Optimization of Acoustic Fields

Advances towards its use for Matter Manipulation and Contactless Fabrication

by

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Authorization

Dr. Asier Ruperto Marzo Pérez: Profesor contratado de la Universidad Pública de Navarra en el Área de Conocimiento de Lenguajes y Sistemas Informáticos.

HACE CONSTAR que el presente trabajo titulado *"Optimization of Acoustic Fields"* ha sido realizado bajo su dirección por D. Iñigo Fermín Ezcurdia Aguirre. Autorizándole a presentarlo como Memoria para optar al grado de Doctor por la Universidad Pública de Navarra.

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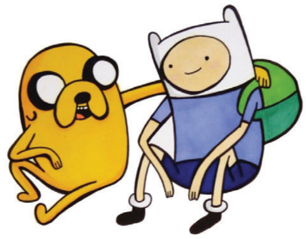

DUDE, SUCKING AT SOMETHING IS
THE FIRST STEP TO BEING SORTA
GOOD AT SOMETHING.

- Jake the Dog

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Abstract

Acoustic pressure fields are capable of patterning and levitating particles of a wide range of materials and sizes through air, water or biological tissue. This has applications in crystallography, cell manipulation, *lab-on-a-chip* scenarios, pharmacology, containerless transportation and even levitation of living things. Overall, the research domain of acoustic pressure fields has seen significant advances in recent years. Its flexibility and potential applications have been greatly increased with the development of holographic techniques and the use of optimizers. However, there is still room for improvement, as limitations hinder the application of acoustic fields in various research scenarios. For example, there is no unified hardware platform that can flexibly support exploratory research in acoustic holography applications. Most commercial or DIY devices lack the resolution or power that researchers require, so they need to fabricate more complex, cumbersome and expensive devices. Moreover, previous research has focused on the levitation and manipulation of small particles and droplets; however, a full prototype for contactless fabrication has yet to be developed since there is no existing work on trapping elongated objects in position and orientation. Furthermore, microfluidics is limited in terms of three-dimensional (3D) manipulation, droplet size and cross-contamination.

This thesis provides a comprehensive introduction to the optimization of acoustic fields, reviewing its importance in applications across multiple research and industry domains. This thesis also examines the previously stated limitations and shortcomings of the design and application of acoustic fields. Novel algorithms are proposed to generate desired target fields and to significantly improve their resolution and power through spatial and temporal multiplexation. An open and affordable hardware platform is presented to facilitate customisation for experimental requirements by researchers exploring novel applications for ultrasonic holograms. Optimum acoustic traps are designed and evaluated to lock elongated elements in position and orientation. Contactless fabrication using full acoustic trapping of elongated parts is demonstrated through additive manufacturing based on levitated particles, sticks and UV resin; the addition on top of other objects and building inside containers is also illustrated. Finally, a 3D digital microfluidics system is proposed based on focused ultrasound through a hydrophobic mesh. Able to handle a large number of liquid droplets ($> 40\mu L$), and capable of merging/splitting them or vertically propelling them, this system significantly improves already existing EWOD systems generating less surface contamination.

This thesis presents these achievements and their related works, models, methodologies, procedures and conclusions. I hope that these pieces of work are a significant advancement in the research of acoustic fields and may inspire and facilitate future novel applications of acoustic holograms by researchers in various domains of academia and industry.

Resumen

Los campos de presión acústica son capaces de modelar y levitar partículas de una amplia gama de materiales y tamaños a través del aire, el agua o el tejido biológico. Esto tiene aplicaciones en cristalografía, manipulación celular, escenarios *lab-on-a-chip*, farmacología, transporte sin contacto e incluso levitación de seres vivos. En general, la investigación de campos de presión acústica ha experimentado avances significativos en los últimos años. Su flexibilidad y sus posibles aplicaciones han aumentado considerablemente con el desarrollo de técnicas holográficas y el uso de optimizadores. Sin embargo, aún hay margen de mejora, ya que las limitaciones dificultan la aplicación de los campos acústicos en diversos escenarios de investigación. Por ejemplo, no existe una plataforma de hardware unificada que motive de forma flexible la investigación exploratoria en aplicaciones de holografía acústica. La mayoría de los dispositivos comerciales o de caseros carecen de la resolución o la potencia que necesitan las personas investigadoras, por lo que tienen que fabricar dispositivos más complejos y caros. Además, investigaciones anteriores se han centrado en la levitación y manipulación de pequeñas partículas y gotas; sin embargo, aún no se ha desarrollado un prototipo completo para la fabricación sin contacto; no existen artículos científicos que estudien el atrapamiento de objetos alargados tanto en posición como en orientación. Además, la microfluídica está limitada en cuanto a la manipulación tridimensional (3D), el tamaño de las gotas y la contaminación cruzada.

Esta tesis ofrece una introducción exhaustiva a la optimización de los campos acústicos, repasando su importancia en aplicaciones de múltiples ámbitos de la investigación y la industria. Esta tesis también examina las limitaciones y deficiencias previamente expuestas y presentes en el actual diseño y aplicación de campos acústicos. Se proponen algoritmos novedosos para generar los campos deseados y mejorar significativamente su resolución y potencia mediante multiplexación espacial y temporal. Se presenta una plataforma de hardware abierta y asequible para facilitar la adaptación a los requisitos experimentales de los investigadores que exploran nuevas aplicaciones de los hologramas ultrasónicos. Se diseñan y evalúan trampas acústicas óptimas para manipular elementos alargados controlando su posición y orientación. Se demuestra la fabricación sin contacto utilizando trampas acústicas de piezas alargadas mediante fabricación aditiva basada en partículas levitadas, varillas y resina UV; también se ilustra la adición sobre otros objetos y la construcción dentro de contenedores. Por último, se propone un sistema, destinado a microfluídica 3D, basado en ultrasonidos focalizados a través de una malla hidrófoba. Es sistema es capaz de manejar un gran número de gotas ($> 40\mu L$), y capaz de fusionarlas/dividirlas o propulsarlas verticalmente, este sistema mejora significativamente los sistemas EWOD ya existentes generando una menor contaminación superficial.

Esta tesis presenta estos logros y sus trabajos relacionados, modelos, metodologías, procedimientos y conclusiones. Espero que estos trabajos supongan un avance significativo en la investigación de los campos acústicos y puedan inspirar y facilitar futuras aplicaciones novedosas de los hologramas acústicos por parte de las personas investigadoras en diversos ámbitos del mundo académico y de la industria.

This Thesis is a Compendium of Research Papers

This dissertation is presented as a compendium of research papers. That is, the contribution is justified by gathering and placing together various research papers with a coherent theme that have been accepted in indexed journals or high-impact conferences. These works have been done during the PhD and the doctorate has played a significant role in them.

The two main papers that comprise the core of this thesis are the following:

- Morales R, Ezcurdia I, Irisarri J, Andrade MAB, Marzo A. **Generating Airborne Ultrasonic Amplitude Patterns Using an Open Hardware Phased Array.** Applied Sciences. 2021; 11(7):2981.
  - 5-Year Impact Factor: 2.921 (2021)
  - Categories: Chemistry; Engineering;Materials Science; Physics
  - Annexed paper: file:applsci-11-02981-with-cover.pdf - `https://doi.org/10.3390/app11072981`
- Iñigo Ezcurdia, Rafael Morales, Marco A. B. Andrade, and Asier Marzo. 2022. **LeviPrint: Contactless Fabrication using Full Acoustic Trapping of Elongated Parts.** In ACM SIGGRAPH 2022 Conference Proceedings (SIGGRAPH '22). Association for Computing Machinery, New York, NY, USA, Article 52, 1–9.
  - Impact Factor: The Computing Research and Education Association of Australasia, CORE Inc. classifies SIGGRAPH as an A* - Assigned to the flagship conference, the one that is the leading in that area of discipline.
  - Categories: Graphics, augmented reality and games.
  - Annexed paper: file:3528233.3530752.pdf - `https://doi.org/10.1145/3528233.3530752`

The request of presenting this thesis by compendium has been approved by the thesis director (annexed file: requestCompendium.pdf) and the doctoral school (annexed file: authComittee.pdf) following the rules of the Public University of Navarra for presenting a thesis in this modality (annexed file: Acuerdo A3/2015.pdf).

In Part II - Annexed items, there is a summary and access link of each paper.

Contents

Part I

Main Thesis Content

Throughout this PhD, much time and effort have been invested into different research projects and activities. When I enrolled on this PhD program, my mentor helped me to define an elaborated "Plan de Investigación" based on my interests and his expertise. This "plan" would serve as a research compass to steer my efforts towards constructive endeavours.

However, as Alexander Fleming said, "One sometimes finds what one is not looking for". During this journey, I have had the opportunity to participate in several projects and activities that were not initially planned but completely enriched the experience. This has helped me to define my research interests better, to collaborate with different and diverse colleagues from diverse backgrounds and to gain a better understanding of other fields of work, allowing me to form a broader view of the academic world and its idiosyncrasies.

For these reasons, this thesis may have taken a slightly different path from the one initially planned while still heading in the same direction. As such, this thesis has been divided into two parts:

Part I comprises those pieces of work directly related to the main theme of this thesis, "Optimization of Acoustic fields". In this Part I, an introduction on acoustic levitation is included, providing the reader with context and a general understanding of the overall topic while also reviewing some of the most important state-of-the-art pieces of work. This introduction will lay the foundations for the following compiled scientific papers. These papers should be interpreted as the main core of this thesis. After that, the Conclusions chapter will summarize the most relevant findings extracted from the previously presented papers, reviewing the key points of the dissertation and explaining to the reader why this work is relevant.

Part II contains all those other academic works that I was fortunate to participate in but are not directly related to the main theme of this dissertation. This part II will also serve as additional evidence that I have performed sufficient research, divulgation and teaching work to continue my career.

1 Introduction

This chapter introduces the working principle of acoustic fields and acoustic levitation. Sound shows some interesting properties that can be exploited to exert forces on small objects, even counteracting gravitational forces, thus levitating them. This thesis will discuss the optimization of Acoustic Fields, it is also important to understand the nature of sound waves and the underlying physics involved in the design of acoustic fields. To fully contextualize the compiled papers that compose this document, it will also be essential to know about the categorization of the different acoustic levitators proposed in the literature, as long as their capabilities and limitations. Finally, to understand the relevancy of the progress exposed in this thesis, it is considered of particular interest to inform the reader about the possible applications for which this technology can be used.

1.1 Optical, Magnetic, Electrostatic, and Aerodynamic levitation.

Optical levitation, also known as "optical trapping," is a technique that uses light to suspend small objects, such as particles or droplets, in mid-air. The technique works by using a high numerical aperture lens to sharply focus a laser beam. When the laser beam interacts with the object, it exerts a force on the particle due to the momentum transfer of photons. If the laser beam is focused correctly, this force can counteract the force of gravity and hold the particle in place. The particle size range is 0.01-10 μm and the materials need to be dielectric or optically transparent [163].

Diamagnetic levitation is a type of magnetic levitation in which an object is levitated without the need for energy input in a magnetic field due to its diamagnetic properties [202]. Diamagnetic materials, such as copper, silver, gold, and graphite, have a negative susceptibility to magnetic fields. When placed in a strong magnetic field, the electrons in the material are repelled by the magnetic field and move to the opposite side of the object, creating a magnetic field that opposes the external field. This effect is what causes the object to levitate, as the repulsion force from the magnetic field balances out the force of gravity. A frog was levitated in this way [24] since water is slightly diamagnetic. However, this technique requires strong magnetic fields given the weak diamagnetism of most materials of interest.

Electrostatic levitation is a method of levitating objects using electric fields. This technique uses the principle that like charges repel each other and opposite charges attract each other [93, 144]. A charged object is suspended in mid-air between two oppositely charged plates while the force of the electric field balances the force of gravity, allowing the object to float without any physical contact with a support. The strength of the electric field can be adjusted to control the levitation height and stability of the object. However, it requires for a high-voltage output and when the electric field is strong enough, electrostatic levitation can lead to electrical discharge or arcing between the charged object and the electrodes. This can damage the devices or the levitated sample and may pose a safety risk.

Aerodynamic levitation [249] is a method of levitating a spherical object using a gas stream or flow of air. The gas stream exerts a force on the object that balances out the force of gravity, allowing the object to be suspended in mid-air. The jet's divergence results in a reduction of drag as the height increases, thereby promoting stability in the vertical direction. Meanwhile, in the transverse direction, stable levitation is attained through the deflection of the jet towards an off-axis specimen. However, the aerodynamic forces can be difficult to control precisely, agitating and altering the samples in the process.

Although this thesis is focused on acoustic levitation and acoustic fields it is not necessarily a better alternative to these other levitation techniques. Each levitation technique has its unique advantages and limitations, and the choice of technique depends on the specific application and the characteristics of the object to be levitated. However, acoustic levitation provides some advantages. It can levitate a wide range of objects, including liquids, solids, and even living organisms, without the need for any special coatings or materials and can be achieved using relatively simple and inexpensive equipment, making it accessible to researchers with limited resources.

