Haptic Interface Device Using Cable Tension Based on Ultrasonic Phased Array

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This work was supported in part by the National Key Research and Development Program of China under Grant 2016YFB1001301, and in part by the National Natural Science Foundation of China under Grant 91648206.

ABSTRACT This paper presents a new haptics interface device based on cable-driven parallel manipulators and an ultrasonic phased array. Unlike previous studies, our method combines force and tactile feedback at the same time. It consists of two main parts: force feedback generated by cable tension and tactile feedback provided by an ultrasonic phased array. While these parts have no direct interference, combining them can offer a synergistic effect on haptic perception. Through a series of experiments, the tactile rendering algorithm for this device is established. The output pressure of ultrasonic phased array is dependent on input command value, modulation frequency, modulation waveform, and the position of the focal point in the workspace. The results of psychophysical experiments are evaluated to determine the absolute threshold of perceivable ultrasonic tactile feedback when the cable-driven force acts on fingers. Finally, we carry out a test to confirm the accuracy advantage of our system in the virtual environment. The results of our study indicate that this device has a wide range of applications in the field of aerial haptic display.

INDEX TERMS Haptic feedback, cable-driven force, ultrasonic tactile, rendering algorithm, haptic perception.

I. INTRODUCTION Aerial haptic feedback is a popular topic in studies on the haptic interface. It allows users to touch graphic objects in the air with their bare hands and feel force feedback. Technologies such as air jets [1], ultrasound [2], and laser [3] have been proposed for aerial haptic feedback. The aerial haptic display has several advantages, namely, avoiding contact between the skin and physical material and providing haptic feedback anywhere in 3D space. Air jets [1] can provide obvious tactile sensation, but their spatial resolution and workspace are limited. Laser haptics [3] can render on a large workspace and have a high resolution. Laser haptics is based on the thermoelastic effect of nanosecond laser or the evaporation effect of femtosecond laser. Most nanosecond pulsed laser-based tactile stimulation uses indirect radiation methods (e.g. work by Lee et al.), i.e. the laser is irradiated onto a thin light-absorbing elastic medium coating the skin. The femtosecond laser can produce haptic images precisely (spatial resolution 1 µm) but it covers only small areas, which can be enlarged by using a larger lens to enable a larger angle range of the galvano mirror [23].

Cable-driven force has the advantages of lightweight structure, low energy consumption, easy control, low moment inertia, and higher accuracy et al. Additionally, it has wide-ranging application potential. Research on cable-driven force began in the United States in the 1980s [4], mainly for shipbuilding and mechanical processing. Then, the theoretical research and engineering applications of the cable-driven parallel robot were extended to aircraft wind tunnel experiments, hoisting operations, large-scale radio telescope observation, human rehabilitation training, and haptic interfaces [5], [6].

Recently, several haptic interface studies have focused on immersive virtual reality headsets and depth cameras, such as CamBourd nanosensors [7]. These studies focused on a single physical quantity. In the present study, our device combines force and tactile feedback simultaneously.

A. ULTRASOUND TACTILE FEEDBACK Ultrasound tactile feedback attracted our attention because of its large workspace, high degree of freedom, safety, and reliability. Ultrasound as a non-invasive method to stimulate the human body was first systematically researched by Gavrilov, a researcher from Russia in the field of biological sciences [8]. The use of acoustic radiation force
to generate physical sensations was first demonstrated by Dalecki et al. [9]. The tactile sense could be stimulated by a non-focusing ultrasonic transducer submerged in a water bath on the subject’s finger with the corprene™ disk (an acoustic reflector). Airborne ultrasound tactile feedback was first investigated by Iwamoto et al. [2]. Although the produced force is weak for users to feel constant pressure, it is sufficient for a vibratory sensation. The ultrasonic focus can be moved along two axes of the two-dimensional phased array, which builds a dynamic system [10]. While this technique creates a strong focal point, it suffers from the creation of four side lobes surrounding the central focus. Later, researchers focused on multipoint haptic feedback [11] and rendering volumetric haptic shapes in midair [12]. The spatial resolution and haptic intensity in the ultrasonic rendering were improved compared to the previous investigation [13]–[15]. Marzo et al. proposed an open platform for parametric audio generation, acoustic levitation, and haptic feedback, which included hardware, software, and example applications [19].

