Variable Curvature and Spherically Arranged Ultrasound Transducers for Depth-Adjustable Focused Ultrasound

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Abstract. In haptic feedback using focused ultrasound, a technique has been proposed that involves creating an ultrasound focal point using a spherical surface without the need for phase control. This method is efficient as each transducer faces directly toward the focal point, but it has a limitation – the focal point remains fixed due to the ultrasonic transducers being attached to a static sphere. This study introduces a method to move the focus in the depth direction by dynamically changing the curvature of the spherical surface to which the transducers are attached. We built a device that can adjust curvature using a servo motor, confirming its capability to relocate the focus position.

Keywords: Curvature Control, Focal Point Control, Mid-Air Haptics.

1 Introduction

Airborne ultrasound tactile display can present tactile sensations without directly touching human skin. A typical setup includes ultrasound transducers arranged in a regular pattern on a flat surface. The phase control of each transducer focuses sound waves at any position within the presentation area.

Numerous studies have explored ultrasound focus using phase control [1-7]. Various control methods have been proposed, including the simultaneous formation of multiple focal points [4] and the generation of a strong sensation through fine reciprocating vibration or rotational movement of the focus along the skin while maintaining a constant ultrasound output [5]. In research on user perception, a study [6] investigated the relationship between the number of focal points and their speed. Furthermore, a graphical design tool for the quick presentation of ultrasound tactile sensation [7] has been proposed.

However, phase control represents a relatively costly hardware method. The typical frequency of ultrasound used is 40 kHz, necessitating a control period on the order of MHz for accurate phase control. High-speed control hardware, such as a field programmable gate array (FPGA), is required to control several hundred transducers simultaneously.

Physical methods to form an ultrasound focus without phase control have also been explored [8-10]. For example, methods involving the formation of a focus at the center point of a sphere by arranging ultrasound transducers on the sphere [8], the formation of a focus using the phase difference of sound waves output from a meandering path [9], and the use of a circular deflection diaphragm [10] have been proposed. These methods can create a focal point using ultrasound waves without circuit-based phase control.

However, these methods have limitations in moving the ultrasound focus. For instance, an airborne ultrasound tactile display with ultrasound transducers arranged on a spherical surface has a single fixed focus. While introducing a pan-tilt mechanism to this display facilitates the horizontal or vertical movement of the focus position, moving the focus in the depth direction with this configuration is challenging.

In this study, we propose a method to move the focal point in the depth direction by arranging transducers on a spherical surface and dynamically changing the curvature of the sphere. The contribution of this method is the following two points:

- It simplifies control compared to conventional phase control methods.
- It offers high energy efficiency as the center of the ultrasound transducers consistently aligns with the focal direction.

2 Proposed Methods

2.1 Hardware

Fig. 1 illustrates the proposed method. The system utilizes a parametric speaker experiment kit (K-02617, Akizuki Denshi Tsusho) to establish an ultrasound focus. The resonant frequency of the ultrasound transducers is 40 kHz, and FM modulated signals are simultaneously output from all transducers in response to audio input. The 50 transducers attached to the device, spaced approximately 1 cm apart, are arranged radially on a deformable plastic sheet (K-A-PET-BR, AMHA), which undergoes deformation through a servo motor (MG996R, Towerpro) driven by wires.

This results in a group of transducers positioned on a spherical surface with variable curvature. The ultrasound waves output from each transducer converges at the center of the sphere, i.e., vertically above the device. When the curvature of the sphere changes by wire traction, the ultrasound focus moves in the depth direction accordingly.

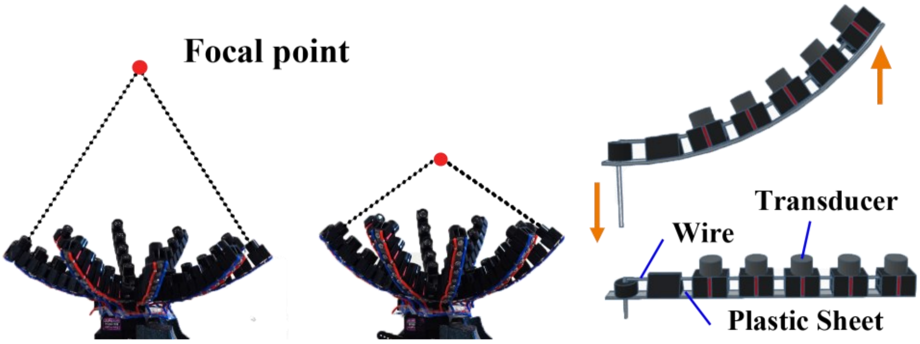

Fig. 1. Focal point movement by changing curvature

2.2 Device Response

To assess the device's responsiveness, we conducted measurements on the time it takes for the servo motor to transition from 0 degrees (when the plastic sheet is parallel to the ground) to a specific angle for each servo motor setting. We conducted five measurements for each angle and present the data in Fig. 2. The offset delay time is approximately 400 ms, with the maximum time required to reach the intended angle being about 1.2 seconds. Despite this, the system exhibits smooth operation, allowing, for example, the focal point to be adjusted seamlessly in response to the hand's up-and-down motion.