1.2 Acoustophoresis

Sound is created when an object moves or changes shape rapidly, producing a mechanical vibration propagating through a medium, such as a gas, liquid, or solid material. As the item producing the sound vibrates, it pushes the air molecules around it, creating a compressed region of higher pressure. When the object moves back in the opposite direction, it pulls back the molecules, creating a lower-pressure area known as a rarefaction. This cycle of compression and rarefaction continues in succession; each repetition is one wavelength of the sound wave. See Fig. 1.1

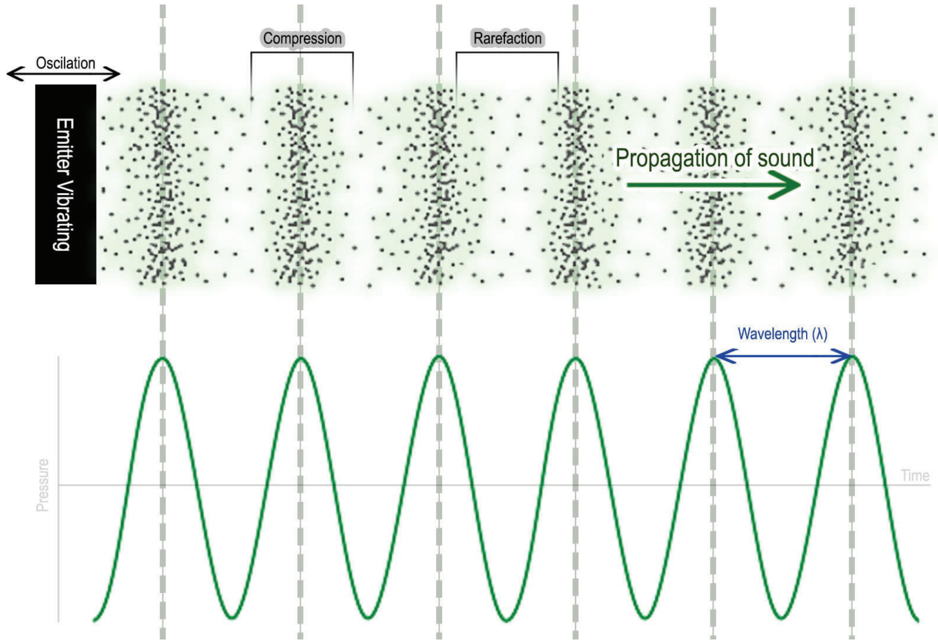

Figure 1.1: Compression and rarefaction of a medium vibrated by sound.

The word "Acoustophoresis" consists of two parts, where phoresis means "migration" and acousto, where sound waves are the movement's modus operandi. Similarly, electric forces move particles in electrophoresis and magnetic forces in magnetophoresis.

However, blasting high-amplitude sound towards an object is insufficient to state that we can control its movement. What forces can acoustic waves exert on an element in order to exert control on its position?

1.2.1 Acoustic Radiation Force

Suppose a fluid surrounds a small object (i.e. polystyrene bead) with different material properties (i.e. air). In that case, the scattering of sound waves can create forces that will be exerted on the object. These forces could set the object in motion through the fluid or hold it still in place. When the acoustic forces counteract the force of gravity acting upon the object, it will hold its position suspended in the fluid, hence levitating.

Standing waves seem to remain in one place and vibrate in segments rather than going from one location to another. This stillness gives them their name. These sound waves have certain spots where pressure is minimal (nodes) and other spots where pressure is higher (antinodes). A suspended particle in a standing wave field will experience a radiation force which moves the particle either to a pressure node or to an antinode depending on the physical properties of the particle. The acoustic contrast factor for most particles is positive, and they tend to move towards the pressure nodes. See Fig. 1.2. In the neighbourhood of a pressure node, the acoustic radiation force acting on the levitated particle is proportional to its displacement from the node.

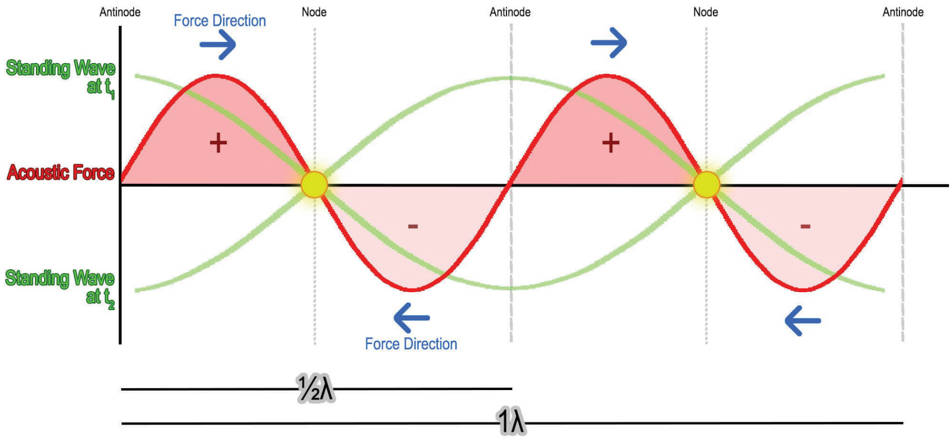

Figure 1.2: Acoustic pressure (green) and acoustic force (red). Blue arrows indicate the force direction for positive contrast.

The pressure-gradient force, F, behaves as a harmonic function:

$$F = F_0 sin(\omega_0 t + \Theta) \tag{1.1}$$

where ω_0 is the angular velocity, t is time and Θ the angular displacement. Under the assumption of linearized acoustic theory, when F is time-averaged, the total net force equals zero, implying that no force that can counteract gravity would exist. By looking into the Navier-Stokes and continuity equations, which govern the motion of fluids, nonlinear effects result in a non-zero acoustic lifting force, F_{rad}. This makes it possible for a small particle to acoustically levitate in a pressure node. The acoustic lifting force acting on a small body can then be calculated with the equation:

$$\mathbf{F}_{rad} = -\boldsymbol{\nabla} U \tag{1.2}$$

where U is the Gor'kov potential. See section 1.2.2. When the particle is within the Rayleigh regime (smaller than $\lambda/2$) the acoustic lifting force is proportional to the volume of the body. Therefore the density of the body is the relevant parameter to establish if it can be levitated, not its weight.

1.2.2 Gor'kov Potential

The Gor'kov potential approximates the radiation forces exerted on a small sphere that is inside an arbitrary acoustic field [71]. It can be defined in terms of the complex acoustic pressure p and its spatial derivatives p_x, p_y and p_z. The Gor'kov potential U is given by:

$$\begin{aligned} U &= K_1\left(|p|^2\right) - K_2\left(|p_x|^2 + |p_y|^2 + |p_z|^2\right) \\ K_1 &= \frac{1}{4}V\left(\frac{1}{c_0^2\rho_0} - \frac{1}{c_p^2\rho_p}\right) \\ K_2 &= \frac{3}{4}V\left(\frac{\rho_0 - \rho_p}{\omega^2\rho_0(\rho_0 + 2\rho_p)}\right) \end{aligned} \quad (1.3)$$

The volume of the spherical particle is V, ω is the angular frequency of the emitted waves, and c and ρ are the speed of sound and the density, respectively. Their subindex 0 and p refer to the propagation medium and the particle material.

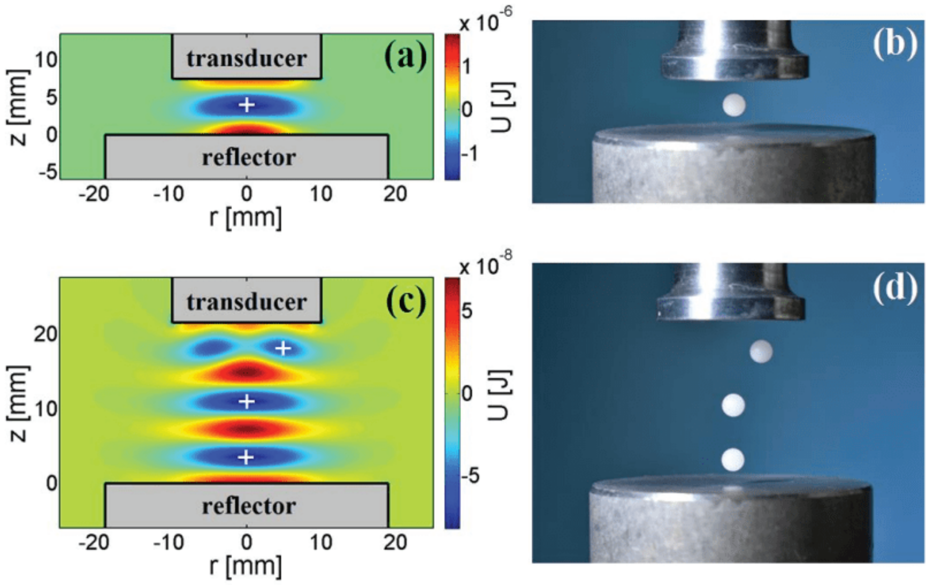

Figure 1.3: Comparison between the Gor'kov potential and the levitation positions of polypropylene spheres in a single-axis acoustic levitator. (a) Simulated potential (Distance = 7.45 mm). (b) Experimental (Distance = 7.45 mm). (c) Simulated potential (Distance = 21.55 mm). (d) Experimental (Distance = 21.55 mm). Extracted from [14].

1.2.3 Force and Stiffness of an acoustic trap

Forces can be represented as the gradient of the potential:

$$\mathbf{F}_{rad} = -\boldsymbol{\nabla} U. \tag{1.4}$$

Therefore, a levitation point is a position to which all the forces converge; that is, a minimum of the potential. The lower the potential is at a position, the stronger the object will be trapped there. In general, the potential can be visualized as a heightmap, and thus minima in the field represent wells where the particles will roll in and get trapped.

Another measure of the strength of a trapping position is the positional stiffness, which represents how converging the forces are at that position. The Laplacian operator (convergence of the gradient) can be applied to the potential to get a mathematical representation of the stiffness.

$$stiffness = \nabla^2 U = U_{xx} + U_{yy} + U_{zz} \tag{1.5}$$

where $U_{aa} = \frac{\partial^2 U}{\partial a^2}$ and $a = x, y, z$ are the Cartesian axes. Large positive values of stiffness represent large converging forces.

1.3 Types of Acoustic Levitators

Acoustic levitation has advanced from not moving the levitated element to actively managing hovering objects. Different acoustic levitation techniques have been proposed in the literature exploiting different physics phenomena to reach this point. Numerous devices have been implemented for each of these techniques aiming to improve their capabilities focusing on specific requirements.

In this section, the broadly divided categories of acoustic levitation proposed in the literature are reviewed and some of their implementations are examined.

1.3.1 Standing Wave Acoustic Levitation

1.3.1.1 Resonant

Single-axis levitators consist of two opposite emitters that generate a standing wave between them. A transducer and a reflector on top is a simple configuration for a static single-axis levitator [241]. In this method, objects smaller than half of the acoustic wavelength are held in the pressure nodes of the standing wave, as explained on Section 1.2.1.

In a resonant device, the separation distance between the emitter and the reflector should be adjusted to one of the resonant modes of the cavity. The distance between the emitter and the reflector should be set to a multiple of a half wavelength in order for the resonant device to achieve its resonant modes. Further, the distance can be adjusted to a higher-order resonance, granting the capacity to lift multiple spheres at different pressure nodes acoustically. Resonant levitators offer the advantage of generating high acoustic pressure levels, which enables the levitation of high-density substances. However, they need to be adjusted to operate in their resonant frequency, considering changes in temperature and humidity.

Replacing the reflector with another transducer and ramping up or ramping down the phase difference between the two transducers is a simple configuration for a one-dimensional static single-axis levitator. This change in phase difference causes the standing wave to shift up or down, thus resulting in an oscillating motion of the trapped particles.

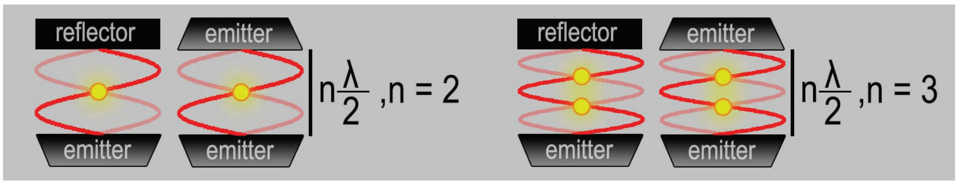

Figure 1.4: Resonant standing waves. Left) Second resonant mode creates one node to acoustically trap one particle. Right) Third resonant mode creates two nodes to acoustically trap two particles.

1.3.1.2 Nonresonant

The primary benefit of nonresonant levitators is that the gap between the transducer and the reflector (or the space between transducers) is adjustable, without requiring the separation distance to be set to a multiple of half-wavelength.

The development of a non-resonant acoustic levitator was first proposed in 1981 [189], and then demonstrated in 2007 [111]. Similarly, Andrade et al. demonstrated a non-resonant levitator with a concave reflector and transducer in 2015 [13].