In [20], the applications of psychophysical techniques used to measure haptic perception thresholds were reviewed. The details of how absolute and difference thresholds can be measured were provided. The investigations in [21] highlight the importance of the speed of stimulation movement in the design of tactile patterns. In [22], participants estimated the perceived strength for patterns rendered with different sampling rates and discussed the sense of touch from the perspective of psychophysics. Another study [23] evaluated the perceptual threshold for acoustic radiation pressure and cross-field (light and acoustic fields), the results show laser tactile sensation is repressed in an acoustic field. In [13], evaluated the minimum perceivable radiation force for the focal spot proposed by 70 kHz phased array was smaller than that for the 40 kHz case on average under 40 or 100 Hz modulations. The absolute threshold of perceivable ultrasonic tactile feedback was estimated by a series of psychophysical experiments [24]. Ultrasound haptic feedback has recently been applied in many scientific fields [25]–[29].

B. CABLE-DRIVEN FORCE FEEDBACK

In [30], a purely rotational three-degree-of-freedom (3-DOF) tendon-driven haptic device was described. Feriba-3 [31] is a four-wire-driven planar haptic device, whose major features are low inertia, low friction, and full dexterity in a large workspace. Trevisani et al. presented a novel planar translational cable-direct-driven robot, including a passive planar 2-DOF SCARA-type serial robot to provide stiffness normal to the plane of motion [32]. WiRo-6.3 is a 6-DOF device whose end effector is driven by nine wires operated by motors, and its forward kinematics were analyzed in [33].

The cable-driven force feedback apparatus in this paper is inspired by the work done by Sato and Hirata in [34]. They proposed a string-based haptic interface device named SPIDAR—the first prototype of the device has four strings attached to a finger cap and allows users to use a fingertip to interact with the virtual environment. Later, the SPIDAR system was modified to two fingers [35], both-hands [36], [37], a human-scale virtual environment [38], seven degrees of freedom [39], and an inner string haptic device [40]. The SPIDAR series has broad application prospects with excellent force feedback accuracy, low inertia, and lightness.

C. POSITION OF THIS STUDY

This study aims to produce haptic imagery by employing cable-driven force feedback and ultrasonic tactile feedback. Force feedback is provided by cable tension, and tactile feedback is generated by an ultrasonic phased array.

Initially, most of the studies about ultrasonic tactile feedback focus were on improving the physical rendering pressure by advancing hardware and developing rendering tactile patterns [14]–[18]. The intensity can be improved by utilizing standing waves [14] or enlarging the size of the ultrasonic array [15]. The Cross-Field Aerial Haptics, which was proposed in [23], employs dual physical quantities: femtosecond-laser and focus ultrasound. The laser haptics can compensate for the intensity and spatial resolution of ultrasonic tactile feedback. Recently, research on ultrasound tactile feedback in midair has shifted to investigate different rendering methods on perception [21]–[24]. All of the studies in [21]–[24] used the methods described in [20] to evaluate the perception of ultrasound tactile feedback. This paper is concerned with both of them.

We expect that cable-driven force may be able to compensate for the shortcoming of the ultrasonic array’s output pressure. To improve the rendering effect of ultrasound tactile feedback, the modulation waveform is introduced as an influencing parameter to establish the rendering algorithm. Theoretically, string-based tension force and ultrasound tactile feedback are physically independent of each other, but when they work together at the same time, they will have an interaction effect on human perception. According to the up-down method, which estimates the 50th-percentile point of the psychometric function [20], the absolute threshold of perceivable ultrasound tactile feedback is estimated under the preload of cable-driven force on the finger. This will help us to better use their superposition and synergistic effects in the haptic rendering of this system.

The main contribution of this paper is to analyze and evaluate the proposed device. This paper is organized as follows. In section II, the analysis carried out on the principle and system of our device (Fig. 1) is described. Then, the design of three experiments is presented. The first experiment established the rendering algorithm for our ultrasonic tactile apparatus. The second evaluated the tactile feedback absolute threshold of our system. The third verified its working accuracy in the virtual workspace. Then, the application prospects of our research are discussed in section IV. Finally, this paper is concluded in section V.

II. DEVICE ANALYSIS

In this section, the models and system of our ultrasound tactile and cable-driven force feedback apparatus are presented.
A. ULTRASOUND TACTILE APPARATUS

1) MODELS

Ultrasound tactile feedback can be perceived by the hand because the mechanoreceptors within the skin receive shear waves [9], which are induced by acoustic radiation force. The ultrasonic phased array in our haptic interface device consists of $16 \times 16$ transducers (Fig. 1(b)), and it uses the phased array focusing technique to generate multiple focal points.

