An Interactive Tool for Simulating Mid-Air Ultrasound Tactons on the Skin

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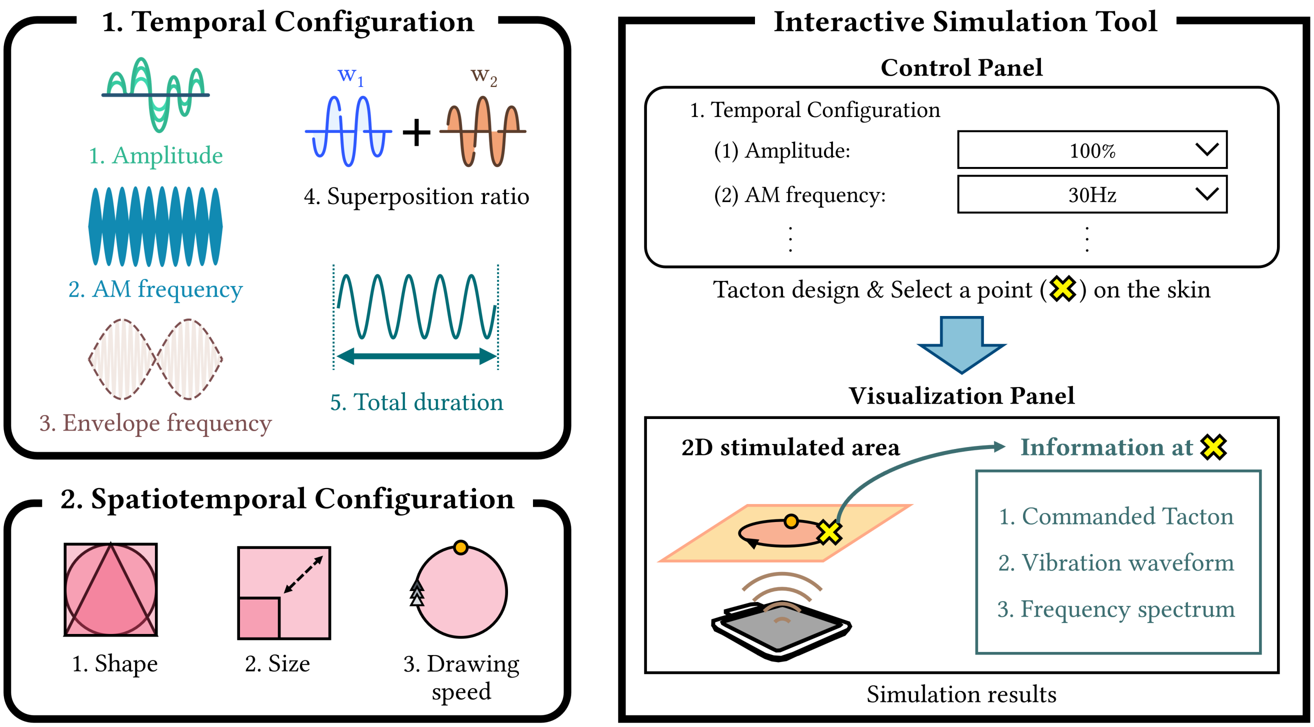

Figure 1: Overview of our interactive simulation tool for testing design parameters in mid-air ultrasound technology. Haptic designers can control five temporal and three spatiotemporal parameters to design a mid-air ultrasound Tacton. They can also select a point on the 2D plane to visualize the temporal waveform and frequency spectrum of the Tacton at that point on the skin.

ABSTRACT

Mid-air ultrasound haptic technology offers a myriad of temporal and spatial parameters for contactless haptic design. Yet, predicting how these parameters interact to render an ultrasound signal is difficult before testing them on a mid-air ultrasound haptic device. Thus, haptic designers often use a trial-and-error process with different parameter combinations to obtain desired tactile patterns (i.e., Tactons) for user applications. We propose an interactive tool with five temporal and three spatiotemporal design parameters that can simulate the temporal and spectral properties of stimulation at specific skin points. As a preliminary verification, we measured vibrations induced from the ultrasound Tactons varying on one temporal and two spatiotemporal parameters. The measurements and simulation showed similar results for three different ultrasound rendering techniques, suggesting the efficacy of the simulation tool. We present key insights from the simulation and discuss future directions for enhancing the capabilities of simulations.