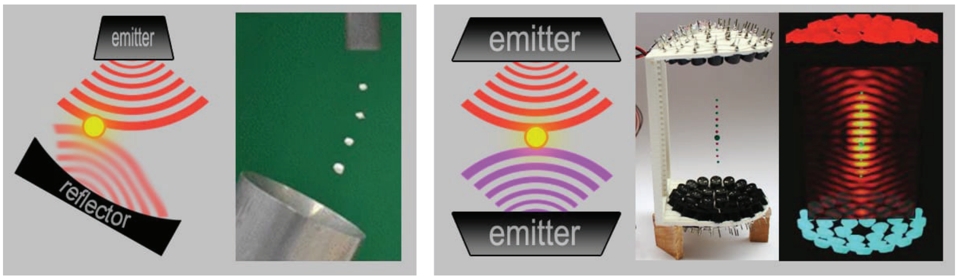

Figure 1.5: Non-Resonant standing waves. Left) Working principle of a non-resonant standing wave when using a reflector. Photo extracted from [13] Right) Working principle of a non-resonant standing wave when using opposed transducers. TinyLev photo extracted from [135]

1.3.2 Near-field Acoustic Levitation

Near-field acoustic levitation, also known as squeeze film levitation, is the process where a large plane object is suspended slightly above/below the vibrating surface of a transducer. We can observe that the acoustic radiation forces that act on the object show a considerable increase when the reflector approaches the transducer surface (See figure 1.6.Middle). The levitated object itself acts as a reflector and the object levitates at the near field of the transducer. This method typically causes the object to levitate at a height ranging from tens to hundreds of micrometres above the surface.

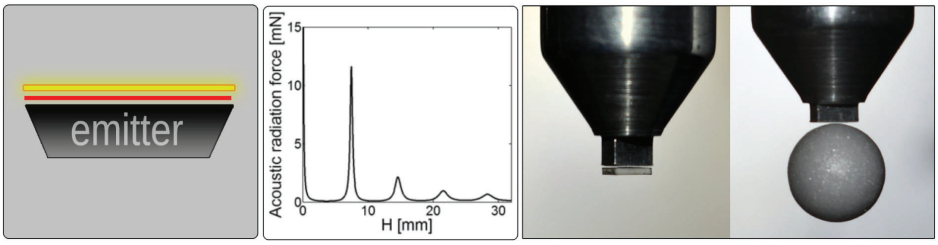

Figure 1.6: Left) Working principle of a near field levitator. Middle) Simulated acoustic radiation force on the reflector of a levitation device formed by a 25.25 kHz ultrasonic transducer and a plane reflector as a function of the separation (H). Extracted from [14]. Right) Demonstration of near-field acoustic levitation. Photo extracted from [15]

1.3.3 Phased Array Levitators (PAL)

Phased arrays are a cluster of elements that transmit or receive with specific phases or time delays. They are in widespread use in radar, sonar, and ultrasonic imaging since they can dynamically steer and shape the beam [138]. Phased arrays of transducers can be used to create acoustic pressure fields able to levitate far-field located elements.

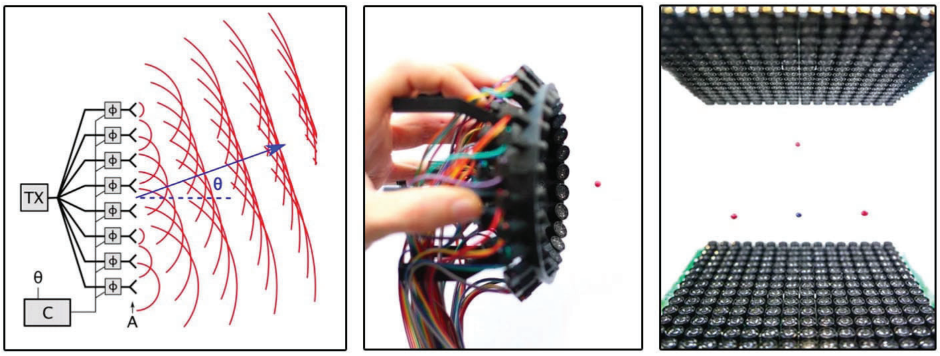

Figure 1.7: Left) Working principle of phased arrays. Also applicable to acoustics. Middle) A simplified PAL with fixed phases using the geometry of the levitator to focus the field. Photo extracted from [142]. Right) Single axis phased array levitator. Two opposed flat phased arrays (SonicSurface [153])

Phased arrays can change the position of the focal point by varying the phase sent to each transducer.

1.3.3.1 Single-Axis and Multi-Axis levitator

When a single-phased array or reflector is set up on one axis, it is known as a single-axis levitator. If there are one or more additional phased arrays added in an orthogonal direction, it is referred to as a multi-axis phased array levitator.

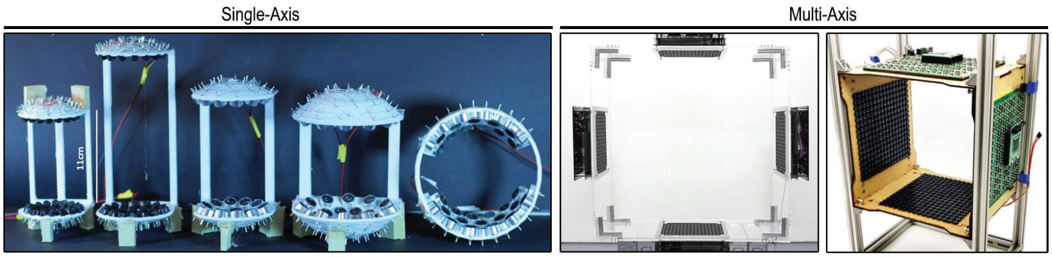

Figure 1.8: Left) A variety of Single-Axis Levitators. Photo extracted from [135] Right) Two different Multi-Axis Levitators. Photos extracted from [170] and [52]

Unlike resonant acoustic levitators, which require the distance between the phased array or reflector to be a multiple of the wavelength, single/multi axis levitators do not usually require this. Usually, the reflection from the transducers' surfaces is so small that is considered negligible.

1.3.3.2 Single Beam Levitators

Single-beam (or single-sided) levitators can levitate small objects by using only a single-sided emitter. They are inspired by the Nobel Prize-winning technology of optical tweezers, in which laser light is used to push small particles towards the center of the beam and to hold them there. Single-beam levitators are often referred to as "tractor beams".

Marzo et. al [141] proposed in 2015 the use of an optimizer with an objective function that simultaneously maximizes the Gor'kov Laplacian and minimizes the pressure amplitude at the target point to report the existence of three optimum acoustics to levitate particles in air:

- **Tweezer-like twin traps:** These traps have two finger-like cylindrical regions of high amplitude, which tweeze the particle with amplitude gradients in the x direction. Velocity gradients constrain in the other two axes.
- **Twister-like vortex traps:** The xy section of the trap shows a high-amplitude ring that generates lateral trapping forces with amplitude gradients. Along the z axis, the trapping force is due to velocity gradients.
- **Bottle-shaped traps:** These traps create a high-amplitude cage around the levitation point and all the forces result from amplitude gradients.

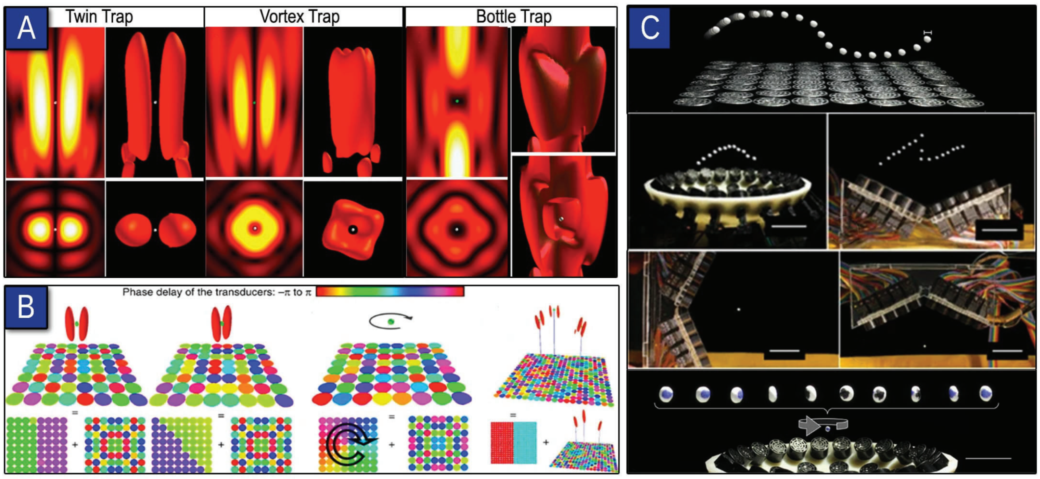

Figure 1.9: A) Amplitude fields and amplitude isosurfaces obtained when generating twin, vortex and bottle traps. B) Combinations of holographic signatures with holographic focusing elements to create traps at different positions. C) One-sided levitation in mid-air. Translation along 3D paths and rotation of asymmetric objects. Extracted from [141].

1.4 The Designing of Acoustic Fields

Designing and generating acoustic fields with specific characteristics is of great significance in many applications (See section 1.7), such as ultrasonic imaging, nondestructive testing, and high-intensity focused ultrasound HIFU therapy. Additionally, the emergence of new applications that involve generating ultrasonic fields with target shapes or volumes in air has opened up possibilities for noncontact tactile feedback volumetric displays [34], parametric audio generation [27], and contactless manipulation of objects [14].

For these reasons, the accurate design of specific acoustic pressure fields is crucial for future applications. To achieve this, one must first understand the physics of the medium across which the acoustic field will propagate (air, water or tissue), the possible existence of reflections and the sizes and shapes of the elements present in the working volume. The engineering behind the devices creating the acoustic field should also be considered. That is, its power consumption, resolution, number of transducers, spatial configurations and algorithms employed.

Modern ultrasonic phased-array controllers are electronic systems capable of delaying the transmitted or received signals of multiple transducers, enabling control over the transmission of narrowband airborne ultrasound. As stated in 1.3.3, some Phased Arrays of ultrasonic Transducers offer advanced control on the field (e.g. focusing the acoustic energy in specific locations). With these systems, the position of the levitated object can be adjusted by altering the transducers' phases [233] or amplitudes [57], allowing for the successful levitation of multiple objects in predetermined positions.

Alternatively, other strategies have also been explored without individually addressing the phase or amplitude of each transducer. In 2016, Melde et al. proposed a technique consisting of a monolithic acoustic hologram placed in the path of the ultrasound wave, as a lens that would shape the resultant acoustic field [148]. Following a similar philosophy, Polychronopoulos proposed in 2020 the use of optimized reflective metamaterials in a reflector where the local height of the surface is used to introduce delay patterns to the reflected signals [182]. See Figure 1.10. While moving the design limits to the resolution of 3D printers, these techniques are constrained to static fields and incapable of dynamic manipulation of the generated acoustic fields.

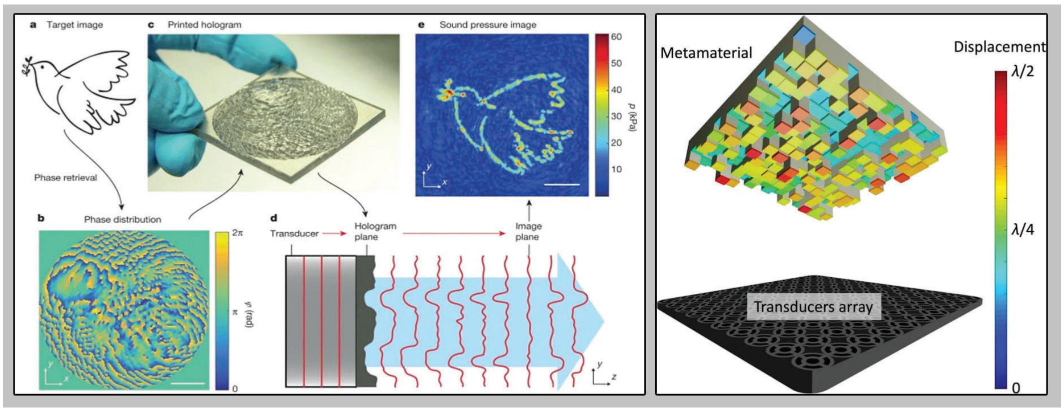

Figure 1.10: Left) Workflow for generating and reconstructing arbitrary acoustic images. Extracted from [148]. Right) Transducers array and a reflective metamaterial (on top) with unit cells of variable heights (displaced from 0 to $lambda/2$). Extracted from [182].

The piston model is usually employed [169] to calculate the complex acoustic field generated by a single emitter that has a radiating part in the shape of a piston vibrating at a single frequency. In the complex pressure, the magnitude represents the amplitude and the angle, the phase. All the papers presented in this compendium thesis use phased arrays formed by multiple emitters operating at the same frequency and varying their amplitude and phase in a controlled way. The total field generated by an array of n emitters is the addition of their emitted fields:

$$P(\boldsymbol{x}) = \sum_{i=1}^{n} \frac{P_0 J_0(kr \sin\theta_i)}{d_i} e^{i(\varphi_i + kd_i)} \tag{1.6}$$

where P_0 is the amplitude power of the transducer, defined by its efficiency and driving voltage amplitude. J_0 is the Bessel function of order zero. $k = 2\pi/\lambda$ is the wavenumber and λ is the wavelength. r is the radius of the piston, d_i is the distance from the emitter i to the point $\boldsymbol{x}$ in space. θ_i is the angle between the normal of the emitter and the transducer to point $\boldsymbol{x}$ vector.

This model is commonly used and implemented in various frameworks [138], it is designed to work in open space where there are no large obstacles in the field. Using it in simulations is a straightforward way to visualize the resultant amplitude fields or certain devices under specific configurations. See Figures 1.9 and 1.11.