A single-frequency far-field piston model [41] of each transducer is employed in our research. The acoustic radiation pressure distribution for the focal point was modeled as the Huygens-Fresnel principle (1):

$$p(\rho, \eta) = kF_{p0} \int_{0}^{\alpha_{m}} \phi(\alpha) e^{ik\eta \cos \alpha} J_{0}(k \rho \sin \alpha) \sin \alpha \, d\alpha.$$  \hspace{1cm} (1)

where $\rho$, $\eta$ is the horizontal and vertical coordinates near the focal point, respectively. $k = 2\pi / \lambda$ is the wavenumber, $\lambda$ is the wavelength (8.6 mm in air at 25°C). $F_{p0}$ is defined as the sound pressure at the intersection of the symmetry axis and the wavefront, $\alpha_{m}$ is the central angle of the central axisymmetric spherical wave, $\phi(\alpha)$ is the sound pressure distribution function, $J_{0}$ is the Zero-order Bessel function. As equation (1) shows, the acoustic pressure distribution near the focus can be obtained, and it can be applied to a variety of ultrasound focusing systems.

The spatial resolution of the array is determined by the focus diameter $P_w$.

$$P_w = \frac{4\pi l_r}{kD_n}. \hspace{1cm} (2)$$

where $l_r$ and $D_n$ denote the focal length and the length of the side of the rectangular array, respectively. There is a tradeoff between the spatial resolution and array size.

Ultrasound array transducer geometries can be classified as one-dimensional (1D), two-dimensional (2D), or annular, linear, rectangular, ring-shaped [42]–[44]. However, the method of acoustic wave focusing is the same: controlling the phase or time delay of the excitation signal of each array element on the phased array. The acoustic pulses emitted by the array elements can form a wavefront in the sound field and realize the same phase superposition.

2) ULTRASOUND TACTILE SYSTEM

In our study, we use the Ultrahaptics STRATOS Explore Development Kit (USX). It includes 256 transducers (10 mm in diameter, T4010A1, Nippon Ceramic Co., Ltd.), arranged in a space of $165 \times 165 \, mm^2$, transducer frequency is 40 kHz. It uses two operating modes: Amplitude Modulation (AM) and Time Point Streaming (TPS). Time Point Streaming API is being used in our study gives users direct control over the generated waveform, intensity, position, and modulation frequency for control points.

The position data are calibrated in real-time through the Leapmotion and the cable-driven force apparatus. The phased array is connected to the PC through USB. C++, Python, and Unity3D are used to develop the application of the control system. The PC sends the data, including the positions of the focal points, modulated frequency, modulation waveform, and input command intensity to the driving board.
The ultrasonic tactile sensations can be felt from 5 cm from the array surface, the Ultrahaptics array performs best between 15 cm and 50 cm.

Based on the average work range of hands for male adults [45] and the operational characteristics of ultrasound phased array, the arrangement of the actuators and ultrasound phased array is shown in Fig. 1. A PC monitor (20.8-inch LCD) is set up behind the frame to display the real-time virtual environment. The frame is placed on a table, which is about 70 cm high.

B. CABLE-DRIVEN FORCE APPARATUS

1) MODELS

The force feedback apparatus is designed based on the effect of cable-driven tension. It allows a participant to use two fingers to interact with the virtual environment, and each finger ring is attached to four strings, which can enact force feedback on a finger in any direction in the workspace.

Force feedback is useful when the user is trying to move or change the shape of a virtual object. The magnitude of the force feedback is determined by the physical properties of the object, such as solidity, mobility, and gravity. Taking a virtual rigid body as an example, in our virtual space, the rigid body’s spring-damper characteristic can be expressed as follows:

\[ F_{rig} = k_c x_d + d_c \dot{x}_d \]  

where \( F_{rig} \) is the force to finger, \( k_c \) is the spring constant, \( d_c \) is the damper constant, \( x_d \) is the deformation distance of surface.

To generate force feedback, we need the position and movement direction of the finger and the physical properties of the virtual objects. Four strings are connected to a finger-ring. Each string is wound around a pulley attached to a rotary encoder. When the finger ring moves, the pulley rotates, and the length from the finger to the fulcrum changes. Pulses corresponding to the rotation of the pulley are generated from the rotary encoder. By counting the number of pulses, the degree of rotation of the pulley can be measured. The distance from the finger to fulcrum can be calculated through the rotation degree and diameter of the pulley.

