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Acoustic Pressure Foci Field Generation for Ultrasound Phased Array by NSGA-II

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Abstract: Haptic is a significant part of the VR environment. It is able to form a tactile feeling by acoustic pressure on human skin. Therefore, in this study, we expect to simulate acoustic pressure to generate foci fields. In order to provide a better tactile experience, some methods have been proposed to produce foci fields based on single-objective optimization, but sometimes the single-objective optimization cannot obtain the global optimal solution. So, we proposed a multi-objective optimization method, NSGA-II, to generate better foci fields. We considered the sum and variance of foci pressure for better rendering and evaluated it. As a result, we generated acoustic pressure foci fields by NSGA-II successfully.

Keywords： Haptic, NSGA-II, Foci field, Virtual Reality

1. Introduction

In the virtual reality environment, visual and auditory studies start first, with the technique development, by applying the demonstrated camera-based and hand tracking technology, researchers can interact with projected images with their hands. In this situation, tactile feedback is the next demand.

One significant method to form tactile feedback is using an airborne ultrasound, which is the technique of pressing the skin by the acoustic radiation pressure of converged ultrasound. There are many studies on a tactile presentation using ultrasound. Hoshi et al. presented a tactile display using airborne ultrasound by a phased array to feel virtual objects without mechanical contact on any display devices [1]. Similarly, Monnai et al. presented a mid-air interaction system called HaptoMime [2]. By tracking a fingertip with an electronically steerable ultrasonic beam, the fingertip encounters a mechanical force consistent with the floating image.

In addition, by designing the acoustic field, different types of tactile feedback can also be presented. For example, it is possible to stimulate multiple locations simultaneously by producing the acoustic field as having multiple ultrasonic foci.

The simplest method to form a foci field is Linear Synthesis Scheme (LSS) [3]. However, when the number of foci increases, the pressure will become weaker and there is interference between each focus. To solve this problem, researchers tried lots of methods. For example, Long et al. presented a method of producing foci for creating three-dimensional haptic rendering by solving global optimization problem [4].

The previous works used single-objective optimization to generate foci fields, which sometimes cannot obtain optimal solutions. And in single-objective optimization, since there is only one object, an undisputed optimal solution can be obtained in any two solutions that can be compared according to the single object. But in the case of generating multiple foci fields, setting a single object may not give equally good results for every focus. For example, to present a better tactile experience, it may be necessary not only to increase the sound pressure at foci but also to reduce the variance of the sound pressure between them.

Therefore, this time we propose the use of Non-dominated Sorting Genetic Algorithm II (NSGA-II) as an algorithm for acoustic field reconstruction, especially when multiple foci are formed simultaneously. NSGA-II is a genetic algorithm to solve multi-objective problems with the advantages of good convergence of solution sets. Therefore, we expect to get better foci fields under the feature of NSGA-II.

In this study, At the current stage, we simulate the case of from $(10, 12, 14, 16)$ foci using 18×14 transducers that emit acoustic radiation pressure. In this paper, we confirmed that NSGA-II could form the intended acoustic field and its intensity is improved compared to LSS results.

2. Foci field generation

2.1 Single focus generation

An ultrasound phased array is an array of ultrasound transducers whose phases can be individually controlled. The phase set $\boldsymbol{q}$ is defined as,

$$\boldsymbol{q}(\phi_1, ..., \phi_M) = \left[\mathrm{e}^{-\mathrm{j}\phi_1}, ..., \mathrm{e}^{-\mathrm{j}\phi_M}\right], \quad (1)$$

where ϕ_i is the phase of the i-th transducer. To generate a focus at a position $\boldsymbol{r}_f$, the ϕ_i of each transducer is calculated as,

$$\phi_i = k\|\boldsymbol{r}_f - \boldsymbol{r}_i\|, \quad (2)$$

where $\boldsymbol{r}_i$ is the position of the i-th transducer and k is the wavenumber. The acoustic fields $p(\boldsymbol{r})$ generated by the transducers is expressed as,

$$p(\boldsymbol{r}) = \sum_{i=0}^{n} \frac{1}{4\pi\|\boldsymbol{r} - \boldsymbol{r}_i\|} \mathrm{e}^{\mathrm{j}k\|\boldsymbol{r}-\boldsymbol{r}_i\|}. \quad (3)$$

In addition, we define the phase set $\boldsymbol{q}(\boldsymbol{r}_f)$ generating the focus at $\boldsymbol{r}_f$ under all transducers as,

$$\boldsymbol{q}(\boldsymbol{r}_f) = \left[\mathrm{e}^{-\mathrm{j}k\|\boldsymbol{r}-\boldsymbol{r}_1\|}, ..., \mathrm{e}^{-\mathrm{j}k\|\boldsymbol{r}-\boldsymbol{r}_M\|}\right], \quad (4)$$

where M is the number of transducers.