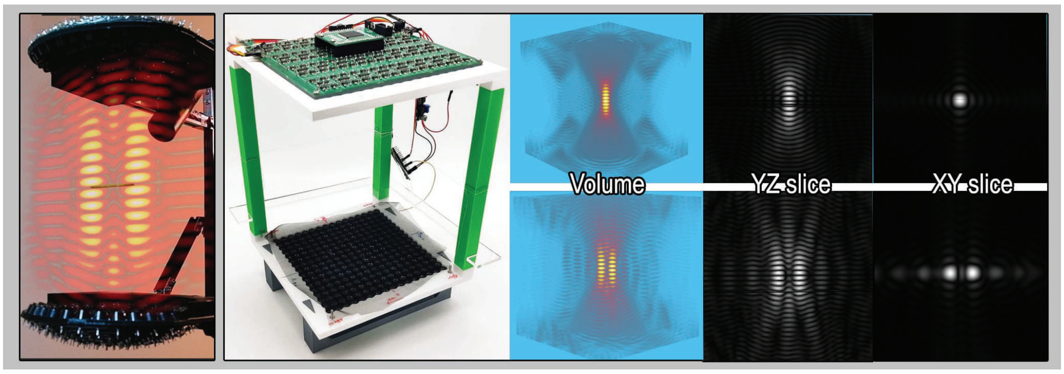

Figure 1.11: Two different devices modulating the phases of their transducers to generate specific amplitude fields. Left) A fixed single-axis levitator when halve of the emitters are driven with an inverse polarity signal (π phase) Right) Two-opposed flat phased-arrays generating two different amplitude fields.

1.5 Acoustic Levitation of Matter

Kundt et al. reported in 1866 the captivating phenomenon of dust particles gathering into a ring-like arrangement in a glass tube when a standing sound wave is present [115]. We could consider this the first demonstration of the possibility of acoustic levitation of matter.

But it is not till 1933 that Bücks and Müller succeeded in the acoustic levitation of ethanol droplets at the pressure nodes of a standing wave created between a vibrating rod and a reflecting wall [29]. See Figure 1.12. This experimental setup is considered to be the starting point of acoustic levitation of matter and would inspire numerous researchers to work on and perfect the technique.

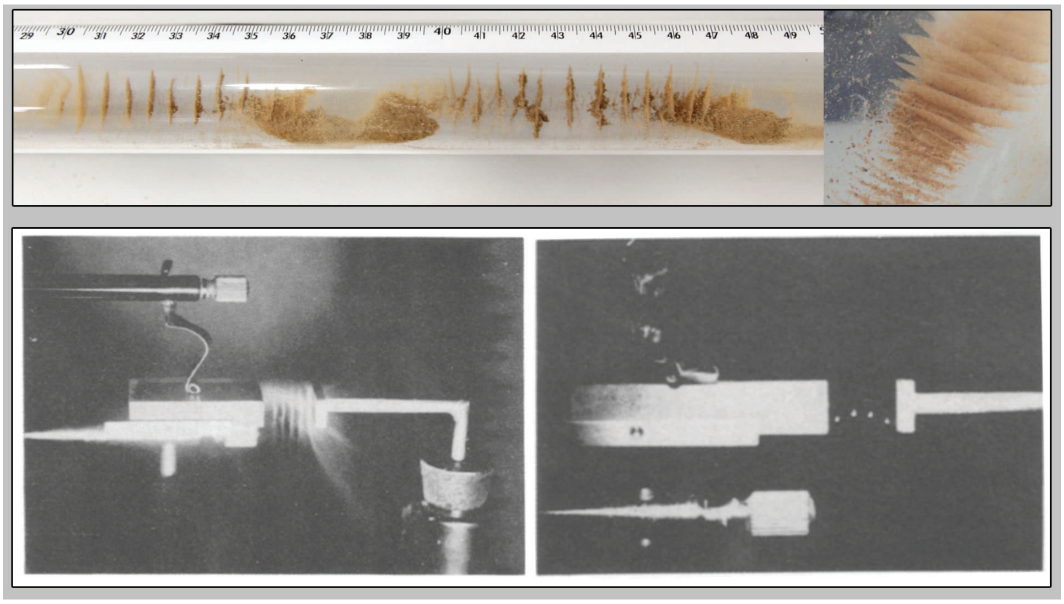

Figure 1.12: Top) Photo replica of Kundt's experiment [115] extracted from [116]. Dust particles gather at the nodes of the standing wave. Bottom) Bücks and Müller experiment figure extracted from [29]. Alcohol mist in a standing wave condensing into droplets.

1.5.1 Levitation of Particles

Nowadays, Expanded Polystyrene (EPS) particles are the most common particles used for acoustic levitation. In general, the radius of the particles is in the range of 0.5mm to 5mm. Most common levitation devices work by emitting sound in the range of 30kHz to 50kHz. The size of these EPS beads suits perfectly in the half-wavelength size limitation, as 40kHz waves generate a wavelength of 8.6mm ($\lambda/2$ = 4.8mm). The low density of the levitated element is a determinant of how robustly it can be trapped. EPS beads can be moulded in a range of densities from as low as $12kg/m^3$ up to $50kg/m^3$. These beads are spheres or spheroids, this shape is ideal for acoustic levitation because of its symmetrical design. The spherical shape allows for even distribution of the acoustic force, remaining stable and balanced in the air. These beads are easy to find, non-dangerous and cheap to buy in bulk. All of this makes EPS particles one of the preferred particles to use when working with acoustic levitation.

But acoustic levitation is not constrained to spherical EPS beads. The literature shows us a plethora of other elements that have been successfully levitated. Ranging from sugar, sand and other small crystals, dirt or small PCB components, to small bugs or food. See figure 1.13.

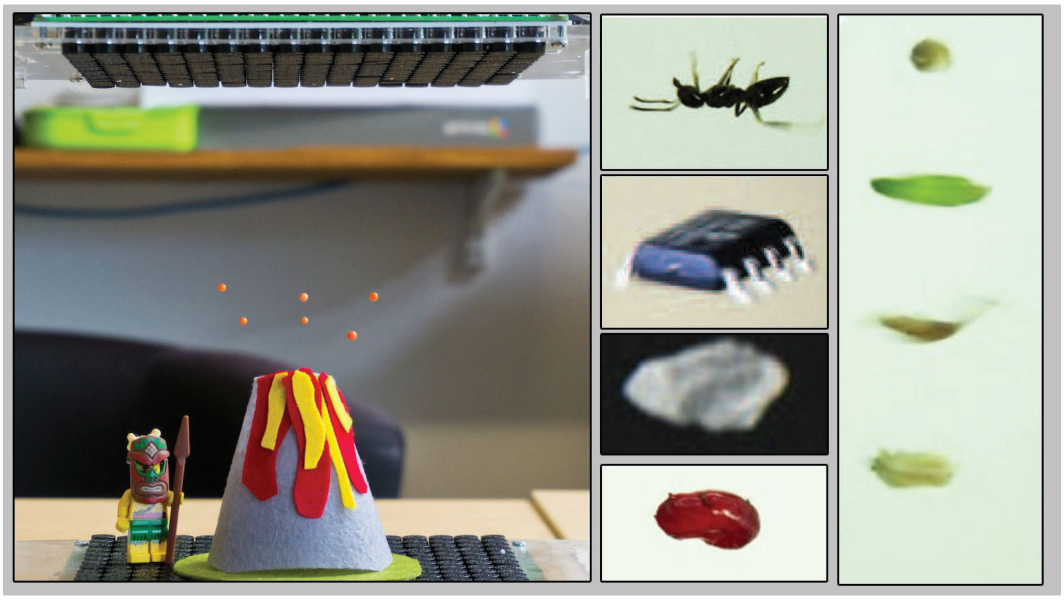

Figure 1.13: A) Six EPS particles being levitated to illustrate lava emerging from a volcano. B) Examples of acoustic levitation. Ant, MOSFET, sugar, raspberry seed, lettuce, breadcrumb. Extracted from [61], [135] and [227]

1.5.2 Levitation of Liquids and Viscous Matter

To achieve successful acoustic manipulation of drops, it is necessary to have a good understanding of the stability of levitating drops when exposed to high-intensity acoustic fields. This is not a straightforward task, as the acoustic field must be powerful enough to counteract the force of gravity, yet remain below a certain threshold that would cause the liquid droplets to be disintegrated. The dynamic behaviour of the acoustically levitated drop is related to its rheological properties (characteristics of a material that defines its deformation and flow), and must be taken into consideration to avoid the bursting and undesired oscillations of the levitated sample.

Acoustic levitation of liquids has been previously demonstrated in the literature. Foresti et al. [57] demonstrated the contactless transportation and merging of multiple drops in two dimensions using an array of high-power Langevin transducers and an opposing reflector. Other examples are the works of Watanabe et al. and Andrade et al. , in which the contactless transportation of liquid droplets is demonstrated by manipulating the phase of the emmiters. See Figure 1.14. Watanabe et al. did explore the feasibility of contactless coalescence and mixing of liquids focusing on mode oscillation [233]. Andrade et al. did numerically and experimentally research the stability of a drop in a single-axis acoustic levitator [10].

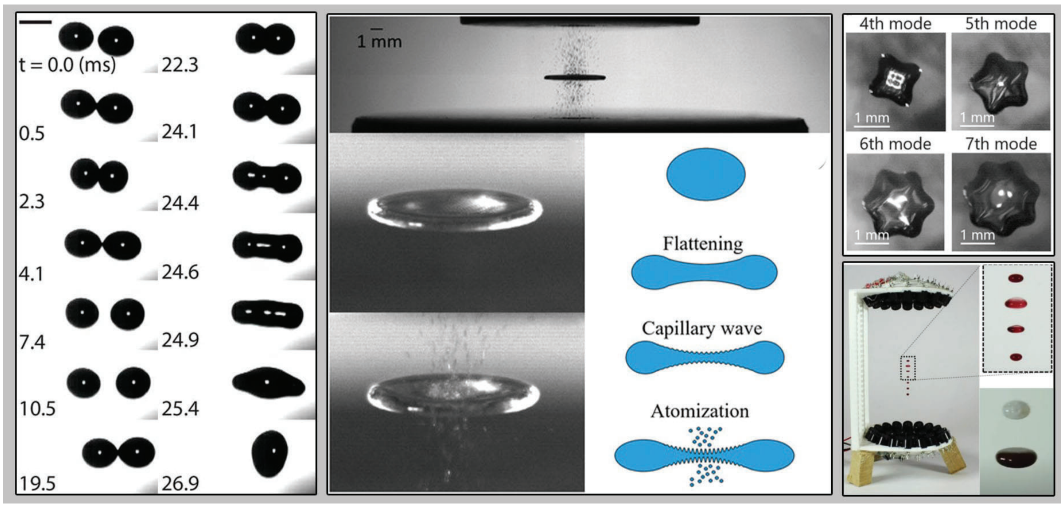

Figure 1.14: Left) Tetradecane droplets bouncing and subsequently coalescing. Extracted from [57]. Midde) Atomization of a drastically flattened drop. extracted from [10]. Top Right) Typical 4th to 7th mode behaviour of acoustically levitated droplet. Extracted from [233]. Bottom Right) Acoustic levitation of droplets of wine, milk and coffee. Extracted from [227].

1.5.3 Elements larger than the acoustic wavelength

Acoustic levitation is also no longer restricted to small objects and, thanks to the advances made in the last decade, acoustic levitation can now be employed to levitate objects larger than the acoustic wavelength.

In 1975, Whymark reported the successful levitation of a brass disk, 70 mm in diameter, approximately half a wavelength away from the surface of a 20 kHz transducer (between a reflector). See Figure 1.15. This is thought to be the first time an object larger than the acoustic wavelength was levitated, as documented in the literature [241].

In 2011, Zhao and Wallaschek levitated a compact disk (CD) at half wavelength above the radiator [258]. Their system produced a vertical force on the CD, but radial stability was attained by the utilization of a central pin in contact with the CD. See Figure 1.15.

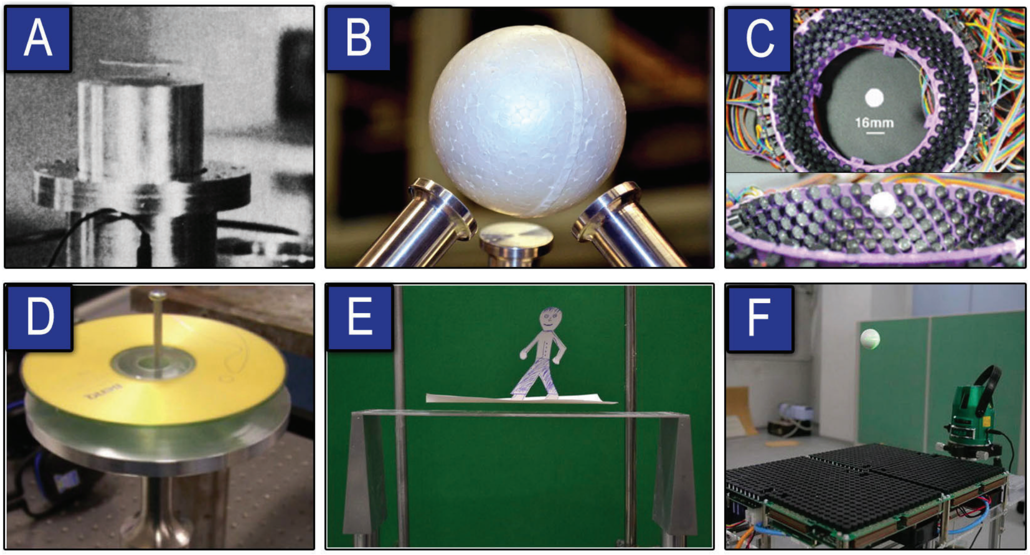

Figure 1.15: A) Acoustic Levitation of a 70mm diameter brass disc. Extracted from [241]. B) Acoustic levitation of an EPS sphere of 50mm diameter by using three circular ultrasonic transducers of 25kHz. Extracted from [9]. C) An EPS particle of 16mm=1.86λ diameter trapped in a virtual vortex. Extracted from [137]. D) Stable levitation of CD at a half wavelength above the radiator. Extracted from [258]. E) Acoustic levitation of a curved object weighing 2.3g. Extracted from [12]. F) A sphere with a diameter of 30mm levitates at a point 200mm above a single-sided 966 array. Extracted from [94].