The position of the finger can be obtained with equation (4):

\[
\begin{align*}
X &= (L_1 + L_2 - L_3 - L_4) / 4 \alpha_0, \\
Y &= (L_1 - L_2 + L_3 + L_4) / 4 \beta_0, \\
Z &= (L_1 - L_2 - L_3 + L_4) / 4 \gamma_0,
\end{align*}
\]

where \( L_i (i = 1, 2, 3, 4) \) represents the length of \( i \)-th line, \((X, Y, Z)\) is the coordinate of the finger position, \( \alpha_0, \beta_0, \gamma_0 \) denotes framework’s length, width, and height, respectively.

The dynamic equations of motion for cable-driven force are expressed using the Lagrangian method in Maple. However, since the dynamic equations are fairly nonlinear and complex, only the qualitative form of the dynamic equation is described in this paper. Mathematically, the problem can be expressed as equation (5). The resultant force is composed of the tensions of the four strings, and the tension on each string is generated by controlling the amount of electric current entering each motor. The resultant force is expressed as follows:

\[
J(q)^T \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \end{bmatrix} = F_0 \begin{bmatrix} x \\ y \\ z \end{bmatrix},
\]

\[
J(q)^T = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \end{bmatrix}. 
\]

where \((a_{mj}, a_{mj}, a_{mj}) (m = 1, 2, 3; j = 1, 2, 3, 4)\) is the unit vector of the tension on line \( j \)-th, \( J(q) \) is a \( 4 \times 3 \) Jacobian matrix relating cable tensions to joint moments. \( F_j \) describes the tension of cable \( j \)-th. \((F_j)\) is the vetor of cable tensions. \( F_0 \) is the resultant force. \((x, y, z)\) presents the unit vector of the finger displacement.

Cables can pull but not push, so the cables must be kept in tension to maintain control. Mathematically, equation (5) is underdetermined since the number of cables is greater than the number of DOFs. The optimal set of cable tensions can be found using the following linear programming problem [46]:

\[
\min \sum_i (F_j), \quad s.t. F_{min} \leq F_j \leq F_{max}. 
\]

where \( F_j \) is the force value on each string. The objective of (6) is to minimize the sum of all cable tensions such that each cable tension falls within the tension limits \( F_{min} \) and \( F_{max} \). The optimization problem is formulated as a linear programming problem due to computational efficiency.

2) CABLE-DRIVEN FORCE SYSTEM

The finger ring is made of a nylon polyester blend material. Its width is only 5 mm. It can be adjusted according to user needs, acting on different positions of the finger joints, and it will not interfere with the ultrasonic tactile effect on the fingertips and palm, or block the ultrasound. Fig. 1(a) shows an overview of the cable-driven force feedback device, which is constructed with eight actuators and a rectangular cubic frame.

An actuator consists of a planetary gearhead, a DC motor, a rotary encoder, a pulley, a holder, and a string. Fig. 1(c) shows a photograph of the actuator. The DC motor (25 mm in diameter, RE 25, Maxon Co., Ltd.) is connected at the back of the gearhead (20 mm in diameter, reduction gear ratio 1:4.4, Maxon Co., Ltd.). The rotary encoder (500 pulses/round) is connected at the back of the motor. A pulley is attached on the same shaft in front of the motor. The diameter of the pulley is 20 mm, and the distance is measured with a precision of 0.126 mm. Because it is lightweight and non-elastic, the polyethylene string (0.5 mm in diameter) is wound inside the pulley. The actuator is attached to the frame by the holder, where the string passes through the string fulcrum. The other components of the cable-driven apparatus are the driver and communication module. The DC driver owns a 12-bit D/A converter, yielding 4096 torque levels. Each motor
can generate a tension range from 0 to 6 N. A USB-CAN bus adapter is chosen to establish communication because of its excellent real-time performance and strong anti-interference ability compared with other bus structures. These devices are operated by applications created using LabVIEW and C++. The workspaces of single-finger and two-finger modes are a tetrahedron and an octahedron, respectively, as shown in Fig. 2.

The phased array and DC motors can work independently or synchronously when participants use our system. The cable-driven apparatus is operated by the PC to get the pulses of the encoder and current feedback value from DC drivers, and to enter the current to the DC drivers to control the tension of strings. DC motor drivers are connected to the computer with a USB-CAN adapter.

