HAPTOGRAM: AERIAL DISPLAY OF 3D VIBROTACTILE SENSATION

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ABSTRACT

We introduce Haptogram, a system designed to provide a 3D tactile feedback by employing acoustic radiation pressure; similar to a hologram providing a 3D visual display. Haptogram system is made up of a two-dimensional array of ultrasonic transducers to project discrete points of tactile feedback moved in three orthogonal directions to create a 3D tactile experience. A mathematical model describing the Haptogram system is presented. A simulation experiment is conducted by constructing a 3D tactile hemisphere to showcase the proposed system. Simulation results are encouraging and good enough to implement the Haptogram system in our immediate future work.

Index Terms—3D Haptic interfaces, Aerial Display, Vibrotactile sensation, 3D tactile display

1. INTRODUCTION

Natural and 3D interfaces are getting popular these days. It is mainly due to the spread of 3D capture, authoring, and display interfaces (such as 3D contents generation technologies, 3D authoring tools, 3D display interfaces, hologram technology). Adding 3D haptic feedback to these interfaces is the next natural step to achieve a natural and intuitive human computer interaction.

A tactile interface displays information using the sense of touch such as shape, surface texture, roughness, and temperature onto the human skin. Tactile displays have been proposed in a wide spectrum of applications, including virtual reality, Tele-operation, interpersonal communication, entertainment and gaming, military, and health care [1].

The noncontact tactile display is based on the phenomenon of acoustic radiation pressure [2]. When the focused ultrasound beam is reflected by the surface of an object, the surface is subjected to a constant force in the direction of the incident beam.

In this paper we introduce Haptogram, a system that provides 3D tactile feedback via focused ultrasound, and requires no physical contact with the human skin. The tactile sensations are displayed by generating acoustic radiation forces where a phased array of ultrasonic transducers is used to exert forces on a target point in 3D space. Moving the point of tactile stimulation at very high speed along a 3D model creates 3D tactile experience.

The remainder of the paper is organized as follows: Section 2 presents the related work and highlights distinguished features of the proposed system. In section 3, we introduce the mathematical model for the Haptogram system. Section 4 presents the simulation setup, procedure, and results, and discusses our findings. Finally, section 5 summarizes the paper contents and provides perspectives for future work.

2. RELATED WORK

Previous research related to tactile displays can be divided into three categories: wearable display, touch screen display, and non-touch display. Wearable tactile display embeds vibrotactile actuators in wearable devices to make a direct contact with the human skin. The touch screen display has vibrotactile actuation technology integrated in the visual/auditory display interface (such as the touch screen) and displays tactile information when the user makes a contact with the touch screen. Non-touch tactile display uses wireless means to stimulate tactile sensation on the human skin (such as focused ultrasound waves).

Most of the current tactile display devices are of the wearable display class (few can be found in the literature such as [3-5]). The iFell_IM system is a wearable interface designed to enhance emotional immersion in a virtual world called second life [6]. Three groups of haptic gadgets are built. First group is intended for emotion elicitation implicitly (HaptiHeart, HaptiButterfly, HaptiTemper, and HaptiShiver), the second type functions in a direct way (HaptiTickler), and third one uses a sense of social touch (HaptiHug) for influencing the mood and providing some sense of physical co-presence [7].

Touch panel (screen) interface enables a user to manipulate graphical user interfaces through tactile stimulation to strengthen the intuitiveness and directness of interaction. There are commercially available touch screen devices with tactile interaction capabilities (such as TouchSenseTM [8] from Immersion and “Sensegs Tixel” from Senseg [9]) as well as research prototypes [10-12]. For instance, the authors in [13] introduced a lateral-force-based 2.5-dimensional display and found that users' impressions of "press", "guide", and "sweep" are essential features for touchscreen.

A contactless touch screen with tactile feedback that stimulates tactile sensation 1-3 cm in front of the screen surface is proposed in [14]. Single point of tactile stimulation is generated using airborne ultrasound phased array.

Air jets are utilized in [15] to create non-contact force feedback where fans or air cannons are used in theme parks to amaze visitors. Although they are effective in simulating a rough "force" feedback, their spatial/temporal properties are limited and they cannot provide fine tactile feedback.