In order to solve the problem of horizontal stability, in 2016, Andrade et al. [9] employed three 25 kHz transducers in a tripod arrangement, achieving vertical and horizontal stability, to levitate an expanded polystyrene sphere of 50 mm in diameter. See Figure 1.15. In 2017, Andrade would also levitate a large object consisting of a human figure made of cardboard paper at half a wavelength from the emitter [12]. This was achieved by attaching the figure to a curved sheet responsible for producing a horizontal radiation force providing horizontal stability to the object. See Figure 1.15.

More recently, in 2017, special vortices of high aperture have been used also to levitate objects larger than the acoustic wavelength. This is the case of Marzo et al., who used virtual vortices for Mie particle levitation [137]. In this study, stable trapping inside acoustic vortices is demonstrated by generating sequences of short-pulsed vortices of equal helicity but opposite chirality. Not much later, in 2018, Inoue et al. proposes the "boundary hologram method" to showcase the acoustic levitation of a sphere of 30 mm diameter (3.5 wavelengths at 40 kHz) using an array of 996 low-power transducers [94]. See Figure 1.15.

However, all these works are constrained to large planar objects, spheroids, or objects estimated as spheroids. When studying the acoustic levitation of elongated and non-spherical elements, we can find a few examples of work that achieved it in different degrees of success. In 2013, Foresti et al. [57] briefly reported the controlled translation and 1DoF rotation of a tooth stick (9cm; 6λ). They used spatial and temporal modulation of the acoustic field to apply several nodes collaboratively working on the task. In 2016, Omirou et al. showcased the levitation of short pieces of thread attached to EPS spheres to enrich acoustically levitated representations [173]. These threads do not directly affect the sound field, but they make the levitated objects heavier and more unstable when they move. Back again in 2019, Morales et al. will present LeviProps [155], animating levitated optimized fabric structures using holographic acoustic tweezers. Spherical particles were used again as levitated buoys to which acoustically transparent fabrics were attached. Similarly, in 2021, Fender et al. would also levitate shape primitives composed of fabric, threads and beads, to explore their mid-air assembly[54]. See Figure 1.16.

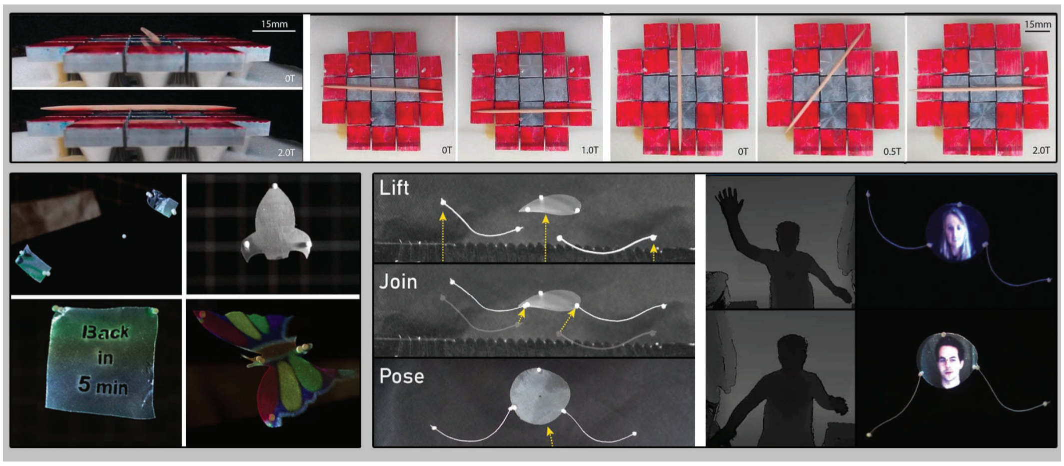

Figure 1.16: Top) Contactless translation and rotation of an elongated object. Extracted from [57]. Bottom Left) Different props being levitated using beads as buoys. Extracted from [155]. Bottom Right) A teleconferencing example based on ArticuLev. Extracted from [54]

1.6 Limitations of Acoustic Levitation

Different devices and methods of acoustic levitation suffer from different limitations and constraints. In this section, a review will be conducted on some of the most common restrictions and technical challenges that need to be overcome to extend the capability of current acoustic levitation devices.

1.6.1 Size

As previously stated, a standing wave can only levitate spherical particles smaller than half-wavelength and with positive acoustic contrast (i.e., the acoustic impedance of the particle is larger than that of the propagation medium). When the medium is water-based, it is also possible to have particles with negative contrast; in this case, the particles go to the anti-nodes. Considering that, it is straightforward to conclude that the maximum size of the element to be levitated is directly limited by the frequency of the sound employed.

Let us propose the levitation of humans just as a fun exercise to understand the implications of this limitation. Consider a perfect cubical human with a size of 1.77m and a mass of 77.5kg (the average height and weight of a Spanish male). That would mean we need to apply a pressure equivalent to $((77.5 \times 9.81)/(1.77^2) \approx 242.7Pa$ applied over the bottom surface of the human to counteract gravity. If we want to get the equivalent in decibels, the Sound Pressure Level, we must apply the following formula: $L_p = 20 \times log(\frac{P}{P_0})$ where P_0 is an agreed upon value of $2 \times 10^{-5} N/m^2$. $L_p \approx 20 \times log(\frac{242.7}{2 \times 10^{-5}}) \approx 326, 2dB$. Therefore an intensity of at least 326.2dB is needed to levitate a man. Given that the human pain threshold is around 140 dB, this sound would be extremely loud. Furthermore, we should note that 196dB are theoretically the maximum decibels that can be reached without distortion, as at that level the negative part of the waveform is a vacuum and cannot rarify any more [26]. Additionally, the standing wave applied should also have a frequency of approximately 96Hz ($\lambda = 3.55m$; $\frac{\lambda}{2} = 1.77m$) to fit the human in one of its nodes steadily, making it audible and dangerous.

1.6.2 Shape

The acoustic trapping of non-spherical objects has usually been neglected in the literature despite being an important problem faced by practical applications of acoustic levitation. Some of the solutions rely on the levitation of traditional spherical EPS beads acting as buoys to levitate non-spherical elements hanging from them. See section 1.5.3. Non-spherical particles have been steadily trapped using the acoustic lock technique [41] but require extra control on the emission of the fields is needed, and the particles must be sub-wavelength sized. There is no existing work on how to trap elongated objects with sizes above the wavelength in position and orientation.

1.6.3 Density

The size of the object is not a major factor in levitation if it is much smaller than the wavelength; instead, the density is the most important property [14]. The minimum acoustic pressure needed for levitation is independent of the object's size in this case. For most solid objects in air, there is a significant difference between the air density and the object density, such that the object can be considered as a rigid material.

In 2001, Xie and Wei [246] achieved the stable levitation of high-density materials such as tungsten $18.92g/cm^3$. Foresti et al. [58] showcased in 2013 the acoustophoretic contactless transport of high-density objects in air. By employing a morphing reflector made of elastic materials, they could enable the acoustic levitation of a steel sphere of 5 mm in diameter (0.5 grams; density of 7.85 g/cm3). However, this technique is considerably limited in how far or high the objects can be levitated and inevitably requires the presence of the customized reflector.

Dynamic levitation of multiple high-density objects would open up numerous possibilities; however, the trapping strength decreases linearly with the number of traps and the current arrays do not have enough power to levitate multiple high-density objects simultaneously [11]. Despite these advances, it is evident that the denser the material, the hardest it will be to achieve its controlled acoustic manipulation. This frontier has been pushed forward, but it is still there, and we still need to reach the acoustic manipulation of dense materials without suffering severe restrictions.

1.6.4 Viscosity and liquids

The liquid drop dynamics, as influenced by sound fields, is far from sufficiently understood, especially due to the multidisciplinary nature of the topic[253]. Acoustic fields could form the basis of a contactless liquid processing platform with the power to programmatically mix, split, and transfer droplets. This platform would possess the same capabilities as current electrowetting systems. However, given the extensive selection of wavelengths that acoustic systems can work with, it would be able to execute procedures from the micro to the millilitre scale.

As shown in section 1.5.2, mixing liquids has been successfully achieved but splitting liquid has not been proven with acoustic levitation. As reported by Andrade and Marzo [10] the stability of levitation, especially for liquid drops, is largely determined by whether levitation works slightly under or above resonance. Given that 40 kHz ($\lambda = 8.5$ mm) is the most widely used frequency, the droplet size range is limited to approximately 40 μL, resulting in limited experimental applicability. Moreover, all droplets must be continually levitated, restricting the number of droplets that can be handled simultaneously.

The dispensation of droplets into the working volume is one of the most prominent challenges in the acoustic levitation of liquids. For droplets deposited onto a surface, controlled detachment from said surface and entry into the air can present a difficulty. Where droplets are dropped directly into the volume, accuracy in positioning the acoustic trap is needed, and the design of the acoustic field must be optimal to avoid bursting the drop while maintaining control over it.

Therefore, a new approach that can handle a large number of liquid droplets of different sizes (greater than 40 μL), manoeuvre them in three dimensions and split them is needed.

1.6.5 Reflections and obstacles inside the working volume

Approximation of the transducer's behaviour as a piston model is common in existing approaches for obtaining the transducers' amplitudes and phases that generate a desired sound field. However, the traditionally employed models assume that the working volume is an empty space, disregarding sound scattering of objects' surfaces; consequently, physical objects within the working volume can distort the sound field and result in undesirable particle fall. Non-levitated objects present within the working volume must be carefully chosen not to affect sound fields. They must be made of acoustically transparent materials or present a shape that avoids creating reflections that distort the final acoustic field. Particles smaller than the acoustic wavelength could also be present in the working volume without distorting significantly the acoustic field, but they would also be affected and dragged by it.

Hirayama et al. [84] recently proposed a fast computational technique that allows high-speed multipoint levitation even with arbitrary sound-scattering surfaces. Their model estimates transducer contributions in real-time by reformulating the boundary element method for acoustic holography. However, this solution is limited to using only static scattering objects. The presence inside the working volume of moving or changing objects is currently out of reach.

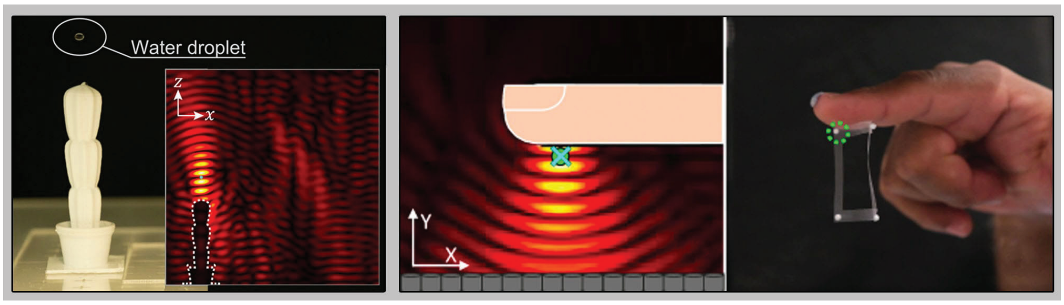

Figure 1.17: Left) Generating an acoustic trap taking into account the reflections caused by an obstacle. Extracted from [84] Right) A focal point reflected off the user's skin creates an opportunistic trap (OT), which can hold particles under the fingertip. Extracted from [95]

An interesting alternative approach is the one showcased by Jankauskis et al. [95]. In this case, the presence inside the working of a moving object is not only possible but encouraged. Their project TipTrap exploits the reflection of ultrasound on the users' skin and employs a closed-loop system to create functional acoustic traps 2.1 mm below the fingertips. While limited to finger-like structures, TipTrap enables direct interaction with the levitated content without disturbing or destroying it.

1.6.6 Resolution

Acoustic fields can be dynamically shaped to specific patterns by using phased-arrays composed of various emitters with controllable amplitude and phases [139]. These arrays can generate different amplitude fields by electronically adjusting the signal of each emitter, but the resulting fields lack spatial resolution given the limited number of emitters, which usually do not fulfil the Rayleigh criterion. On the other hand, passive phase modulators can be manufactured with high-spatial resolution [148, 149] but they are static and generate only one pattern.

Passive structures that modulate impinging waves are an alternative to obtain high-resolution patterns [148], but they are static and one plate is needed per target pattern. Some improvements allow to produce different fields when the modulator is impinged by different frequencies [28], but the number is limited to 2 or 3 fixed patterns.

Combinations of phased arrays and passive modulators provide some flexibility over the static patterns. Cox et al. [42] used this combination for focusing along the vertical direction a trap generated with the array and enhance its trapping performance on a single-particle. Athanassiadis et al. [18] were able to code 10 patterns in a passive modulator, these patterns were projected when impinged by one of the 10 different emitters that were attached to the modulator, yet only 10 fixed patterns were encoded in the modulator with some loss in the resolution.