To straighten the strings and overcome the friction of the fulcrum, pulley, and strings, the normal operation of the cable-driven apparatus needs some amount of compensation force. Through multiple trials, it is found that 0.5 N is a good choice, as it is a robust compensation value to ensure the string tension state. The changing friction is less than 0.5 N. And 0.5 N compensation can guarantee a better tracking performance of the system. The maximum continuous force of the actuator output is 6 N. The maximum cable-driven force feedback of 10.3279 N can be obtained by equation (5). In Fig. 2, the strength of the force is normalized, and it displays the distribution of force feedback in the condition of no load. In other words, the actual force performed on a user’s finger needs to subtract the value of no-load, as below:

\[ F_{\text{actual}} = F_{\text{set}} - F_1. \]  

where \( F_{\text{actual}} \) represents the actual force feedback that users perceived. \( F_{\text{set}} \) is the force feedback value set in the virtual environment. \( F_1 \) denotes the no-load value of the cable-driven system. The minimum renderable force in the workspace of the cable-driven force feedback apparatus can be obtained in Fig. 2.

Fig. 3 shows our system diagram. As the controller, the PC not only processes the data, which includes the current, encoder pulses, focal point intensity, modulated frequency, and coordinate of focus, among others, but also provides a haptic interface server, which uses the Unity3D to establish the virtual environment. The PC can judge whether the finger collides with the virtual object through the data and then calculate the haptic feedback on the finger based on its physical properties. Next, based on the rendering algorithm, the intensity of tactile feedback can be changed by adjusting the input parameters of the ultrasonic phased array. The force feedback value is converted to the magnitude of current and sent back to actuators. At the same time, the movements of hands and virtual objects are updated in the visual subsystem. Finally, users can sense the force and tactile sensation, while the motion and deformation of virtual objects under the action of hands can display on the PC monitor.

### III. Evaluation Experiments

In this section, three experiments are described. The experiments were conducted to establish the tactile rendering algorithm, evaluate our device perception, and study the synergistic effect of cable-driven force and ultrasonic tactile.

#### A. EXPERIMENT OF ESTABLISHING RENDERING ALGORITHM FOR UltraHaptics

The object of this experiment was to establish a rendering algorithm for the ultrasonic phased array. Raza et al. designed
an algorithm to enable the UltraHaptics device to output a desired sensation [24], but only input command intensity, modulation frequency, and position of focus were considered as influencing parameters. In this experiment, besides the above input parameters, the modulation waveform and the duty ratio of the square wave were also used as influencing parameters for ultrasonic tactile feedback.

1) SETUP

The setup, as shown in Fig. 4, was mainly composed of an adjustable frame and an electronic scale (resolution 1 mg). The ultrasonic phased array was installed on the frame, and the direction of the array was set to face down. The gram force (gf) was used in this experiment as a unit of pressure. It is assumed that the pressure acts uniformly on the surface of the electronic scale. The 2-dimensional coordinate system was marked on the bottom surface of the frame. The electronic scale can be moved on this XY plane, while the height of the UltraHaptics was adjusted by moving the z-stage.

The USX has Time Point Streaming API, which enables developers to render pressure with different command intensity, the height of the focal point, the lateral deviation of the focal point from the center, rendered frequency, and the modulation waveform of the focal point. The focal point was displayed on the surface of the electronic scale. Each sample was measured once every ten seconds. There were nineteen samples for each data point. The average of these data was the final result.

2) METHODS

In the first test, the input command value, frequency, height of the device, and modulation waveform were 1, 240 Hz, 150 mm, and cosine wave, respectively. The focal point was rendered in all four directions away from the center at a maximum distance of 60 mm with a step size of 20 mm.

In the second test, the focal point was on the center axis and 150 mm away from the array. The modulation waveform was the cosine wave. The input command intensity value was varied from 0 to 1.

In the third test, the focal point was on the center axis and 150 mm away from the array. The modulation waveform was the cosine wave. The input command intensity value was 1, and frequency was set at 40, 80, 100, 140, 180, 240, and 300 Hz.

In the fourth test, the focal point was on the center axis. The input command intensity value was 1, and the frequency was set at 240 Hz. The modulation waveform was the cosine wave. The height of the device was set at 100, 150, 200, 250, and 300 mm.

In the fifth test, the focal point was on the center axis and 150 mm away from the array. The input command intensity value was 1, and the frequency was set at 240 Hz. There were six periodic waveforms (sine, cosine, sawtooth, square, triangle wave, and the absolute value of sine) selected, they had the same sample frequency (10000 Hz), as Fig. 5 shows.

In the sixth test, the focal point was on the center axis. The input command value, frequency, height of the device, and modulation waveform were 1, 240 Hz, 150 mm, and square wave, respectively. The square wave duty ratio varied from 0.5 to 99%.

