrasound is applied to one of the two points for 0.3 ms and to the other for 0.7 ms, the intensity of applied force at each point will be 3:7.

In initializing the system, 128 by 128 coordinate points on the display surface are chosen and the phases $\phi_{mn}(x_f, y_f, z_f)$ for the 128 by 128 points are calculated and stored in the memory on the driving circuit. The 100 stimulation points are selected from the 128 by 128 points for every 1 ms. Therefore the frame rate of the display is 1 kHz. In order to modulate the intensity of the radiation pressure with the method described above, the same coordinate point is selected several times within one frame. In this case, the total area of the produced pattern is less than 1 cm$^2$. Figure.4 depicts the method described above. The driving circuit is designed to satisfy these conditions. The circuit can vary the position of the focal point every 10 $\mu$s.

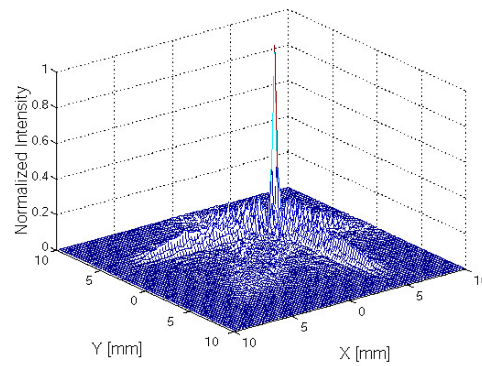


Figure 8: Simulation results for the octagonal arrangement. Note that XY coordinates are ranging from -10 mm to 10 mm. Z axis represents the normalized intensity of the radiation pressure. The coordinate of the focal point was (5mm, 5mm, 30mm).

## 3 Simulation

We verified the feasibility of the octagonal arrangement by simulations. The focal point produced with the octagonal arrangement and other polygonal arrangements were quantitatively compared.

Simulation studies were carried out with MATLAB. Each piece of PZT was approximately regarded as a gathering of acoustic point sources lined along the piece. A schematic drawing of the linear array is shown in Fig. 2. The focal length was set to 30 mm. The focal point was fixed at the center of the transducers.

The simulation results for the octagonal arrangement are shown in Fig. 5. X axis and Y axis represent XY coordinates ranging from -5 mm to 5 mm. Z axis represents the normalized intensity of the radiation pressure. There are second peaks around the focal point. The intensity at the second peaks was 13.1% of that at the focal point. The results for the other polygonal arrangements are shown in Figs. 6 and 7. Figures.6 and 7 show the results for a square arrangement and a dodecagonal arrangement, respectively. Figure.8 shows the results for the octagonal arrangement with the focal point shifted to $(x_f, y_f, z_f,) = (5\text{mm}, 5\text{mm}, 30\text{mm})$. The shifted focal point was successfully focused on the desired position.

In order to quantitatively compare the octagonal arrangement with other polygonal arrangements, the intensities at the second peak were estimated. The results are shown in Fig. 9. The horizontal axis represents the number of sides of the polygon. The vertical axis represents the intensities at the second peaks. Apparently, as the number of the sides increases, the intensity at the second peak decreases, while the design of the display becomes more complicated. Taking these facts into consideration, we chose the octagonal arrangement of linear arrays as an adequate design for the 2-D scanning tactile display.

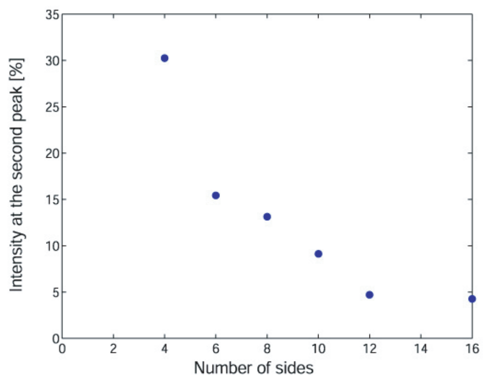


Figure 9: Intensities at the second peak for polygonal arrangements. The horizontal axis represents the number of sides of the polygon. The vertical axis represents the intensities at the second peaks.