2.2 Linear Synthesis Scheme

To obtain a foci field, the Linear Synthesis Scheme (LSS) can be utilized, which is shown in Fig. 1. The LSS, as its name implies, generates the foci field by linearly synthesizing each focus signal. Therefore the whole phase set $\boldsymbol{q}_{\mathrm{LSS}}$which generates N foci is described as,

$$\boldsymbol{q}_{\mathrm{LSS}} = q(\boldsymbol{r}_1) + \cdots + q(\boldsymbol{r}_N). \quad (5)$$

Since there is an upper limit in the amplitude of the transducer, we have to cap it. Here, let us define the maximum amplitude as 1; Hence we set the amplitude in the range of $[0, 1]$ as,

$$\boldsymbol{q}_{\mathrm{normal}} = \frac{\boldsymbol{q}_{\mathrm{LSS}}}{\max\{|(\boldsymbol{q}_{\mathrm{LSS}})_i|\}}. \quad (6)$$

2.3 NSGA-II

However, while the number of foci increases, each focus interferes with others. To generate better foci fields, we try to use the Non-dominated Sorting Genetic Algorithm II (NSGA-II) [5]. NSGA-II is a multi-objective genetic algorithm. NSGA-II has the advantage of good convergence of solution sets. It is able for users to make tradeoffs within a set of requirements, while it is not possible to satisfy all the optimal values at the same time. The set allows the user to restrict attention to the efficient choices, which is called Pareto optimal set.

In NSGA-II, first, several random phase sets are prepared as the initial population. The objective function evaluates the sound fields generated by these phase sets and then ranks them by non-dominated sort. The higher ranked phase set becomes the parent of the next generation. In addition, among the parents, individuals that should be mutated and mated are selected by crowded tournament selection and then obtain their offspring of the next generation by genetic manipulation. The above process is repeated with the parents and offspring of the next generation as new inputs.

3. Experiments

3.1 Foci field generation under NSGA-II

We run the experiments in Python based on the Pymoo library [6]. In this experiment, our simulation is based on an Airborne Ultrasound Tactile Display [7], in which the number of transducers in the x-axis is 18 and the y-axis is 14. We take the center of the transducers plane as the origin of the coordinate system and the transducers are placed at intervals of 10 mm. We also set an objective plane with 100 mm × 100 mm at 1 mm resolution above the transducers plane. We generate foci as a uniform distribution on a circle with a radius of 35 mm on $z =$ 150 mm objective plane. The frequency f of ultrasound is 40 kHz, and the ultrasound wavelength λ is 8.5 mm.

In our NSGA-II simulation, there are two objective functions:

F_1: Minus of the sum of all acoustic pressure at the foci.

F_2: Variance for all focus pairs.

And we set the number of the initial population as 100, and iterations times as 2500. After running NSGA-II with the above parameters, we got 100 phase sets as the output in every experiment.

3.2 Results

We generated $10, 12, 14, 16$ foci to compare the results of LSS and NSGA-II. Figure 2 shows the results of the foci fields of one phase set chosen randomly from the Pareto optimal set. And the ranges of the color chart in the results are different. We chose the Pareto optimal set of the 16-foci, and the x-axis is objective function F_1, while the y-axis is objective function F_2 in Fig. 3.

3.3 Discussion

As the objective functions mentioned above, we use NSGA-II to do the optimization under the sum and variance of foci. In Fig. 2, we tested four different numbers of foci to get the fields and Pareto optimal sets. As we