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CCS CONCEPTS

• **Human-centered computing** → **User interface toolkits**; **HCI theory, concepts and models**.

KEYWORDS

Mid-Air Haptics, Computational Simulation, Ultrasound Tacton Design

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1 INTRODUCTION

Mid-air ultrasound technologies create haptic feedback on the user's skin without physical contact with a device. This technology focuses acoustic waves into one or multiple focal points using a phased array of ultrasonic transducers, and modulates or moves these focal points to create a sense of touch [24]. Designers are exploring the parameter space of the mid-air ultrasound patterns (i.e., tactile icons or Tactons) to deliver information or emotion to users in various applications, including touchless public displays [18, 31], automotive user interfaces [1, 8], medical training simulations [13, 14], and virtual reality environments [12, 16, 20, 32].

Several rendering techniques and parameters exist for creating mid-air ultrasound Tactons. The common approaches include using either temporal parameters (e.g., amplitude-modulated frequency) [9], spatiotemporal parameters (e.g., trajectory or drawing speed of a focal point) [6, 19, 30], or a combination of both [4, 7, 26]. These rendering techniques accompany complex physical effects on the skin. For example, amplitude modulation (AM) focuses acoustic pressures on a static focal point, vibrating the local distribution of skin and activating a group of mechanoreceptors. Spatiotemporal modulation (STM) moves a focal point along a trajectory, thus vibrating the skin at a drawing frequency on the trajectory points. Furthermore, the combination of AM and STM techniques offers both AM frequency and drawing frequency, making it challenging for haptic designers to predict the rendered frequency on the user's palm.

The combinations of parameters from the above techniques usually yield in vibrations that are complex to predict, so the designers resort to repeat trial-and-errors to find a Tacton set of their interests. Thus, the physical simulations of the mid-air ultrasound Tacton can help understand its perception and reduce the Tacton design cost. Prior literature proposes physical simulations for the ultrasound vibrations and their measurement data, for example, AM or STM of a focal point [2, 3] and gap detection thresholds between two static focal points [2, 10]. Yet, as the existing simulations typically simulate one parameter or one rendering technique, more research is needed on interactive simulation tools for testing the interaction of temporal and spatiotemporal parameters in complex ultrasound Tactons and the combination of rendering techniques.

To fill this gap, we developed a Python-based interactive simulation tool for skin vibrations induced by ultrasound Tactons rendered by modulating a single focal point. Our simulation facilitates the design of Tactons with five temporal parameters: amplitude, AM frequency, envelope frequency, superposition ratio, and total duration; and three spatiotemporal parameters: the shape, size, and drawing speed of a focal point's trajectory. These parameters are commonly used by designers for creating Tactons. Designers can manipulate these eight parameters in the control panel and view the vibration waveform and frequency spectrum at any point on the skin in the visualization panel. Thus, the simulation tool enables designers to efficiently explore the physical effects of multiple parameters before rendering the Tactons on the device.

As an initial verification of the simulation tool, we designed 15 mid-air ultrasound Tactons varying in AM frequency, size, and drawing speed and tested AM rendering, STM rendering, and a combination of AM and STM rendering techniques. We selected the three parameters in our preliminary measurements because they mainly affect the spectral peaks of the induced vibrations at a skin point. We used our simulation tool to predict vibrations at five points on the skin. Then, we employed a STRATOS Explore ultrasound haptic device to render the Tactons and measured vibrations induced at these points with a laser vibrometer. Our preliminary measurements showed high correspondence with our simulation results, revealing similar temporal waveforms and spectral harmonics to the simulated predictions. We discuss directions for future research to improve the measurement methodology and to build a high-utility simulation. Our contributions include:

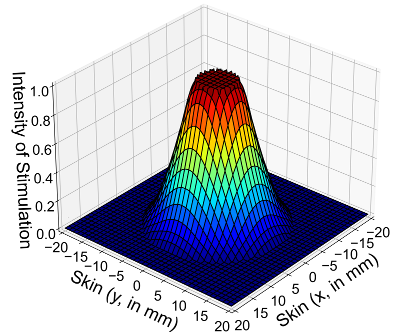
- An interactive tool that simulates the vibrations induced on the skin from physical interactions of five temporal and three spatiotemporal parameters in mid-air ultrasound Tactons.
- Preliminary measurements of vibrations induced by 15 mid-air ultrasound Tactons, suggesting the validity of the simulation tool for AM and STM rendering.

2 METHOD AND IMPLEMENTATION

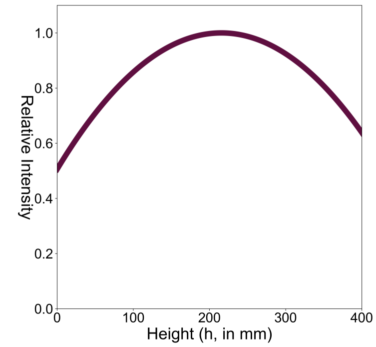
We developed a computational model to simulate mid-air ultrasound Tactons that use a single focal point. This model predicts the vibration waveforms and frequency spectra at any points on the skin area.

2.1 Assumptions for Simulation

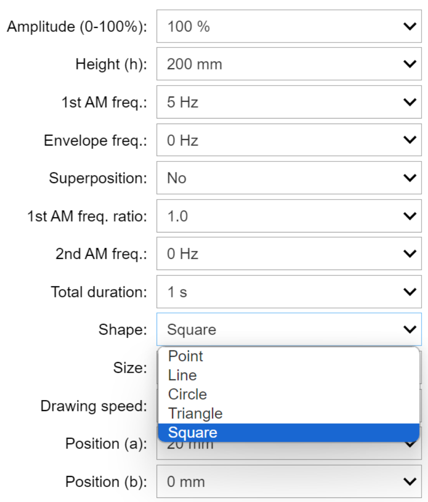
We made several assumptions about mid-air ultrasound stimulation in order to lower the computational complexity of the simulation tool. In the literature, focused mid-air ultrasound at a single focal point creates a central oval-shaped vibration area with maximum amplitude, followed by four smaller vibration areas located at four directions apart 15 *cm* from the center with about less than 30 percent of the center amplitude (side lobes) if the ultrasound device located at the 20 *cm* distance [2, 33]. The amplitudes of side lobes are nearly below the detection threshold at the maximum stimulation [11], while the side lobes vary on the distance between the device and the focal point due to changes in the angles of the ultrasound transducers. Therefore, our model assumes the ultrasound stimulation occurs at a target single circular point on the skin. In addition, we assumed that the skin of the user's palm is a 2D plane, and the propagation of waves along the skin does not occur, considering the computational complexity of the model. We discuss the implications of these assumptions in Section 4.