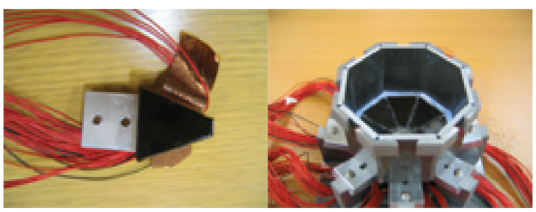

Figure 10: Linear arrays used in the prototype system. Left: One unit of the linear array. It includes 40 pieces of PZT. Right: Linear arrays arranged at the edge of the octagon. Each linear array is fixed at the bottom of the water bath.

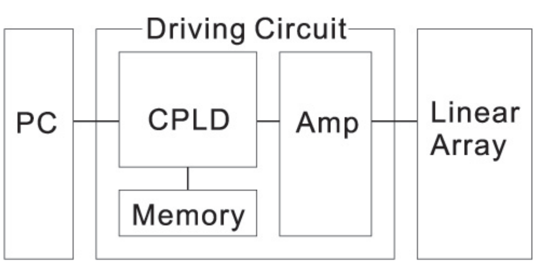


Figure 11: Block diagram of the system. A driving circuit board includes a CPLD, a memory, and 40 channel amplifier. The memory is capable of storing 4 bit data for the delay times associating with 128 by 128 coordinates.

## 4 Prototype System

We are now developing a new system based on the method written in Section 2. The system consists of a PC, a driving circuit and eight linear arrays. In this section, the details of the linear arrays and the driving circuit are described. The result of the preliminary experiment is also shown.

### 4.1 Linear arrays

The linear array consists of 40 pieces of PZT transducers. We used the linear array transducer (Nihon Denpa Kogyo Co., Ltd.) especially designed for high-power driving using PZT. The power limit is given by the maximum electrical field to maintain polarization of the PZT and the maximum temperature as the Curie temperature. In order to avoid the temperature rising, the PZT pieces were attached on a thermally conductive material. These PZT pieces are arranged at 0.5 mm pitch. The length of the shortest piece and the longest piece are 3.3 mm and 20 mm, respectively. In this case, the total radiation area of transducers is about three times larger than that of the 1-D prototype and expected to produce maximum 7 gf of total output force. The thickness of the transducers is 0.64 mm so that the resonant frequency of the transducers is 3 MHz.

Eight linear arrays are arranged at the edges of the octagon and fixed at the bottom of the water bath. Water is used as the medium to transmit the ultrasound. Each linear array is tilted by 20 degree because each PZT piece has directivity. The width of the water bath is 80 mm.

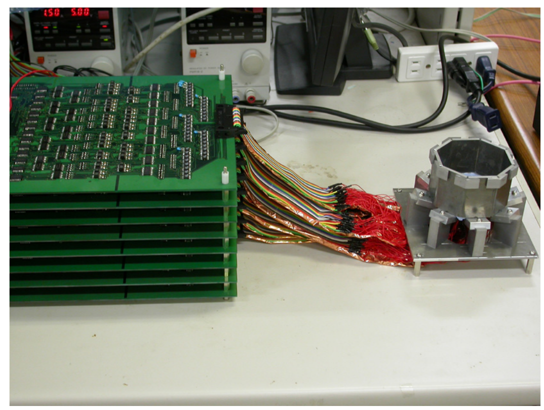

Figure 12: A photograph of the prototype system. Eight linear arrays are connected to eight driving circuit board. The driving circuit is connected to the PC with USB cable.

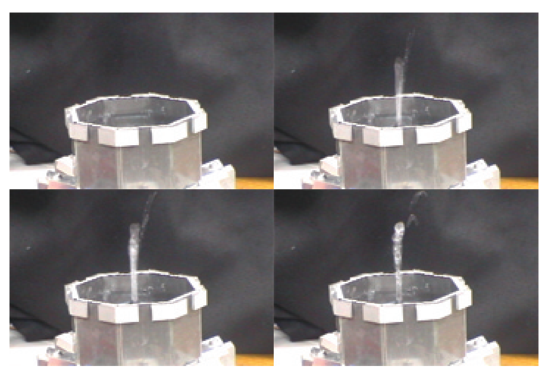

Figure 13: A jet of water created by the prototype tactile display.