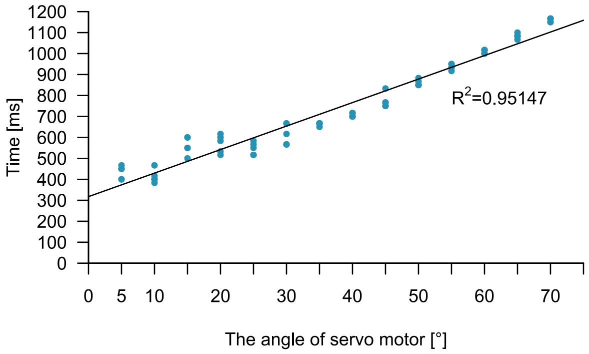

Fig. 2. Curvature formation time for each servo motor angle

3 Experiment: Focal Point Movement with Curvature Change

3.1 Experimental Procedure

This experiment aimed to investigate how the acoustic radiation pressure at the ultrasound focus changes with the traction angle of the servo motor in the depth direction. A mesh screen was put above the transducers, and the change of temperature of the screen that represents acoustic radiation pressure was measured [11]. The experimental setup is illustrated in Fig. 3.

The servo motor varied the traction angles from 5 to 70 degrees in 5-degree increments. For each traction angle, the position of the mesh screen in the depth direction was adjusted by 1 cm, ranging from 9 cm to 42 cm. Subsequently, the surface temperature of the center of the mesh screen was recorded. The height of the mesh screen, corresponding to the maximum surface temperature at the ultrasound focus for each traction angle, was then measured.

The mesh (N No. 420S, Japan Special Fabrics) was arranged in two layers, and a thermal imaging camera (FLIR-E6390) measured the surface temperature. The initial mesh screen position was set at 0 cm when the plastic sheet was parallel to the ground. Temperature and humidity in the room were recorded before the measurement.

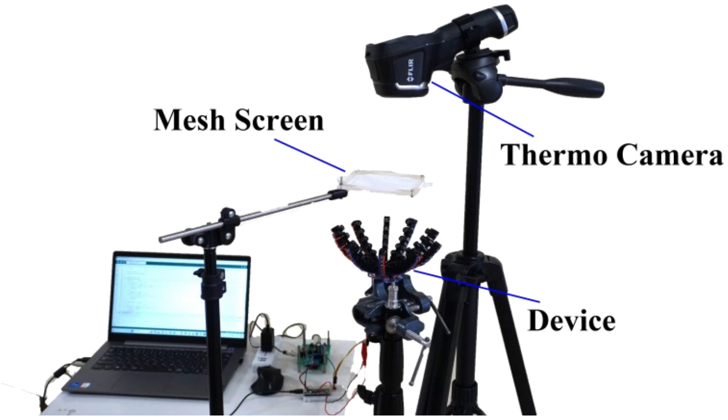

Fig. 3. Experimental setup

3.2 Results

During the measurement, the room temperature was 24.0°C with 25% humidity. Fig. 4 illustrates the temperature variations in the depth direction for each traction angle of the servo motor (a: servo motor angles 5° to 35°, b: servo motor angles 40° to 70°). Furthermore, Fig. 5 depicts the changes at the highest temperature point.