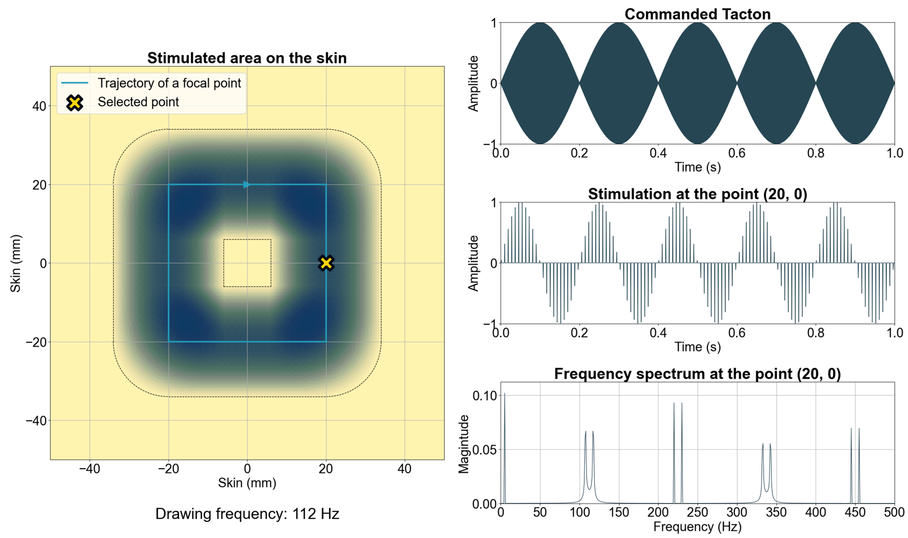
(a) Intensity by a static focal point



(b) Relative intensity by height from a device



(c) Control panel



(d) Visualization panel

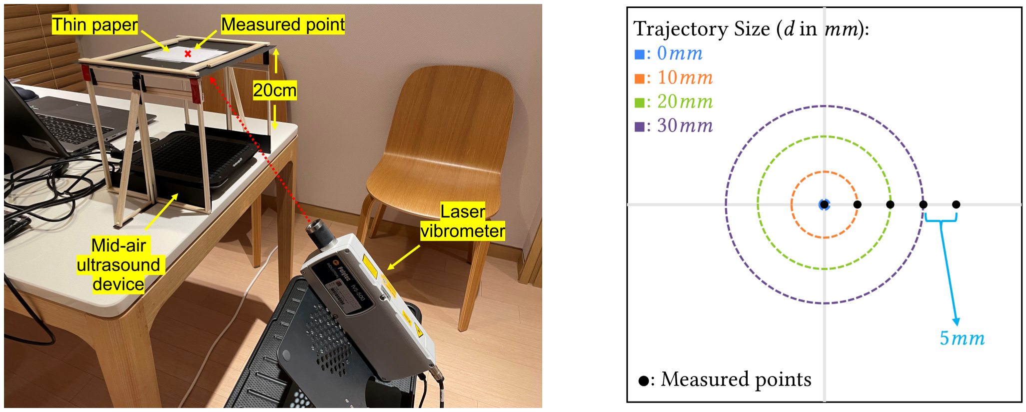
Figure 2: Plots for the intensity of stimulation by a single focal point at the height h and the interactive simulation tool: (a) The intensity of stimulation decreases with distance from the focal point [2]. (b) The relative intensity determined by the distance between a focal point and the mid-air ultrasound device. (c) The control panel in our interactive tool for manipulating parameters in temporal and spatiotemporal configurations. The dropdowns allow users to select design parameters and a position ($\vec{a} = (a,\ b)$) on the skin. (d) The visualization panel showing the 2D stimulated skin area (Left) and vibration waveform (Right) at a specific point on the skin. The sky-colored line represents the trajectory of a focal point, the black dotted line represents the borderline influenced by the stimulation, and the "X" symbol represents the point selected to see the effects of the stimulation by the Tacton. The three plots (Right) display the temporal plot of the Tacton, and the temporal and spectral plots of the stimulation at the selected point $\vec{a}$ by the user .

2.2 Parameter Space of Mid-Air Ultrasound Tactons in Simulation

Our model provides two configuration spaces for rendering mid-air ultrasound Tactons (Figure 1): (1) The temporal configuration includes five parameters of *amplitude*, *AM frequency*, *envelope frequency*, *superposition ratio*, and *total duration*; and (2) the spatiotemporal configuration includes three parameters of *shape*, *size*, *drawing speed* of a focal point trajectory. We selected these parameters based on the most frequently used parameters in Tacton design literature [4, 7, 15, 21–23, 28]. Thus, users can observe the vibration waveform at any point on the skin by controlling these eight parameters of mid-air ultrasound Tactons.