1.6.7 Speed

Some applications may benefit from the high-speed manipulation of levitated elements. See section 1.7. However, increasing the manipulation of the trapped particles requires a more profound knowledge of the involved dynamics. At high speeds, the trapped object may experience larger displacements from the position of minimum potential. In this case, models based on linear trapping stiffness are no longer valid, and the acoustic restoring force must be described by nonlinear stiffness models [11].

In 2019, Hirayama et al. did propose a top-bottom volumetric display capable of manipulating particles at up to 8.75m/s in the vertical direction, and 3.75m/s in the horizontal direction [85]. They confirm that high-speed particle displacements involve more frequent and larger changes to the phase of each transducer, deviating them from the desired operating frequency of 40kHz and resulting in decreased performance. Besides, high speed cannot be kept constant, as the particle must be drastically decelerated when taking tight turns. This work was performed over small, lightweight particles. Moving heavier particles at high speed is still not possible.

It has also been demonstrated that dampening undesired oscillations of trapped solid objects within levitation can be challenging [8]. This difficulty is further augmented when liquid drops are being levitated [10]

1.6.8 Accessibility, price, availability, control and flexibility of the devices

Phased arrays with individually addressable transducers have been encapsulated in commercially available platforms, e.g., Ultraleap, Bristol, UK; Pixie Dust Tech., Tokyo, Japan; SonicEnergy, California, USA, each of which provides technology development and commercialisation towards specific target market solutions. While these ultrasound phased arrays possess a fast update rate, high-power output, and sufficient phase and amplitude resolution, they are comparatively expensive, the software is closed, and the hardware cannot be easily modified. This creates a limitation for researchers, as commercial systems do not allow for easy access to data, embedding new algorithms, or extension of functionality as an open platform would. Despite the numerous scientific advancements made in both industry and academia, there is currently no unifying hardware platform that can flexibly support exploratory research in acoustic haptics and holography applications.

Some researchers have developed open platforms of acoustic phased arrays operating at 40 kHz in air. These platforms allow developers to create their own low-cost array [208, 255]. For instance, the TinyLev platform [136], reduces the number of independent channels while achieving effective levitation. Hirayama et al. [85] implemented a levitation display that could create and modulate multiple focal points at a high-speed update rate (20 kHz) to deliver tactile feedback and parametric audio at the same time. However, only part of the code is public, and the hardware was not provided. Other projects, such as Ultraino [138], have released both hardware and software. This multi-purpose phased array is based on an Arduino MEGA microcontroller, offering 64 channels, a phase resolution of $\pi/5$ and the ability to chain multiple boards together. Its software enables the customisation of phased array arrangements and provides real-time visualisations of the pressure field. Although the Ultraino platform provides low-cost solutions, the operating voltage is limited, and the setup can be time-consuming to build as the transducers need to be wired to the boards individually.

1.7 The Diverse Applications of Acoustic Levitation and Acoustic Fields

Non-contactless manipulation requires a direct interaction between a tool or robot gripper and the object to be manipulated. However, it faces complex challenges [167] such as releasing the object into the desired places due to the sticky force between the gripped object and the ends of the gripper itself [36]. Not all objects have regular surface morphology and enough friction, which enable a steady grip on the object. Some objects may require being manipulated with less or with no contact at all, avoiding contamination or pressure that may damage the delicate object. Acoustic contactless manipulation can deal with these problems and address other specific ones present in different research disciplines, professions and industries. Proposed and demonstrated applications in the literature already demand high positioning accuracy and demonstrate the importance of understanding the dynamics of particles levitated.

The following subsections will review some of the realized and potential applications of acoustic levitation and acoustic fields, highlighting the broad impact that advancements made by research in this domain may have.

1.7.1 Biology, Biomedicine, Medicine and Chemistry

Biomedicine and chemistry have been using microfluidics and acoustic radiation forces for a long time. Particle manipulation in liquid has been studied extensively, aiming towards the manipulation of macromolecules, cells, particles, model organisms, and fluidic flows [121, 257]. Many researchers have already investigated some functions such as particle separators, filters and patterning devices [31, 80, 164, 184, 200, 201, 218, 250].

Acoustic levitators have been widely used as specimen holders for measuring density [220], Mass spectrometry [238], spectroscopy of red blood cells [186], the study of blood disorders [90], amorphilization of molecular liquids of pharmaceutical drugs [23], X-ray protein crystallography [221], spray drying in the development of vaccines [159], or DNA transfection in mid-air [55, 225]. More recently, Phased Arrays Levitators have also been used for specimen holding due to their extended capabilities as position locking or levitation of non-spherical objects. Some examples are the holding of specimens free from excessive evaporation [170], the contactless transportation and merging of droplets [7, 233], or the compartmentalisation of chemical species [126].

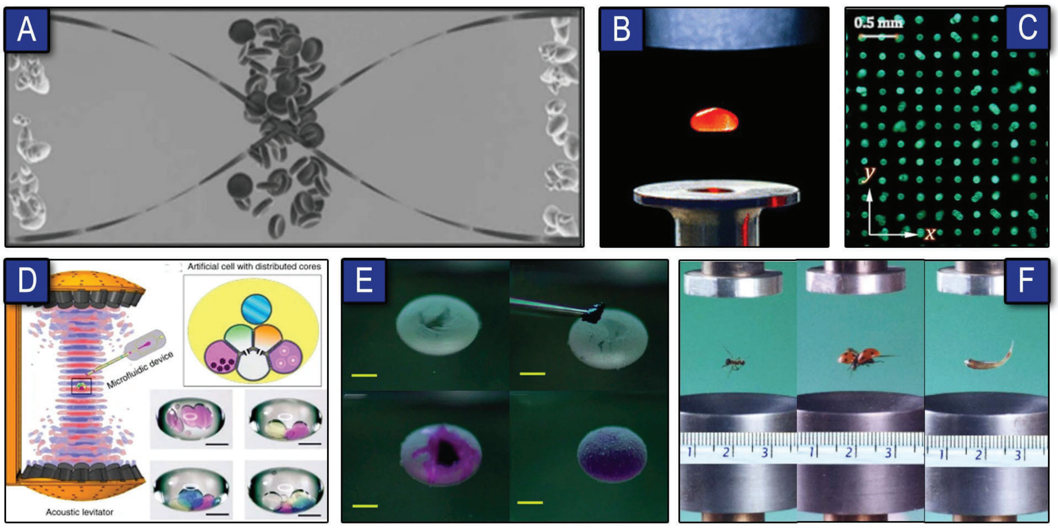

Figure 1.18: A) Separation channel of lipid particles collected in the pressure antinodes DNA red blood cells in the pressure node. Extracted from [121]. B) Raman spectroscopy of a levitated 5μL of red blood cells to detect hemozoin in malaria infected cells. Extracted from [186]. C) Colloidal crystal assembled through acoustic radiation force. Extracted from [31]. D) Compartmentalisation of chemical species in a droplet laboratory platform. Extracted from [126]. E) A block of KMnO_4 being introduced into a liquid marble acting as a microreactor. Extracted from [254]. F) Acoustic levitation in air of an ant, ladybug and a young fish. Extracted from [245].

With the advantages of non-invasiveness, label-free operation, and low power consumption, acoustic tweezers have often been reviewed and proven to be a versatile set of tools to manipulate bioparticles ranging from nanometer-sized extracellular vesicles to millimetre-sized multicellular organisms [150, 175], and to perform all kinds of analytical and bioanalytical chemistry applications [196].

Acoustic levitation is being applied to research small animals [245] or in vivo zebrafish embryos [96, 211].

In general, acoustic levitation is a valuable and flexible tool in biomaterials research [235], pharmacy [129], and chemistry [196] also enabling lab-on-a-drop procedures [183].

1.7.2 Materials Sciences

The study of metallic melts, their physical properties, and their solidification behaviour are of primary importance to understanding the fundamental principles governing this type of material and to the development of metallurgical applications. Many properties of metallic melts are very sensitive to contaminants, so containerless processing techniques have become an essential tool in investigating these systems. [83].

Beyond metallic melts, containerless processing reduces the potential for contamination during the manufacturing process and precludes the possibility of a material's interaction with its container [235]. Eliminating any influence of container walls is vital in studying materials related to metallic melts, fluid flow dynamics, glass formation, preparation of pure substances and undercooling and solidification.

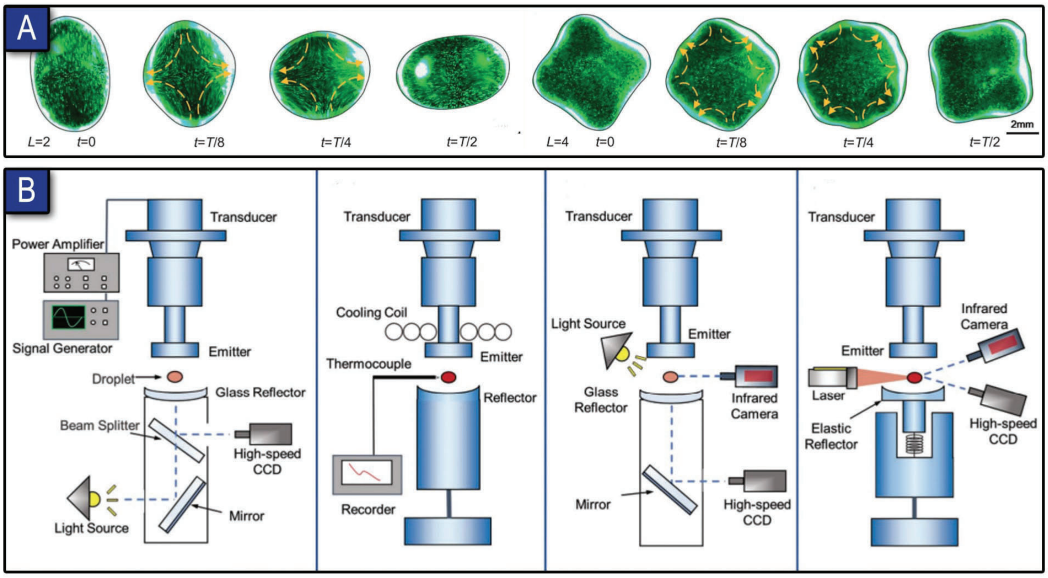

Figure 1.19: Examples of the use of acoustic levitation in the study of materials. Extracted from [66]. A) Internal flow patterns of acoustically levitated droplets undergoing sectorial oscillations. B) Acoustic levitation apparatus for space simulation and rapid solidification. Different approaches for different materials and analysis.

Examples of the use of acoustic levitation in the study of materials are the investigations of the glass-forming ability of non-metallic systems [49], the melting of plastic materials, aluminium, and glass [240], the study on the extraordinary solidification kinetics of liquid alloys [66], the preparation of epoxy blends with nanoparticles [33], estimation of the viscoelastic properties of foam [145], or the organization of carbon short fibres within a photocurable resin [17].

1.7.3 Data Visualization and Displays

Acoustic fields have been widely explored also to conceive new displays. Digital art technologies, data visualization, 2D displays and 3D displays have exploited acoustic forces to develop and study novel display and interaction devices, opening new opportunities in the research of Human Computer Interaction (HCI).

In the area of digital art technologies, pressure projection devices have been used to displace particles or fibres, creating new drawing canvases. Examples of this are *Graffiti fur* [209], in which focused ultrasound was used to raise/flatten the fur found in various items such as carpets in our living environments; Or *Ghost Touch*, in which interactive surfaces were designed through artistic effects performed on sand, milk and ink or liquid soap [140].

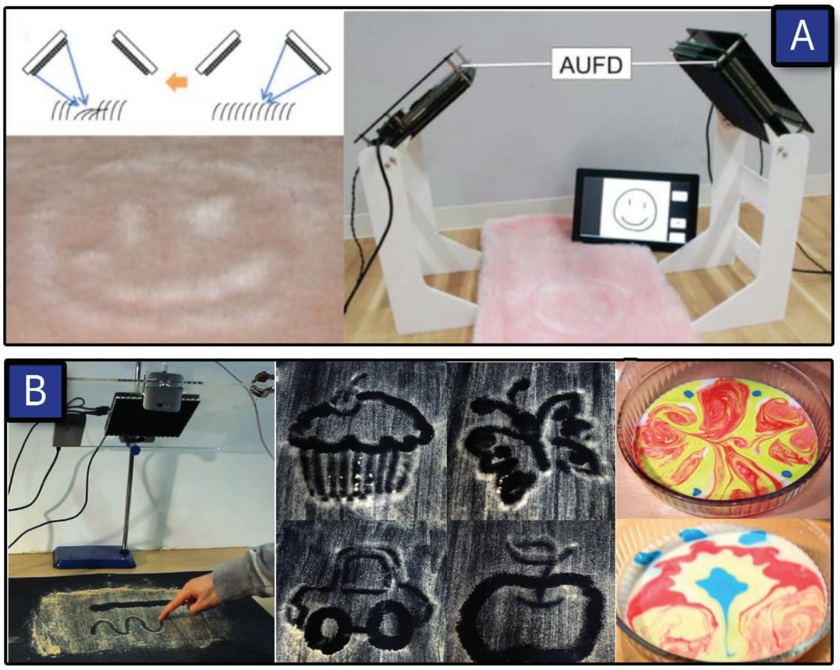

Figure 1.20: A) Principle, composition and result of a pressure projection device drawing on fur. Extracted from [209]. B) Remotely drawing on sand and milk. Extracted from [140].