A tactile display, presented in [16], utilized airborne ultrasound to produce tactile sensations with 16 mN at a virtual point in space. The demonstrated prototype has a spatial resolution of 20 mm and produces vibrations up to 1 kHz. Experiments showed that users could identify the tactile stimulus generated by the device and were able to discriminate its moving direction. A similar work that utilized a two dimensional array of ultrasound transducers to generate concentrated pressure at an arbitrary point in larger workspace is presented in [17]. UltraHaptics is a multi-point haptic feedback system used over an interactive surface that is capable of producing independent feedback points in relation to on-screen elements [18].

Haptogram utilizes the previous work to generate acoustic radiation forces at points in 3D space that construct a 3D object (such as a hemisphere as shown in the simulation analysis section). The system continuously switches tactile display points at a very high speed (1 kHz update rate) to print a tactile stimulation of the 3D object in free space. Results presented in this paper are based on simulation experiments.

3. HAPTOGRAM MATHEMATICAL MODELING

The tactile stimulation produced by Haptogram is based on the Phased Array Focusing technique to produce the radiation pressure perceivable by the human skin. The focal point of ultrasound – a set of these points make up a 3D shape – is generated by controlling the phase delays of multiple transducers at a high update rate. When N transducers are driven so that the phases of the ultrasounds coincide at a point, the radiation pressure that is generated by the array will be large enough to be perceivable by human skin.

The theoretical derivation of the resulting sound pressure field on the 3D surface tactile points is presented here. First, the specifications of the transducer array are listed. The diameters of the transducer housing and the diaphragm are d = 10 mm and 8 mm, respectively. The resonant frequency is 40 KHz whereas the directivity is 80 deg.

Secondly, the sound pressure field is formulated. Assume the coordinate system shown in Figure 1. Let r[m] be the vector for a general transducer on the array (xm, ym, 0) and a general focal point with coordinates (x0, y0, z0) on the Haptogram. The RMS sound pressure p0 from that transducer onto the focal point is inversely proportional to r. Therefore, the resulting sound pressure field P(x0, y0, z0) is written as shown in equation (1). Equations (3) to (6) derive an expression for the acoustic radiation pressure (P) as function of the elevation (z). The final expression of the pressure field becomes as shown in equation (7).

$$P(x_0, y_0, z_0) = \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} \sqrt{2} P(z_0) e^{j(kr - wt)} \quad (1)$$

$$r = \sqrt{(x_m - x_0)^2 + (y_m - y_0)^2 + (z_0)^2} \quad (2)$$

$$\mathrm{P}(z_0) = P_0 e^{-2\beta z_0} \quad (3)$$

$$E = \frac{I}{C} = \frac{P^2}{\rho C^2}, \quad (4)$$

$$E(z_0) = E_0 e^{-2\beta z_0} \quad (5)$$

$$P(z) = \sqrt{E \rho C^2} = \sqrt{E_0 \rho} C e^{-\beta z} = P_0 e^{-\beta z} \quad (6)$$

$$P(x_0, y_0, z_0, t) = \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} \sqrt{2} P_0 e^{-\beta z_0} e^{j(kr - wt)} \quad (7)$$

M and N are the dimensions of the ultrasound array, β is the attenuation coefficient of the air interface, k is the wavenumber of the ultrasound signal, w is the angular frequency (2πf), f is the resonance frequency for the ultrasound transducers, and r is the focal length.

Equation (8) determines the size of the focal point and the total force F [N] contained within a cubic unit of side ω_f (geometrically derived to be as expressed in equation (9)).

$$F = \frac{\alpha}{\rho c^2} \int_{-\omega_f/2}^{+\omega_f/2} \int_{-\omega_f/2}^{+\omega_f/2} \int_{-\omega_f/2}^{+\omega_f/2} \frac{|p(x_0, y_0, z_0)|^3}{3} dx_0 dy_0 dz_0 \quad (8)$$

Where

$$\omega_f = \frac{4\pi r}{k\sqrt{MN} d} \quad (9)$$

4. SIMULATION ANALYSIS

A short simulation experiment was conducted in order to confirm whether the generated acoustic radiation forces are sufficient for human perception of tactile sensation. The