3) RESULTS

Through test 1, the mapping function of the deviation from the center’s effect on output pressure in [24] was proven to

![FIGURE 4. The measurement system used to record focus strength.](image_url)

![FIGURE 5. Modulation waveform used in our measurement (from top to bottom are cosine, triangle, sawtooth, square, sine wave, and the absolute value of sine).](image_url)
be suitable for our system (the error between the measured and formula force was smaller than 10%) [47]. The relation of deviation from the center and output pressure can be expressed as follow:

$$O_{\text{max}}(s) = 2.71 \times 10^{-8}s^3 - 1.07 \times 10^{-5}s^2 - 5.05 \times 10^{-3}s + 0.4152. \quad (8)$$

where $O_{\text{max}}$ is defined as the output pressure in gf, $s$ is the distance from the focus to the center axis in mm.

Fig. 6 and Fig. 7 show the recorded data of test 2 and test 3, respectively. It can be seen that the input command value and pressure have a highly nonlinear relationship. The mapping function (9) was given by the second-order polynomial regression fitting of test data.

$$O_{\text{gf}} = Q_i I_c^2 + N_i I_c + T_i. \quad (9)$$

where $O_{\text{gf}}$ is defined as the output pressure in gf, $I_c$ denotes the input command intensity, $Q_i$, $N_i$, and $T_i$ are the coefficients of the polynomial for different modulation frequency, as Table 1 shows.

In test 4, we empirically established the formula of the relationship between distance from the focus to the array and output pressure. The recorded data are shown in Fig. 8. The mapping function (10) was given by the second-order polynomial regression fitting of test data.

$$z_{\text{ver}}(d) = 1.084 \times 10^{-6}d^2 - 6.951 \times 10^{-4}d + 0.4654. \quad (10)$$

where $z_{\text{ver}}$ is defined as the output pressure in gf, $d$ describes the distance from the array to the focus in mm.

The purpose of test 5 was to study the effect of the modulation waveform on the output pressure. The results are shown in Fig. 9. Equation (11) is the relationship between the modulation waveform and output pressure for our device.

$$F_{\text{waveform}} = F_{\text{wf}} F_{\text{cos}}. \quad (11)$$

where $F_{\text{waveform}}$ is the output pressure for different waveforms, $F_{\text{cos}}$ is the output pressure for cosine waveform. The waveform coefficient is $F_{\text{wf}}$, assume cosine waveform coefficient is 1, the $F_{\text{wf}}$ of the absolute value of sine, sine,
sawtooth, square, and triangle wave are respectively 1.255, 1.001, 0.79, 1.37, and 0.849. Although the noise was louder, the maximum output pressure could be generated by the square waveform on the same condition compared with the other five waveforms. Researchers typically use the cosine wave as a modulation waveform because it can produce strong tactile points without loud noise disturbance. But under a normal operating environment, the users of our device need to wear headphones with white noise to block out external noise. Hence, we can ignore the influence of the noise factor on the waveform selection.

The result of test 6 shows the relationship between the square wave duty ratio and output pressure as shown in Fig. 10. As the duty cycle increased, the output pressure increased, displaying a linear relationship. The linear function was used to fit the test data and obtain equation (12):

\[
S_q = 0.01244R_{duty} - 0.07189. 
\]

where \( S_q \) denotes the output pressure, and the unit is gram force, \( R_{duty} \) is the duty ratio of the square wave.

The influence trend of the input parameters on the output pressure was maintained under different conditions based on the empirical verification. Therefore, as the impact factor, the position of focus was normalized into the influence coefficient, as shown by equations (13) and (14).

\[
F_{plane} = \frac{O_{max}(0)}{O_{max}(s)}. \tag{13} \\
F_{ver} = \frac{z_{ver}(100)}{z_{ver}(d)}. \tag{14} 
\]

where \( F_{plane}, F_{ver} \) is the influence coefficient of deviation from the center, and impact factor of height of phase array, respectively. \( O_{max} \) and \( z_{ver} \) can be obtained from the equation (8) and (10).

Then these coefficients were multiplied by \( O_{gf} \) in equation (9) as follows:

\[
O_{ultra} = O_{gf} F_c. \tag{15} 
\]

where \( O_{ultra} \) describes the output pressure of the UltraHaptics used in our system, \( F_c \) can be represented as combination of these factors: \( F_c = F_{ver} F_{plane} F_{wf} \).