Using levitated particles to represent objects is also a developing research field. In the project *Floating Charts* [173], levitating graphical representations serve as dynamic physical displays for data visualization. These data visualizations would be enhanced further by *DataLev* [64] through reconfigurable and dynamic physicalization animated to illustrate different chart types. *Leviprops* [155] also includes in the working volume levitated tangible structures as free-form interactive elements and as projection surfaces, to create interactive mid-air experiences. Levitating particles have also been used to add dynamic display elements enhancing the appearance of static physical objects [60].

This new way to visualize and physicalize data also implies the study on how to directly interact with models in 3D space and perform multi-point gestures to manipulate them [162].

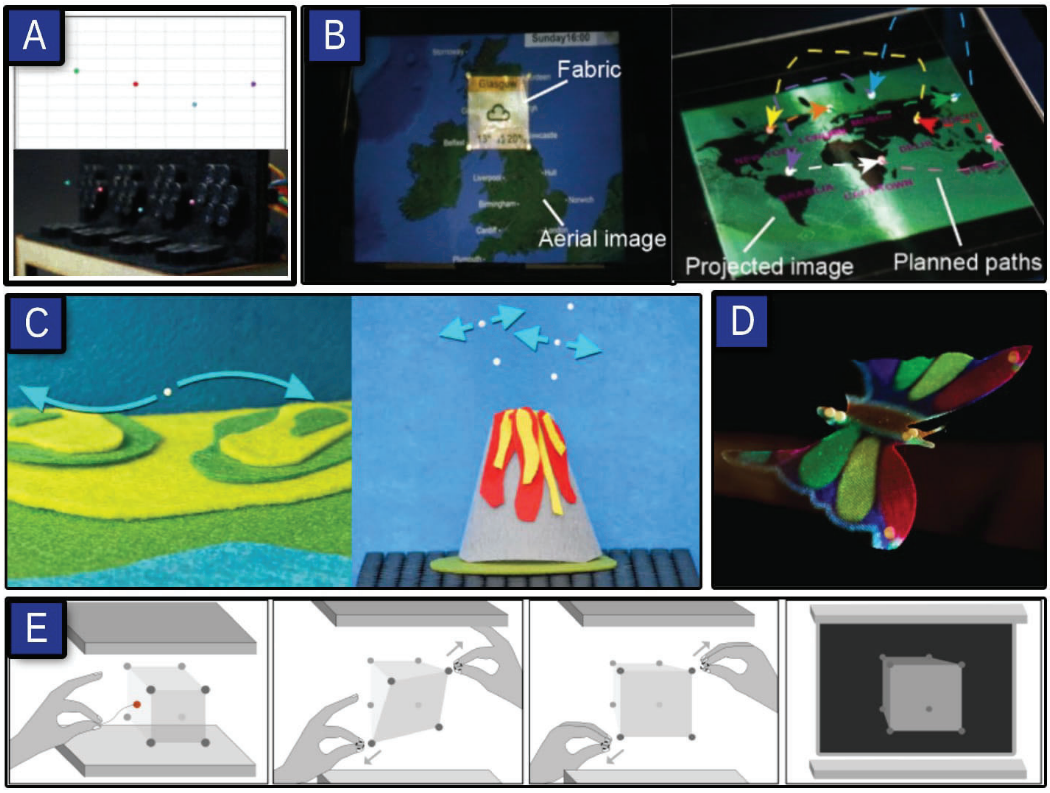

Figure 1.21: A) A floating chart composed of 4 L-shape blocks and its digital counterpart. Extracted from [173]. B) Phyicalisations of an interactive weather forecast and an airport network diagram. Extracted from [64]. C) Examples of levitated particles used to present dynamic visual content. Extracted from [60]. D) Levitated prop used as a mid-Air display with projection mapping. Extracted from [155]. E) Physicalized control points for manipulating 3D objects. Extracted from [162].

Projection displays have also been explored by using ultrasonic Bessel beams to create and redirect laminar flows of fog to be used as projection screens [166] or by levitating organza cloth serving as surfaces for projection mapping [54].

Understanding of the 2D pixel as a display primitive, *JOLED* proposes using Janus objects (whose surfaces have two or more distinct physical properties) as physical voxels, controllably rotated with electrostatics to reveal their different physical properties [195].

Evolving towards volumetric displays, several works explore fast-moving levitated particles to render simple figures in real-time or to raster images at low framerates [62, 86, 177]. A quickly rotating levitated screen (5rpm) has also been used to project 3D content [84].

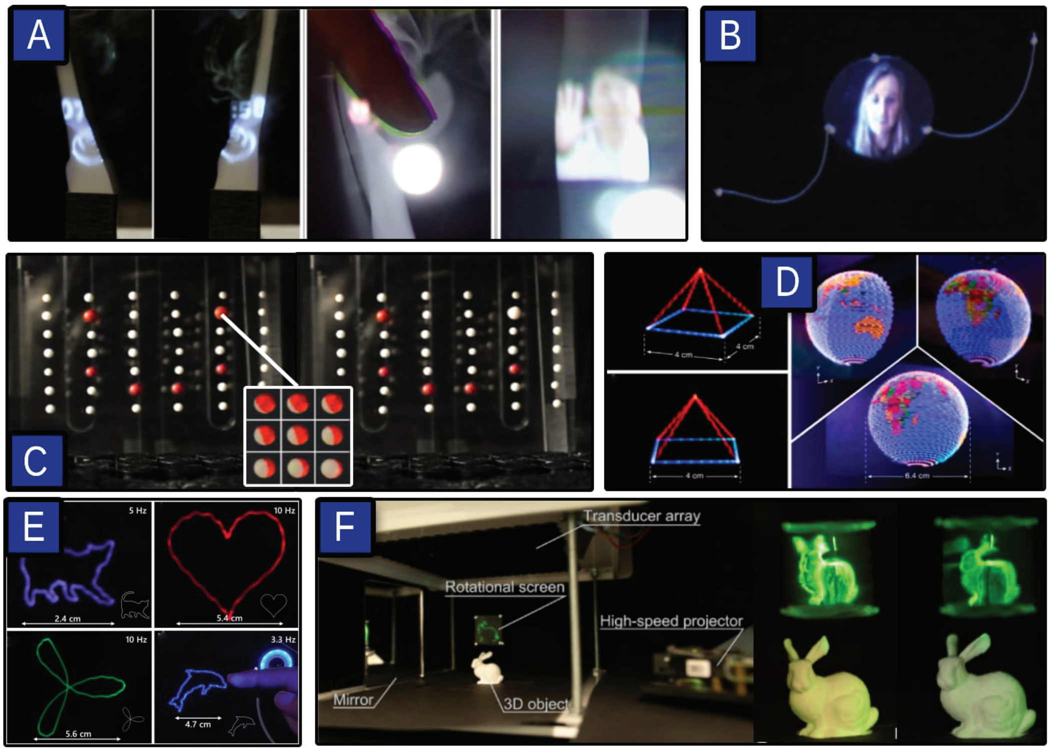

Figure 1.22: A) Visualising a graphical clock in mid-air by laterally oscillating its narrow mist, enables direct interaction and other projections. Extracted from [166]. B) A levitated disk serves as a projection surface to display the users' faces in a teleconferencing example. Extracted from [54]. C) Continuous control of rotation over a Janus voxel to show the dynamic image of a smiley face winking one eye. Extracted from [194]. D) Volumetric contents (2s and 20s exposure). Extracted from [86]. E) Rendering generic complex paths with sharp edges. Extracted from [177]. F) Example of the creation of volumetric POV images using a quickly rotating screen. Extracted from [84].

1.7.4 Gaming

The gaming industry can also exploit this technology to create new enriched experiences. In 2020 *Levi-loop* [157] proposed reflecting on the challenges of precisely controlling mid-air levitating objects in the presence of physical constraints and obstacles and improving rehabilitation of upper-body motor skills for people with dexterity impairment after suffering a stroke.

More recently, in 2022, *UltraBat* [232] presents an interactive 3D side-scrolling game inspired by Flappy Bird, and *Top-Levi* [103], exploiting dynamic physical 3D contents, designs a challenge that requires a pair of users to cooperate with an audience around them to fulfil a collective task.

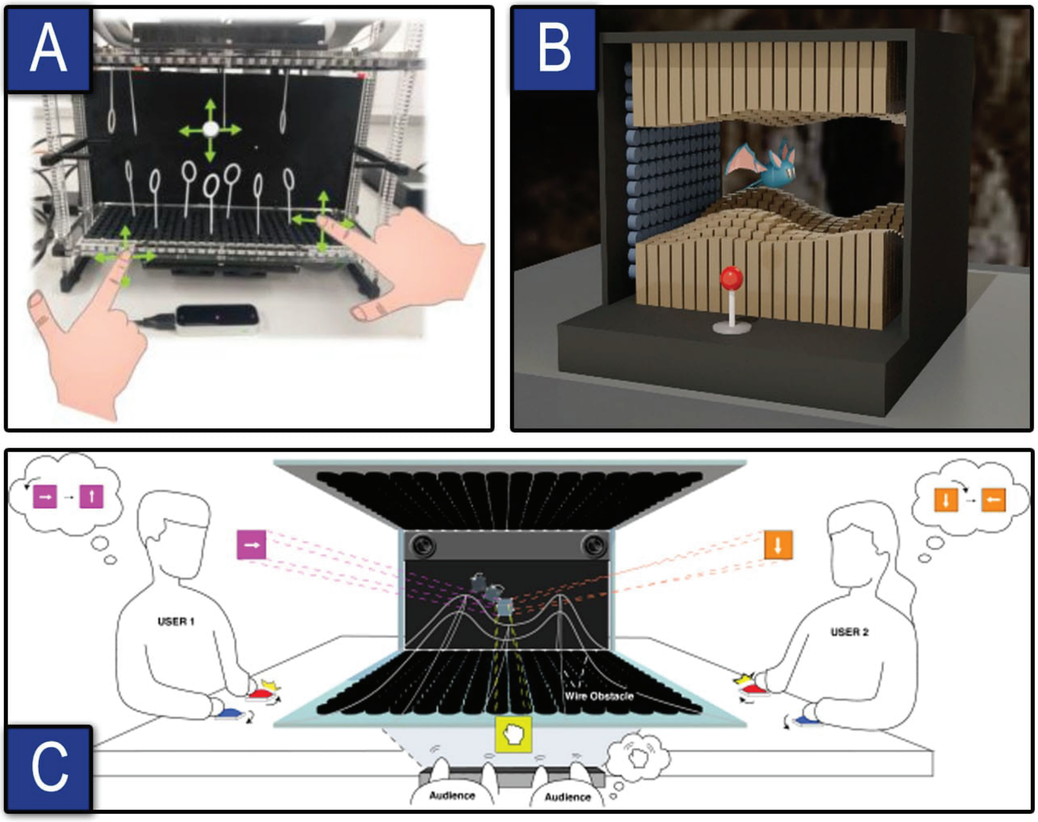

Figure 1.23: A) Illustration showing the *Levi-loop* demo interaction. Extracted from [157]. B) Pin-array creates a shape-changing passage through which the player must levitate a bat to avoid obstacles. Extracted from [232]. C) Overview of *Top-Levi* challenging two users and an audience to complete a collaborative task. Extracted from [103].

1.7.5 Haptics

Mid-air haptic stimulation can enrich user experience during human-computer interaction. Several works have studied using ultrasonic devices to stimulate the sense of touch or to enhance existing interactive surfaces by emitting ultrasonic acoustic waves.

In 2012, Marshall et al. proposed *Ultra-tangilbes*, a project using ultrasound to independently move multiple tangible objects around an interactive surface [133]. In 2013, Carter et al. showcased *UltraHaptics*, a study on focused ultrasound to project discrete points of haptic feedback through the display and directly onto users' hands [34]. Long before, in 1976, Gavrilov et al. already proposed the use of focused ultrasound to stimulate the human arm [65]. This project paved the way for numerous research on creating tactile sensations in the hands through ultrasound [89, 205], or recently exploring its use to convey mid-air buttons [143, 156] and mapping sensations and experiences related to the stimuli [47].

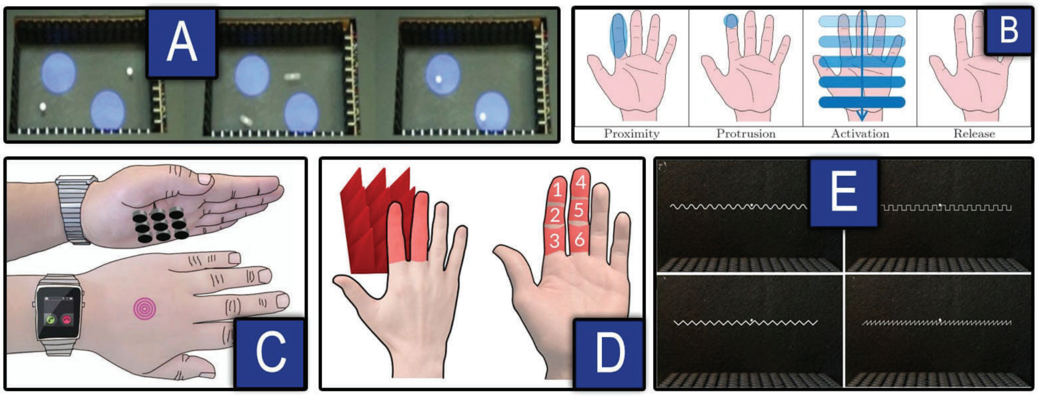

Figure 1.24: A) Two movable tangible objects on an interactive table. Extracted from [133]. B) Whole-hand sensation set showing the spread of the haptic sensation of pressing a mid-air button. Extracted from [143]. C) Ultrasound transmitters used to create tactile feedback in the hand and through the hand. Extracted from [205]. D) Areas of the hand intersecting a mid-air textured surface. Extracted from [59]. E) Different transfer functions for oscillating a moving particle could result in different pseudo-haptic texture sensations. Extracted from [190].