1. Temporal configuration: We defined the temporal configuration of mid-air ultrasound Tactons using the mathematical equation $p(t)$, which controls five parameters:

$$p(t) = \begin{cases} A \cdot U(t)\{w_{AM_1} M_1(t) + w_{AM_2} M_2(t)\}E(t), & \text{if } \textit{superposition ratio} \text{ is used.} \\ A \cdot U(t)M(t)E(t), & \text{otherwise.} \end{cases} \tag{1}$$



(a) (b)

Figure 3: Our measurement setup. (a) We used a laser vibrometer to measure vibrations on paper induced by mid-air ultrasound Tactons. (b) In all measurements, we measured the vibrations at the same 5 points, spaced at 5 mm intervals.

where $U(t)$ represents the continuous ultrasound at 40 kHz (typical frequency from commercial mid-air ultrasound haptic devices), $M(t)$ is an AM sinusoid of $sin(2\pi f_{AM} t)$ with AM frequency f_{AM}, $E(t)$ is an envelope sinusoid of $sin(2\pi f_e t)$ with envelope frequency f_e, and w_{AM_1} and w_{AM_2} is the weights of two AM sinusoids (i.e., $M_1(t)$ and $M_2(t)$).

Amplitude (A) corresponds to the peak acoustic pressure at the focal point, ranging between 0% and ± 100%, as provided by a mid-air ultrasound device. While A represents a commanded amplitude on the device, its relative intensity varies with height, which is the vertical distance between the focal point and the mid-air ultrasound device. The amplitude is known to have an inverted U-shaped relationship with height, reaching a maximum at 200 *mm* [25] above the device. We applied the above findings to calculate relative intensity of A as in Figure 2b. *AM frequency* (f_{AM}) represents a temporal frequency that modulates $U(t)$ [21, 22]. Here, f_{AM} = 0 Hz indicates no AM rendering (i.e., $M(t) = 1$), suggesting that STM rendering is necessary to create tactile sensations. *Envelope frequency* (f_e) refers to a frequency modulating $M(t)$ [23] and f_e = 0 Hz denotes a constant envelope (i.e., $E(t) = 1$). *Superposition ratio* (w_{AM_1}:w_{AM_2}) is the mixing ratio of two sinusoidal signals for creating a superimposed signal. The simulation tool currently provides five ratios: 1:0, 0.75:0.25, 0.5:0.5, 0.25:0.75, 0:1 [15, 17, 35]. *Total duration* (t_d) is the maximum t of the vibrations. While the computational model can handle any duration, we set 10 seconds as the maximum in the current tool, in line with the Tacton durations common in user applications [28].

2. Spatiotemporal configuration: We defined the spatiotemporal configuration as the spatial properties of the temporal formula $p(t)$, consisting of three parameters, *shape*, *size*, and *drawing speed* of a focal point trajectory in a 2D plane above the mid-air ultrasound device (Figure 1). In this configuration, *shape* represents the trajectory of a focal point in the 2D plane. Based on the literature [7, 27], we provide five shapes: point, horizontal line, circle, regular triangle, and square. *Size* (d, in *mm*) refers to the length of the line, diameter of the circle, or the side length for the regular triangle and square. We set the maximum *size* as 60 *mm*, considering the typical size of a user's palm [7, 29]. *Drawing speed* (v, in m/s) denotes the velocity of a focal point's movement. Combinations of these three parameters derive a drawing frequency (f_d), defined as the number of completions or revolutions of a trajectory per second [5, 26, 34], creating a spatiotemporal tactile sensation (i.e., STM) [6]. The three parameters of *shape*, *size*, and *drawing speed* determine the 2D position of a focal point on the moving trajectory at t, represented as $\vec{x}(t) = (x(t), y(t))$. For example, when *shape* is the point, $\vec{x}(t)$ is a constant at (0, 0). When *shape* is the circle, $\vec{x}(t)$ can be expressed as $(\frac{d}{2}\cos(2\pi f_d t),\ \frac{d}{2}\sin(2\pi f_d t))$. With the trajectory $\vec{x}(t)$ from a total of the three parameters, we denoted $p(t)$ at the focal point as $p(\vec{x}(t), t)$.