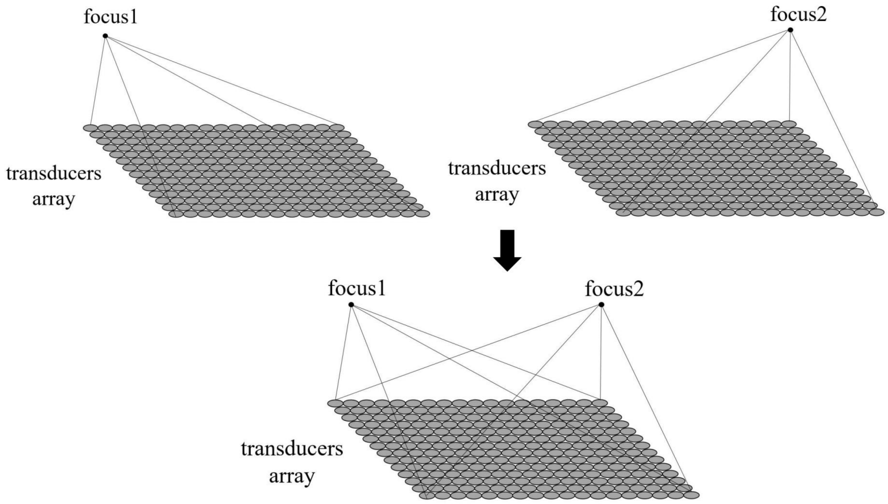

Fig.1: Linear Synthesis Scheme

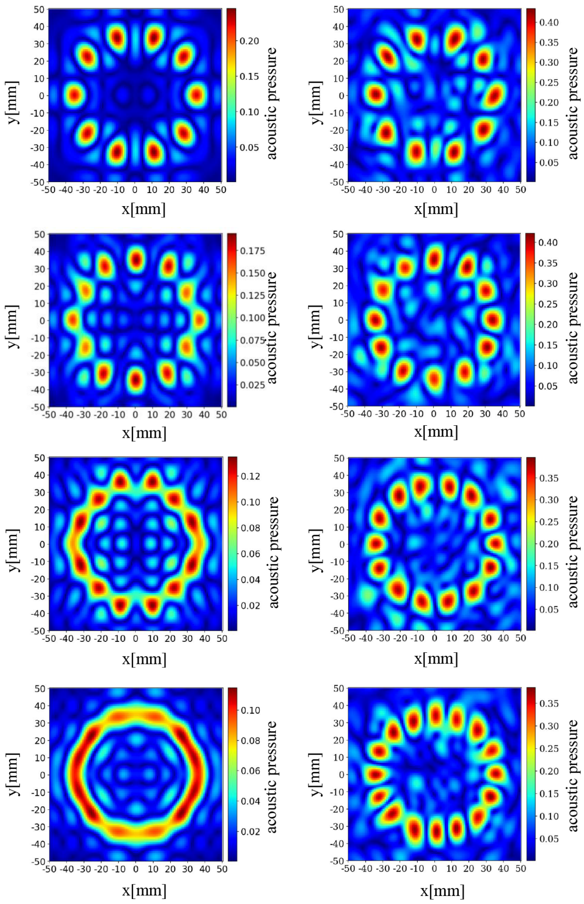

Fig.2: From left to right are the foci plots of LSS and the foci plots of NSGA-II

can see, when the number of foci increases, the interference of each focus becomes more severe in LSS. Since we used a multi-objective optimization method to limit the sum of acoustic pressures and variance of foci at the same time, the problem has been effectively solved. The foci generated by NSGA-II are formed independently. In addition, the acoustic pressure of NSGA-II is also larger

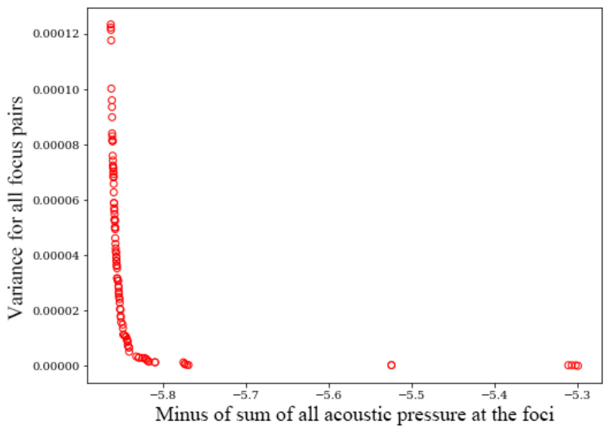

Fig.3: The Pareto Optimal Set

than LSS. As we mentioned before, we generate the foci fied by acoustic radiation pressure, which is proportional to the square of acoustic pressure. Therefore, assuming the total number of transducers remains unchanged, the sum of the sound pressure of the generated sound field is constant. When optimizing the sum of the foci sound pressure, it may implicitly consider the equipartition of energy. As a result, we can see in the Pareto optimal set that the change in the value of the F_1 and F_2 are not obvious.

4. Conclusion

To generate better foci fields, we successfully utilized NSGA-II to obtain phase sets. It generated stronger acoustic pressure fields compared to the LSS. The interference between each focus is much lower. And while the number of foci increases, the performance of the optimization will be more notable. In the future, we expect to try to test more objective functions. Such as utilizing the logarithm of the objective functions is possible, the patterns may be a little bit different. In addition, we will compare the performance of NSGA-II with the single-objective optimization method. Finally, as people expect to have a great haptic experience, NSGA-II provides a new way to generate better acoustic foci fields.

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