B. PERCEPTUAL ABSOLUTE THRESHOLD OF ULTRASOUND TACTILE

This experiment aimed to investigate the absolute threshold of perception for the subject during virtual manipulation. Our haptic interface device allows users to manipulate virtual objects while perceiving force and ultrasound tactile sensations. Rigid body properties are provided by cable-driven force feedback. The surface features of the mid-air tactile pattern are rendered by focused ultrasound. In this section, a series of experiments are conducted to evaluate the absolute threshold of ultrasound tactile perception while simultaneously providing cable-driven force feedback.

1) SETUP

Sixteen participants took part in the user study (six females and ten males, aged from 25 to 35, all right-handed). Participants sat in an office chair in front of the device, which they were free to adjust to their liking. They all wore headphones that played white noise to block out external noise. All subjects used their index finger as shown in Fig. 11. A virtual sphere with a radius of 2 cm was displayed in the workspace. It was located 20 cm away from the array surface and on the central axis. The sphere was rendered with varying force feedback, tactile input intensity, and frequency.

2) METHODS

The adaptive method with staircase procedures was used in these experiments. The varied trend of input intensity command included different staircase procedures. In a descending series, the input command intensity started from 1 to 0. In an ascending series, the input command intensity started from 0 to 1. To avoid errors of expectation, on each trial, one
of the two sequences was randomly selected with an equal a priori probability of 0.5. In the up-down adaptive sequences, participants touched the sphere with the index finger, and the next input intensity increased when the participant indicated the presence of the ultrasound tactile. When the participant reported that ultrasound tactile was no longer perceived, the following input intensity increased. The trial of each sequence stopped once eight reversals occurred. To increase the precision in estimating the threshold, a larger step size (3 dB) was used for the first three reversals, and a smaller step size (1 dB) was used for the remaining reversals. Because the stimulus level had yet to converge near the threshold level being estimated, the first few reversals of a run are not included in the final data analysis [20]. In this experiment, the minimum perceivable ultrasound tactile (or absolute threshold) was computed as the average of the peaks and valleys of values for the last five reversals.

The different force feedback was 1, 3, 6, and 10 N. The different rendering frequencies were 80, 100, 140, 180, 240, and 300 Hz. In the first set of experiments, participants touched the virtual sphere with index finger without cable-driven force feedback. This whole process was repeated for six different rendering frequencies. Different frequency patterns were presented in a randomized order. The second set of experiments added force generated by cable-driven tension on the index finger. This whole process was repeated for six different rendering frequencies and four force feedback values. Therefore, each sequence included 24 different rendering methods for the presentation of the pattern. The patterns were presented in a randomized order. In order to minimize fatigue and sensory bias, after each stimulus, participants were given five seconds to rest. After one staircase experiment of input intensity command, the next staircase experiment was entered after a 45-second break.

3) RESULTS
Compared to the other state-of-the-art methods for detecting the ultrasonic tactile threshold, our method focused on the study of the absolute threshold of ultrasonic perception under the preloading of cable-driven force. To test this, we ran the up-down method to estimate the minimum perceivable ultrasound tactile feedback. In order to better test the effect of cable-driven force on the absolute threshold of ultrasound tactile feedback, two experimental groups were set up for comparison: without cable-driven force and with cable-driven force.

The condition of 240 Hz modulation frequency can be taken as an example. The results show in Fig. 12(a) and (b) show the measurement of minimum perceivable ultrasound tactile without force feedback and with 1 N cable-driven force feedback, respectively (odd-numbered trials begin with the high-intensity command; even-numbered trials begin with the perceptually low stimulus). The staircases converge around a value after a few reversals. Table 2 lists the minimum ultrasound tactile feedback for different force sensations.

![Figure 12](image-url)

**TABLE 2.** The absolute threshold of ultrasound tactile for different force feedback.

| $F_{str}[N]$ | $O_{ultrasonic}[gf]$ |
|--------------|----------------------|
| 1            | (0.027943, 0.046972) |
| 3            | (0.039201, 0.052318) |
| 6            | (0.045011, 0.052917) |
| 10           | (0.051009, 0.060108) |

![Figure 13](image-url)

**FIGURE 13.** The minimum perceivable ultrasonic tactile values for all frequencies.

As shown in Fig. 13, compared with the bare hand experiencing ultrasonic tactile feedback, the minimum perceptible ultrasonic tactile feedback to the fingers under the action of the cable-driven force increased. However, in this case, the optimal ultrasonic tactile rendering frequency on the finger was still 180-240 Hz. When the force feedback...
from the cables increased, the minimum perceivable tactile threshold also significantly increased. This shows that when cable-driven force and ultrasonic tactile feedback are applied to the hand simultaneously, the sensitivity of the hand to ultrasonic tactile feedback will decrease.