2.3 Model Architecture

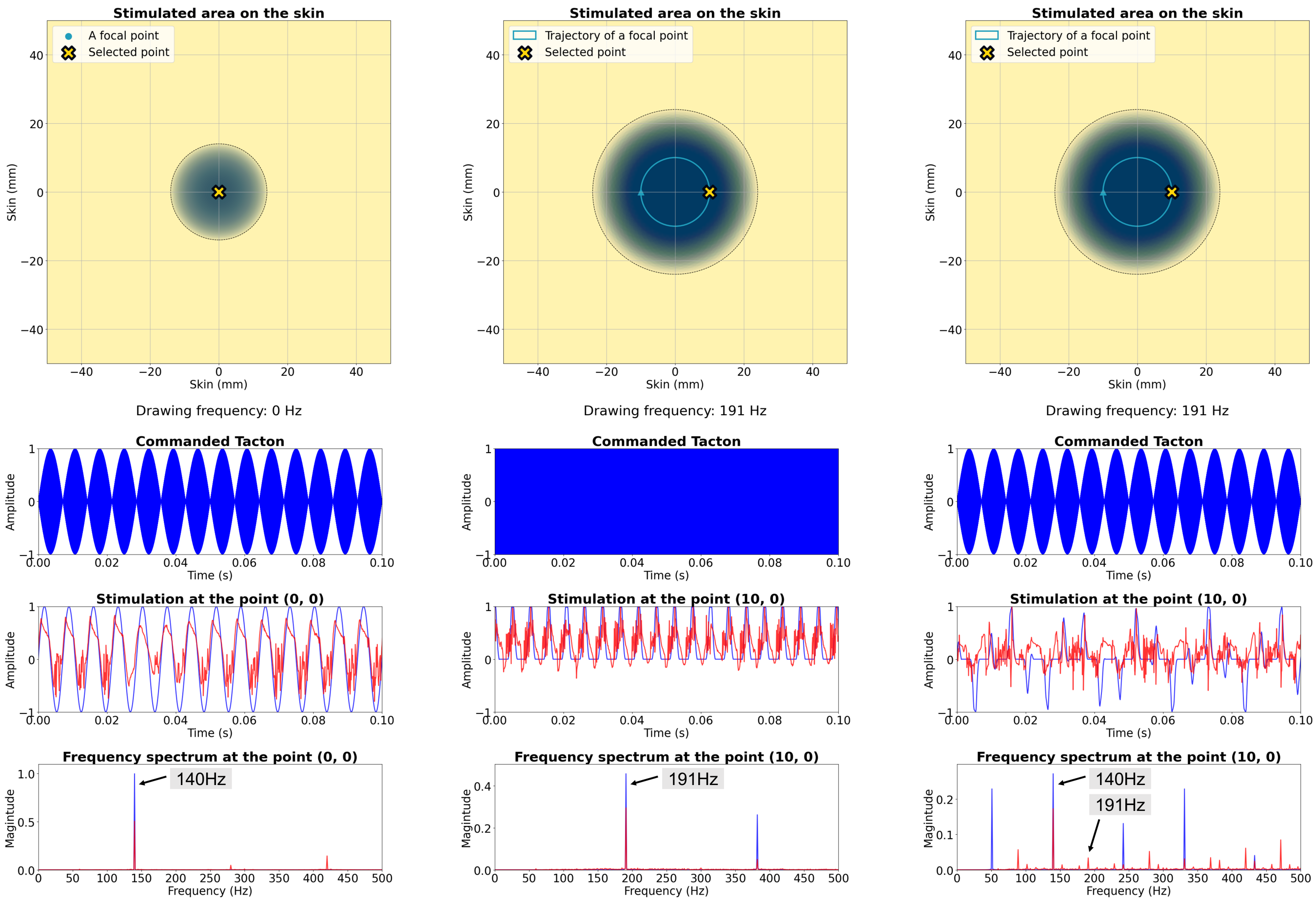
At a selected point $\vec{a} = (a, b)$ on the 2D plane above the device, we can define the Euclidean distance between $\vec{x}(t)$ (location of the focal point) and $\vec{a}$ as $D(\vec{x}(t), \vec{a})$. The distance determines the intensity of stimulation at $\vec{a}$, which we defined as $S(D(\vec{x}(t), \vec{a}))$ (Figure 2a). Thus, we defined the final intensity of stimulation as $A(\vec{x}(t), \vec{a}) = A \cdot S(D(\vec{x}(t), \vec{a}))$ and expressed $p(\vec{x}(t), t)$ at $\vec{a}$ as:

$$p(\vec{x}(t), \vec{a}, t) = \begin{cases} A(\vec{x}(t), \vec{a})U(t)\{w_{AM_1} M_1(t) + w_{AM_2} M_2(t)\}E(t), & \text{if } \textit{superposition ratio} \text{ is used.} \\ A(\vec{x}(t), \vec{a})U(t)M(t)E(t), & \text{otherwise.} \end{cases} \quad (2)$$

With this implementation, our model facilitates tests for the temporal and spatiotemporal configurations, comprising five and three parameters, respectively (Figure 2c). In the interactive simulation tool, we provide the stimulated areas on the skin by $p(\vec{x}(t), t)$ (Figure 2d Left). Our tool also presents the temporal plot of the commanded Tacton (i.e., Equation 1) considering $U(t)$ as 40 kHz sinusoid. For the temporal plot for the signal at $\vec{a}$ (i.e., Equation 2), we substituted 1 to $U(t)$ because the ultrasound stimulation acts as a constant pressure [6, 29]. Then we applied Fourier transform to the temporal waveform to estimate the frequency spectrum (Figure 2d Right).

3 PRELIMINARY MEASUREMENT

For preliminary verification for the capability of our simulation tool, we designed and measured 15 mid-air ultrasound Tactons considering three rendering scenario: (1) Pure AM rendering (*PureAM*), (2)



(a) *PureAM* (f_{AM} = **140 Hz**)

(b) *PureSTM* (d = **20** mm, v = **12** m/s, f_d = **191 Hz**)

(c) *AM+STM* (f_{AM} = **140 Hz**, d = **20** mm, v = **12** m/s, f_d = **191 Hz**)

Figure 4: Three exemplar comparisons for pure AM rendering, pure STM rendering, and combination of AM and STM rendering, between simulations (blue) and measurements (red).

pure STM rendering (*PureSTM*), and (3) a combination of AM and STM (*AM+STM*).

3.1 Methods

We selected ultrasound Tactons for the measurements, focusing on *AM frequency* (f_{AM}) in the temporal configuration and *size* (d) and *drawing speed* (v) in the spatiotemporal configuration, as these three parameters mainly determine the AM frequency and the drawing frequency of the ultrasound Tactons which affects vibration spectrum. We did not use the other temporal parameters and we kept *total duration* at 1 second. In addition, we maintained *shape* as the circle and *height* at 200 *mm*. We used four f_{AM} values: 0, 80, 140, and 210 Hz. We selected f_{AM} = 0 Hz to test pure STM rendering (*PureSTM*) and f_{AM} > 60 Hz, as the power lines in our country introduces a constant 60 Hz measurement noise. We also used four combinations of size and drawing speed as (d in mm, v in m/s): (0, 0), (10, 6), (20, 12), (30, 18). We chose (0 mm, 0 m/s) to test pure AM rendering (*PureAM*), and maintained the same ratio of $\frac{v}{d}$ for the other three combinations to have the same drawing frequency at 191 Hz.