### 4.2 Driving circuit

Figure. 11 shows a block diagram of the system. Each driving circuit board has a CPLD (Complex Programmable Logic Device), a memory, and 40 channel amplifier. The CPLD includes signal delay circuits implemented with 4-bit counters. The memory holds a look-up table which associates the position of the focal point with

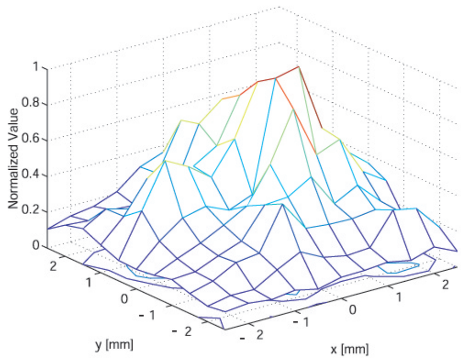


Figure 14: Spatial distribution of acoustic radiation pressure for a single focal point (3D plot).

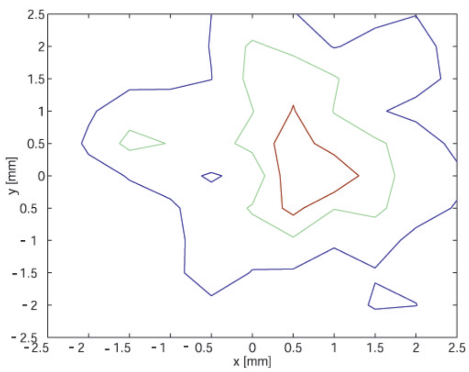


Figure 15: Spatial distribution of acoustic radiation pressure for a single focal point (contour plot): Each line represents 25%, 50%, 75% of the peak value, respectively.

the delay time for each channel. When the position of the focal point is given by the PC, the CPLD reads the delay time associating with the position of the focal point from the memory and outputs signals to drive the transducers. In order to produce 100 points within 1 ms, the position of the focal point is given to the CPLD every 10 $\mu$s.

### 4.3 System

Figure. 12 shows the prototype system. The system consists of a PC, a driving circuit and eight linear arrays. The driving circuit was connected to USB port on a PC. Eight boards were used to drive 320 PZT pieces. When applying tactile stimuli on the userfs finger, we used ultrasound reflective film[3]. The film was placed just on the focal plane.

As a preliminary experiment, only 16 PZT pieces on each linear array (total 128 pieces) were used and driven. 16 PZT pieces close to the center were selected. The driving signal was 3 MHz rectangular wave. The amplitude of the applied voltage was 35 V. The driving signal was applied for 100 ms. The focal point was set to 30 mm above the center of the arrays. Figure. 13 shows the results. At the center of the water bath, water was thrown up as the result of the high intensity ultrasound.

### 4.4 Spatial distribution of radiation pressure

The spatial distribution of radiation pressure around a single focal point was measured to evaluate the spatial resolution of the prototype. The results are shown in Figs. 14 and 15. Figure.14 is a 3D plot of the measured spatial distribution of the acoustic radiation pressure. Z-axis in Fig. 14 represents the pressure obtained at each point normalized by the largest value in the data (i.e. the value at the focal point). Figure.15 is a contour plot of the same data.

As shown in Figs. 14 and 15, the radiation pressure was not successfully focused. The reason is that the alignment of the transducers was not sufficiently accurate. Therefore, it is necessary to adjust the driving signals so that they compensate the difference between the ideal positions of the transducers and the actual ones. We are going to carry out this calibration with a needle hydrophone.

## 5 Summary

We proposed a new design for the 2-D scanning tactile display with ultrasound linear arrays. The results of the simulation studies validated the feasibility of the proposed octagonal arrangement of linear arrays. We confirmed that the prototype system could produce sufficient force of radiation pressure at the focal point. We are now trying to calibrate the alignment of the transducers and produce 2-d tactile patterns.


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