C. POINTING THE VIRTUAL SPHERE

1) SETUP
Another set of eight participants (three females and five males, age from 24 to 30, all right-handed, wearing headphones that played white noise) took part in this experiment. Participants sat in an office chair in front of the device, which they were free to adjust to their liking. A virtual sphere with a radius of 2 cm was displayed in the workspace. The height of the sphere center was 200 mm and located on the central axis. Participants touched the haptic sphere in midair provided by our system with the index finger and retracted their finger after validating the haptic sensation. Meanwhile, the locus path was recorded (Fig. 11).

2) METHODS
In this experiment, the sphere’s rigid body properties were provided by cable-driven force feedback, and the value of the force was set to be constant at 1 N. The surface features of the virtual sphere rendered by ultrasonic tactile feedback were defined by the input command value, frequency, and modulation waveform, which were 1, 240 Hz, and cosine wave, respectively. The rendering methods included three distinct patterns: (a) with ultrasound tactile feedback, (b) with cable-driven force feedback, and (c) with ultrasonic tactile feedback and cable-driven force feedback working together. These rendering patterns were presented in a randomized order. After participants sensed the haptic feedback, the next experiment condition was presented after a 45-second break until participants completed experimental tasks.

3) RESULTS
Fig. 14 shows the error value of the finger pointing over the object surface in three cases. The horizontal axis is the distance from the finger to the sphere’s surface. The vertical axis is time. The vertical dotted line represents the surface of the sphere. In order to compare the finger paths clearly, the coordinate scales of (a), (b), and (c) were adjusted to obtain (d), (e), and (f), respectively.

The results in (a) and (d) show that the locus path went inside the sphere. In cases (b) and (e), with the cable-driven force feedback, the finger rested stably at the surface of the sphere, but the locus path went inside the sphere. In the cases with ultrasonic tactile feedback and cable-driven force feedback (c) and (f), the finger rested stably at the surface of the sphere. Because the ultrasonic tactile feedback felt like airflow, and it was smaller than the cable-driven force, the delay in (d) was greater than in (e). In (f), because of the ultrasound and cable-driven haptic rendering on the sphere, the finger can point to the sphere more precisely and stop more quickly.

Through this experiment, we can manipulate the virtual objects more accurately and sensitively due to the synergistic effect of cable-driven force feedback and ultrasound tactile feedback.

IV. APPLICATIONS
In this paper, we employ ultrasonic tactile feedback for the surface characteristics rendering of virtual objects. On the other hand, we employ the cable-driven force feedback for the rigid characteristics rendering of virtual objects. Adding haptic feedback devices to VR is an important way to improve
its immersion. But at present, the skin, hair characters of virtual objects, and petting movement could not be displayed by haptics devices used in VR. This system can fill this gap. Multi-resolution haptics for VR is an important way of applications for this haptic device, which can expand the system to the clothing sales on the internet, research on precious silk painting or fabrics unearthed, help patients with fur allergies, and so on.

**V. CONCLUSION**

In this paper, a new haptic interface device is proposed, using cable-driven force feedback and ultrasonic tactile feedback. Compared to the conventional haptic interface device, our device has the advantage of simultaneously combining cable-driven force feedback and ultrasonic tactile feedback.

Haptic images can be rendered by the ultrasonic phased array and cable-driven parallel manipulators. To enhance the rendering effects of ultrasonic tactile feedback, the input intensity value, modulation frequency, and position of focus are considered as the input parameters for the rendering algorithm, and experiments are conducted to study the relationship between modulation waveform and output pressure. The rendering algorithm for the ultrasonic tactile feedback of our device is established. The combination of cable-driven force and ultrasonic tactile feedback not only compensates for the shortcoming of the ultrasonic array’s output pressure but also offers synergistic effects on haptic perception. Our results show that the cable-driven force feedback affects the tactile perception of ultrasound haptics. A series of experiments shows that the absolute threshold of ultrasound tactile perception will increase under the condition of cable-driven force preloading. Due to the synergistic effect of cable-driven force feedback and ultrasound tactile feedback, virtual objects can be manipulated more accurately and sensitively.

In future work, an optimal haptic rendering algorithm and multifinger manipulators for our system will be developed. The device presented in this paper offers a promising approach to implementing the ultrasonic tactile feedback. We believe that this device has a large exploration and application space.

**ACKNOWLEDGMENT**

The authors would like to thank LetPub (www.letpub.com) for its linguistic assistance during the preparation of this manuscript.

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