We rendered the ultrasound Tactons using the STRATOS Explore device by Ultraleap and measured the Tactons using a 1D laser vibrometer (Ploytec IVS-500) on paper (Figure 3a). Initially, we tried to measure the displacements induced by the ultrasound device on the skin of palm but the induced displacement was too weak and lower than the vibrometer's minimum resolution. After much experimentation, we configured a system to measure displacements induced by the ultrasound Tactons on a thin paper. For the Tactons varying on *AM frequency*, *size*, and *drawing speed*, we measured vibrations at 5 points inside, on the trajectory, and outside the shape, spaced at 5 mm intervals (Figure 3b).

3.2 Results

The preliminary measurement results showed similar results to those reported in [3], although we measured the vibrations on paper. *PureAM* introduced frequency harmonics (multiples of AM frequency or f_{AM}) (Figure 4). *PureSTM* rendering showed frequency harmonics (multiples of drawing frequency or f_d), which appeared consistently for different drawing speed and size as long as the drawing frequency (the ratio of speed to size) was the same. The combinations of AM and STM (*AM+STM*) also resulted in frequency harmonics at multiples of both AM frequency and drawing frequency. Also, the highest magnitude occurred at the inputted AM frequency among all harmonic frequencies, regardless of the STM parameters.

Our model for *PureAM* and *PureSTM* simulated the exact AM frequency and drawing frequency (f_{AM} and f_d) as observed in the measurements (Figure 4). In particular, simulations for *PureSTM* showed the same frequency harmonics at multiples of the drawing frequency. However, for both *PureAM* and *AM+STM*, the simulations and measurements showed less correspondence, perhaps due to the different characteristics between paper and human skin. The simulated waveform for *PureAM* included a single component at the inputted f_{AM} in the spectral domain, while the measured waveform for *PureAM* introduced frequency harmonics at multiples of f_{AM} in the measurement. In *AM+STM*, both the simulations and measurements showed the highest magnitude at the inputted AM frequency, regardless of the STM parameters. However, the simulations showed the f_{AM} component and pair frequency components at multiples of $f_d \pm f_{AM}$, while the measurements included frequency harmonics at multiples of both f_{AM} and f_d. These frequency harmonics have a much lower magnitude than the AM frequency, so the extent of their impact on user perception is not fully known.

4 DISCUSSION

Our simulation can provide insights for designing mid-air ultrasound Tactons, as the designer can visualize the complex frequency spectrum induced by *PureSTM* or *AM+STM* and anticipate its impact on the end-user experience of the Tactons. In other words, our proposed simulation can inform actual stimulation at any points above the device, aiding as an effective means for testing the physical effects of the created Tactons by haptic designers.

The preliminary measurement data suggested the limitations of the current measurement setup and simulation model. At the current setup, the paper had different characteristics from human skin, such as elasticity and shear wave propagation, thus this measurement did not perfectly reflect the stimulation process on the human skin. Moreover, our model architecture was built on the simplified assumptions (Section 2.1) and on data collected from a scale hung in the air [25] and a microphone placed away from the device [2], instead of using human skin stimulation data.

In the future, we aim to improve the measurement methodology, for example, by using a higher resolution laser vibrometer or employing a silicon-based replica of human skin [3, 6]. Also, we plan to improve the simulation's accuracy by relaxing our current assumption such as the propagation of vibration waves on the skin to fully capture the complexity of mid-air ultrasound stimulation. Finally, we plan to improve our interactive simulation tool by including more design parameters, such as rhythmic structure and the number of focal points, and by adding the borderline of perceptible intensities considering detection threshold. We plan to make our simulation tool open-source after making the above improvements and further validating the model with a larger set of Tactons.

5 CONCLUSION

A physical simulation for skin vibrations can offer new possibilities for rapidly prototyping mid-air ultrasound Tactons for user applications. We proposed an interactive simulation for mid-air ultrasound Tactons that allows designers to easily test combinations of eight ultrasound parameters (five temporal and three spatiotemporal) and visualize the vibrations induced at different points on the skin. Our initial results suggest high correspondence between our simulation and measurements of a set of Tactons. We hope the simulation can assist haptic designers in creating rich mid-air ultrasound Tactons that vary on temporal and spatial parameters.

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