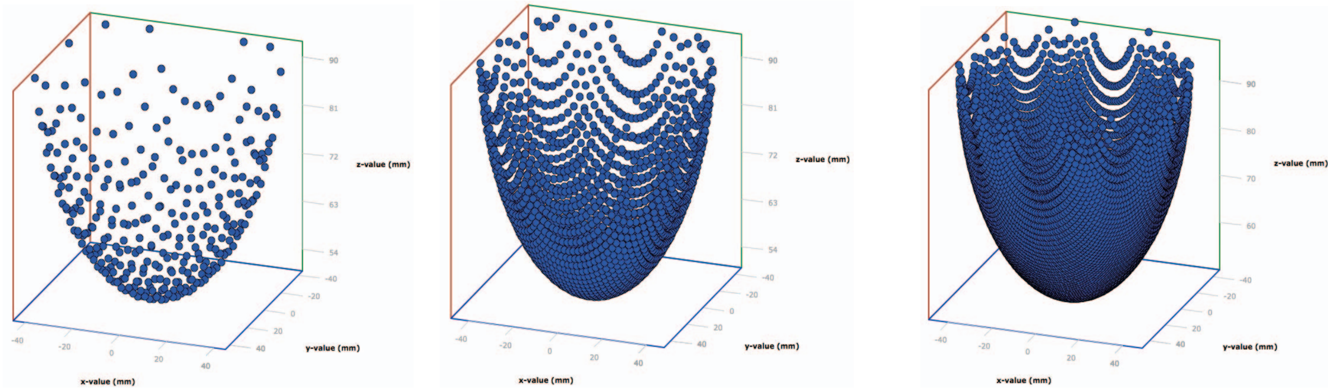

Fig. 2. Tactile 3D constructions for a semi sphere (left) 10 mm resolution, (middle) 5 mm resolution and (right) 2 mm resolution.

pressure field distribution and force calculations are computed using a fast object-oriented C++ ultrasound simulator library called FOCUS [19] that works with MATLAB.

4.1. Simulation Setup

The 3D object used in this simulation is the lower half of a sphere located centered 100 mm above the transducers array with a radius of 50 mm. A graphical representation of the hemisphere is shown in Figure 4.

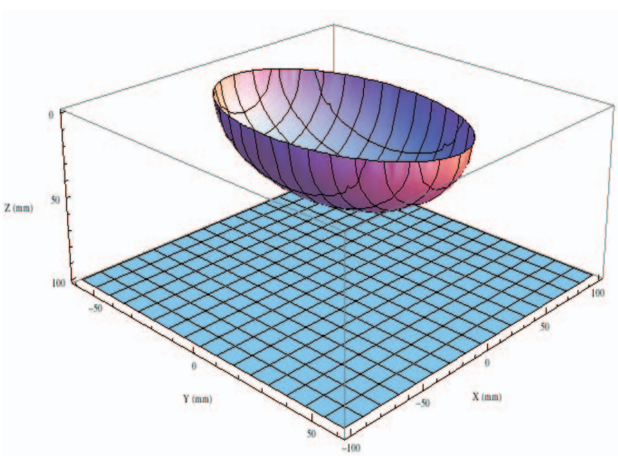

Fig. 1. 3D tactile object stimulation.

The current simulation consists of 256 (16x16) transducers. The transducer housing is square shaped with a side length of d = 10 mm. The resonant frequency is 40 kHz while the directivity is 80 deg. We use MxN (=16x16) transducers and arranged them into a 180 x 180 mm2 rectangle. The followings are the parameters used to run the simulations presented in this section:

- Frequency = 40 kHz
- β=1.15 x 10-1 Np/m
- C = 340 m/s
- P0 = 8.59 x 10-3 Pa
- Voltage = 10 Vrms
- K = 2π/λ = 730.603 rd/m
- W = 2πf
- α = 2
- Medium: air interface (lossless)

Another configuration parameter that we can control through the simulation is the resolution of tactile 3D object. Figure 2 demonstrates examples of low resolution (10 mm), intermediate resolution (5 mm), and high resolution (2 mm) displays. Note that higher resolution display takes more time to display the entire 3D object and thus require faster hardware to implement. However low resolution display might degrade the quality of user perception of 3D tactile sensation. Usability testing will be conducted in the future work to find the optimal tradeoff.