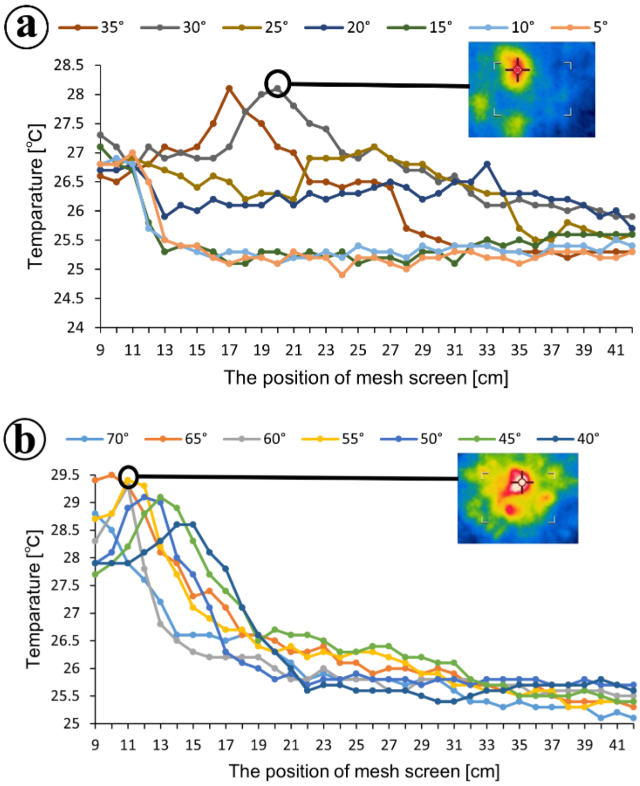

Fig. 4. Temperature changes in distance for each servo motor angle. The figure includes thermal images of the mesh screen surface captured at 30 and 55 degrees as examples.

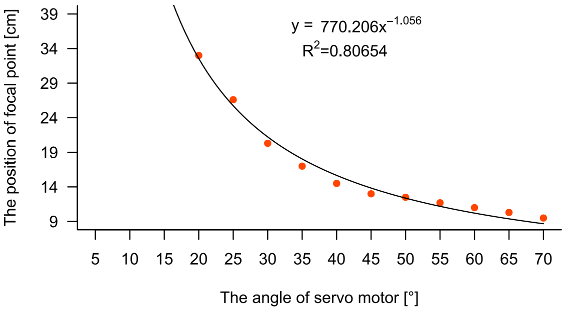

Fig. 5. Dependence of focus position on servo motor angles

4 Discussion

In Fig. 4, local temperature rise is evident at various servo motor traction angles. At 65 degrees, for instance, the temperature peaks at 29.5°C at 10 cm, and at 30 degrees, it reaches 28°C at 20 cm. These temperature changes are ascribed to the ultrasound focus. As the servo motor traction angle decreases, temperatures at these focal points decline. This decline may be due to attenuation resulting from reduced curvature as the traction angle decreases and the ultrasonic waves focus over a longer distance, or because the focal point becomes more spread out in the depth direction. Notably, no local temperature increase was observed at traction angles of 15, 10, and 5 degrees. Additionally, the accuracy of the device might contribute to these effects. The device's design introduces minute differences in the curvature of the 10 frames on which the transducers are mounted. The longer the focal distance, the more pronounced the difference in curvature of each frame, potentially causing a shift in the focusing of the sound waves.

A power approximation for nonlinear regression was applied to analyze Fig. 5. It is evident that as the traction angle of the servo motor decreases, the position of the focal point extends in the depth direction. The relationship between the traction angle and the radius of curvature (focal point position) is nonlinear. The focal point shifts approximately 24 cm, moving from 34 cm to 10 cm. As illustrated in Fig. 2, the duration of this transition is less than 1 second. In essence, the system demonstrates sufficient responsiveness to respond to subtle up-and-down hand movements.

When this system is installed on an inclined surface, the plastic sheet to which the ultrasound transducers are attached may bend due to gravity. Therefore, there is a possibility that the acoustic radiation pressure of the focal point formed will weaken or that the focal point itself will not form.

While a detailed subjective evaluation was not conducted, we verified that the tactile sensation is distinctly perceptible when the hand is placed over the system. For instance, at an angle of 70 degrees, tactile sensations were experienced in the range of 9 cm to 10 cm, and at 55 degrees, in the range of 11 cm to 12 cm. These observations are consistent with the physical measurements.

5 Conclusion

This research investigates a device created to deliver ultrasound tactile sensations through a simple control method. The device comprises ten spherical frames with attached ultrasound transducers. The curvature of the spherical surface adjusts according to the servo motor's traction angle, enabling the formation of ultrasound focal points at different positions in the depth direction. Acoustic radiation pressure at the focus was observed for each traction angle using temperature measurements on a mesh screen. The results confirmed that the focus position in the depth direction varies with the servomotor's traction angle in the range of 70 to 20 degrees, indicating that the focus movement in the depth direction can be easily controlled.

Based on the results of this experiment, we will conduct psychological evaluation experiments on human subjects to examine the effectiveness of the proposed method.

For example, in the experiment concerning the perception of softness using this device, a hand tracking device (LeapMotion, UltraLeap) is placed nearby to determine the position of the user's hand. By adjusting the angle of the servo motor and the intensity of the ultrasound focus according to the user's finger movement, we can evaluate the sensation of softness when the user presses in with their fingers.

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