4.2. Simulation Procedure

The simulation works as shown in Figure 3. Initially, the geometry of the transducer array is setup with the following dimensions for each transducer (width = 1 mm, height = 5 mm, edge-to-edge spacing – s_x and s_y = 0.5 mm). Next a loop that runs at 1 kHz rate is executed.

```
% M, N dimensions of the array
% w and h are width and height of array
% s_x and s_y are x and y spacing
array = create_rect_array(M,N,w,h,s_x,s_y)
% Loop update rate 1 kHz
Loop
   %setup coordinate grid
   coord_grid = set_coordinate_grid(delta,
   xmin, xmax, ymin, ymax, zmin, zmax);
   % Calculate the next point coordinates
   point = getNextPoint (3D object)
   % focus the array to point
   array = get_focus_phase (array, point,)
   % calculate pressure field
   p = pressure(array, coord_grid, freq,)
Repeat Loop
```

Fig. 3. Simulation loop.

Table 1: Simulation results for various configurations for the Haptogram system.

Ultrasound Array Configuration	*20% Resolution (2 cm)*		*10% Resolution (1 cm)*		*5% Resolution (0.5 cm)*		*2% Resolution (0.2 cm)*	
	Avg (mN)	*Std Dev. (mN)*	*Avg (mN)*	*Std Dev (mN)*	*Avg (mN)*	*Std Dev (mN)*	*Avg (mN)*	*Std Dev (mN)*
128X1	3.30	0.38	3.17	0.41	3.14	0.46	3.04	0.54
64X2	3.90	0.96	3.85	0.94	3.78	0.83	3.70	0.76
32X4	4.33	0.67	4.24	0.62	4.07	0.53	3.83	0.38
16X8	4.33	0.97	3.96	0.88	3.89	0.66	3.62	0.34

The loop starts by setting up the coordinate grid to cover the full width of the transducer array in the x direction and to measure the pressure field in the z direction. Then the coordinates of the next point on the 3D model are retried and used to generate a focal point at the desired point and hold on for specific time. Figure 4 shows a simulation that demonstrates the ability of ultrasonic transducers to stimulate tactile feeling at a desired point in 3D space.

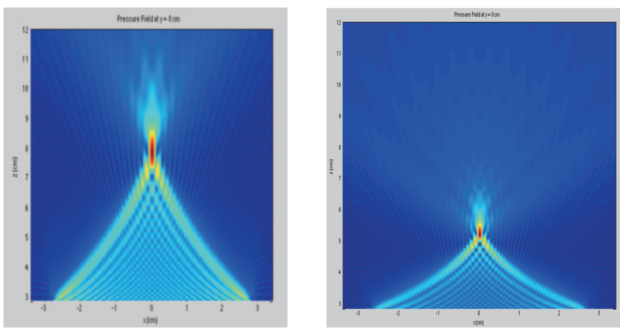

Fig. 4. x=0, y=3cm, z=9cm (64x1, cylindrical), x=0, y=6cm, z=7.5cm (64x1, cylindrical).

4.3. Simulation Results

Table 1 shows simulation results for a combination of 16 different configurations (four resolution levels of display and four layout configurations, as shown in the table). The forces are calculated by utilizing equation (8) with a cubic unit of 1 mm^3. Results show that:

1. In all the considered configurations, the average force ranges from 4 mN to around 3.5 mN (while standard deviation ranges from 0.75 mN to 0.5 mN). According to several haptic studies [20], this force is comfortably capable of stimulating tactile sensations on the human skin.
2. We observed that the higher the display resolution, the smaller the average forces are. However, the standard deviation of forces is found to be mostly decreasing with an increase in the display resolution. This implies that even though higher variations of displayed forces are experienced, the average forces have increased. We would like to investigate in our future work the impact of force variations onto the quality of user experience.
3. The average force has increased from a one-dimensional configuration (1x128) to a two-dimensional configuration (8x16), with the same total number of ultrasound transducers. This implies that using a two dimensional array of ultrasound transducers increases the ultrasound forces. However, higher discrepancies in the magnitude of generated forces are experienced.

5. CONCLUSION AND FUTURE WORK

In this paper, we introduced Haptogram, a system that is capable of generating 3D tactile stimulation using an array of ultrasonic transducers. Simulation results have shown that the proposed system is capable of generating forces that are within comfortable margins of forces that are perceived by the human skin. Furthermore, the Haptogram system is capable of generating a sequence of tactile points (that altogether construct a hemisphere in this paper) at 1 kHz update rate.

Our immediate future work is to build a prototype for the simulated system and compare the experimental results with the simulation results obtained in this paper. Furthermore, we plan to conduct usability testing to measure the quality of user experience with tactile 3D objects. Finally, the proposed system can be integrated with graphic hologram to build a complete multimodal immersive experience (auditory, visual, and tactile feedback).

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