Textured surfaces can also be rendered using techniques that render tessellated 3D haptic shapes with different waveform properties, creating surfaces with distinct perceptions [59]. Similarly, the perception of visual roughness has also been incorporated into mid-air textures using machine learning models [22]. Furthermore, pseudo-haptic effects of Friction, Sliding, Textures and Stickiness have also been explored to enrich the interaction with new sensory experiences and provide simulated touch feedback [190].

1.7.6 Food industry

Research involving food and gustatory experiences with acoustic levitation has also been done in recent years. Examples of this are *TastyFloats* [227], studying users' taste perception using acoustic levitation to deliver food morsels to the users' tongue, or *LeviSense* [228], a system designed for multisensory integration in gustatory experiences based on levitated food. Acoustophoretic printing of food has also been explored [56].

Figure 1.25: A,B) Setups to levitate and experiment with small food samples. Extracted from [227, 228]. C) Acoustophoretic printing of honey on white chocolate. Extracted from [56].

1.7.7 Wireless Power

Wireless power transfer creates new opportunities for interaction with tangible and wearable devices by freeing designers from the constraints of an integrated power source. The use of focused ultrasound to transfer power to a distal device has also been researched, transforming passive props into dynamic, active objects [4, 5, 158].

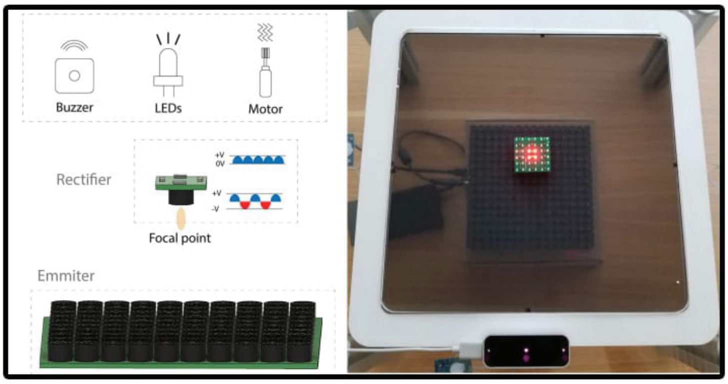

Figure 1.26: Focused ultrasound used to wirelessly transfer power to components. Extracted from [158].

1.7.8 Additive Manufacturing

In traditional assembly and manufacturing techniques, a common characteristic is that the parts or materials that are manipulated or dispensed are in direct contact with the machine. Consequently, special equipment is required to manipulate small or fragile components, and the handling of liquids, powders or hot materials is challenging. Furthermore, contact-based processes inherently lead to cross-contamination, so when dangerous materials or bio-materials are employed, it is necessary to have multiple manipulators or sterilise them between the changes of materials.

For these reasons, acoustic levitation may be beneficial in new additive manufacturing techniques. The ability to merge and combine objects in mid-air enables the generation of physical objects in space. One patent from Boing (United States) [77], another from Neurotechnology Ultrasound (Lithuania) [187], and another from Siemens Energy, Inc. (Germany) [192] presents the idea of a contactless manufacturing system, yet no full realisation is shown.

Melde et al. have achieved acoustic fabrication using acoustic manipulation [147]; however, it is in a liquid-based system and buoyancy of the particle assists favourably to ease the process of acoustic fabrication. Llewellyn-Jones et al. have also explored ultrasonic manipulation on microscale structures to distribute glass microfibres within a resin matrix [130].

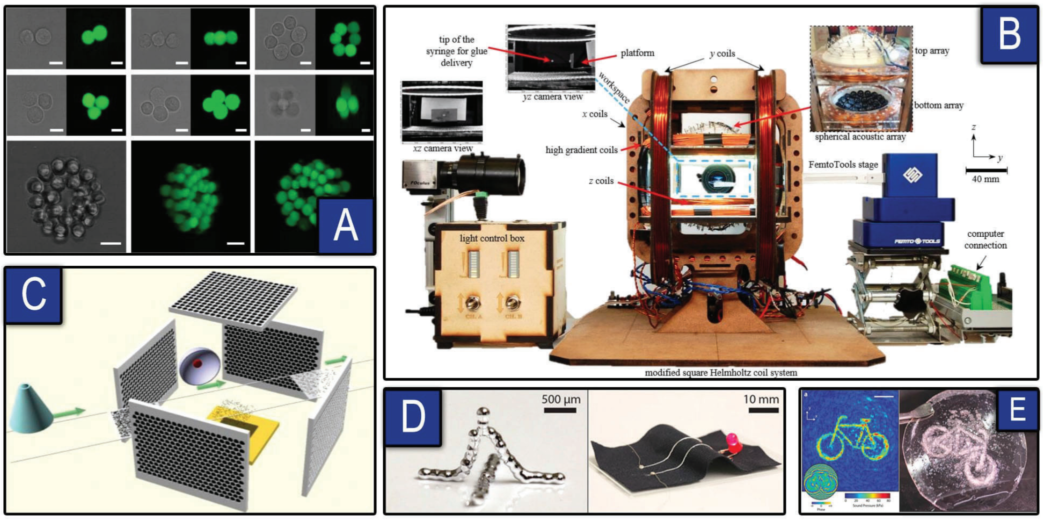

Figure 1.27: A) Mouse embryonic stem cells patterned into precise 3D structures using holographic *optical* tweezers. Extracted from [106]. B) Micro-manipulation device with electromagnetic coils and acoustic levitator. Extracted from [252]. C) Conceptualization of a system capable of realizing layer-by-layer deposition of powder materials on flat surfaces using acoustic levitation in air. Extracted from [210]. D) Acoustophoretic printing of a liquid metal ink composed of eGaIn. Extracted from [56]. E) Pressure field and assembled silicone particles after curing. Extracted from [147]

Acoustic levitation has been complemented with an external magnetic field to control the orientation of magnetically active components for use in micro-assembly applications [252]. Optical tweezers have been used to manipulate micrometric spheres to create microstructures [203]. A prototype could move spherical particles and stack them together using biotin [106]. However, optical tweezers are limited to micrometric sizes.

Acoustophoretic droplet-based printing methods were proposed in 2018 by Foresti et al. enabling drop-on-demand patterning of a broad range of soft materials [56]. Inspired by resin 3D printers, a method of layer-by-layer deposition of particles on a flat surface was also proposed in 2020 [210].

Nevertheless, no system integrates the insertion, manipulation and fusing of droplets or sub-wavelength particles; moreover, there is no possibility of working with elongated parts.

1.7.9 Pick and Place

Manufacturing is usually complemented by the assembly, which is the placement of the parts that compose the final object; a common example is the pick-and-place of electronic components on a printed circuit board (PCB) [19]. Assembly can be defined as the process of picking the parts that compose an object and placing them with the correct orientation and position.

The classical assembly processes are no longer usable for very small components, typically ranging from 10μm to 10 mm, since usually neglected surface forces disturb the handling task by causing adhesion between the component and the gripper. A promising alternative to tackle surface forces consists in levitating the handled components. [224]. Levitating the components drastically reduces the friction effect, enabling high resolution and accuracy motion devices by avoiding the stick-slip effects, and opens the possibility of handling tricky components (fragile, freshly painted, sensitive or micron-sized structured surfaces). Furthermore, cross-contamination from and of the end-effector can be avoided; this could be particularly important when dealing with food or lubricants.

The contactless pick-and-place of millimetric objects has been investigated using inverted near-field acoustic levitation [15], but the transducer and target object must be placed closely. Additional research has been made on using acoustic tweezers and phased arrays to contactless pick and place elements from acoustically reflective surfaces [108, 191]. Whilst these grippers are capable of picking objects of any material and shape, the best stability is achieved if the object's shape is similar to that of the acoustic trap and the size of the gripped object is limited to approximately 5 mm.

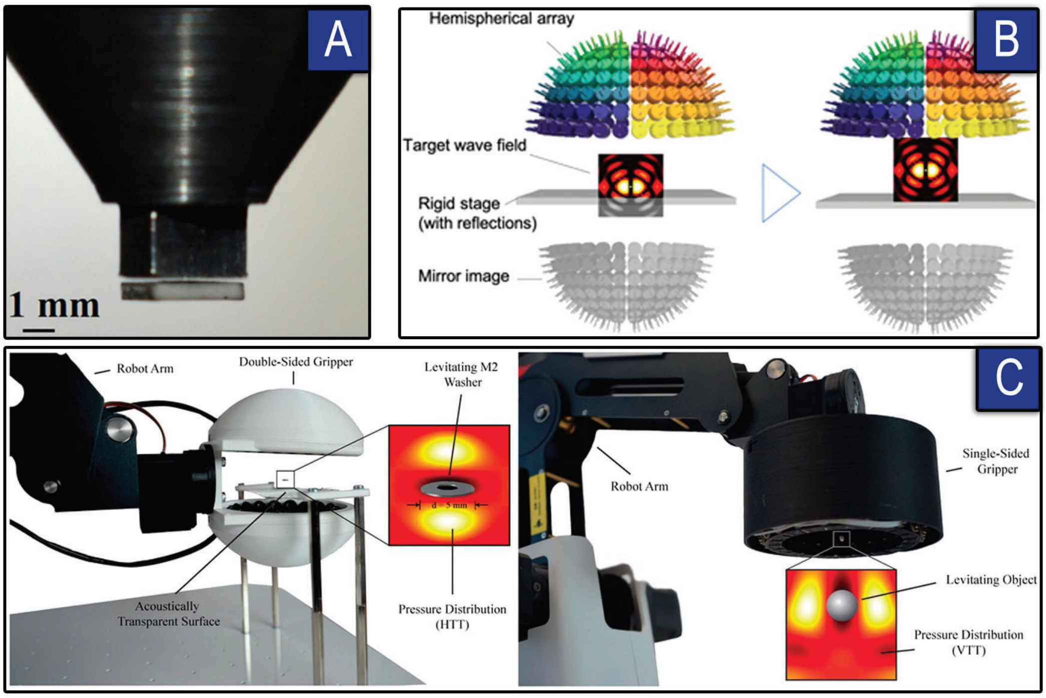

Figure 1.28: A) Inverted near-field acoustic levitation of an SMD weighing 9mg. Extracted from [15]. B) Schematic of a single-sided hemispherical array creating acoustic tweezers for non-contact pick-up. Extracted from [108]. C) Double-sided and single-sided acoustic grippers acoustically manipulating a M2 washer. Extracted from [191].

2 Compiled Research Papers for this Thesis

2.1 Generating Airborne Ultrasonic Amplitude Patterns Using an Open Hardware Phased Array

Title:	*Generating Airborne Ultrasonic Amplitude Patterns Using an Open Hardware Phased Array*
Access link:	https://doi.org/10.3390/app11072981
Authors:	Rafael Morales, Iñigo Ezcurdia, Josu Irisarri, Marco AB Andrade, Asier Marzo
Publication date:	26 March 2021
Venue:	Applied Sciences-Basel
Impact Factor:	2.838 (Q2 in Engineering, Multidisciplinary | JCI Percentile: 64.29)
Article Views:	5943
Citations:	8
Abstract:	Holographic methods from optics can be adapted to acoustics for enabling novel applications in particle manipulation or patterning by generating dynamic custom-tailored acoustic fields. Here, we present three contributions towards making the field of acoustic holography more widespread. Firstly, we introduce an iterative algorithm that accurately calculates the amplitudes and phases of an array of ultrasound emitters in order to create a target amplitude field in mid-air. Secondly, we use the algorithm to analyse the impact of spatial, amplitude and phase emission resolution on the resulting acoustic field, thus providing engineering insights towards array design. For example, we show an onset of diminishing returns for smaller than a quarter-wavelength sized emitters and a phase and amplitude resolution of eight and four divisions per period, respectively. Lastly, we present a hardware platform for the generation of acoustic holograms. The array is integrated in a single board composed of 256 emitters operating at 40 kHz. We hope that the results and procedures described within this paper enable researchers to build their own ultrasonic arrays and explore novel applications of ultrasonic holograms.
Attached Media:	DIY video-tutorial: https://youtu.be/vAEZvYlUnEM (11min long)

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Article

Generating Airborne Ultrasonic Amplitude Patterns Using an Open Hardware Phased Array

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Special Issue
Holography in Acoustics and Ultrasonics

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Article

Generating Airborne Ultrasonic Amplitude Patterns Using an Open Hardware Phased Array

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Abstract: Holographic methods from optics can be adapted to acoustics for enabling novel applications in particle manipulation or patterning by generating dynamic custom-tailored acoustic fields. Here, we present three contributions towards making the field of acoustic holography more widespread. Firstly, we introduce an iterative algorithm that accurately calculates the amplitudes and phases of an array of ultrasound emitters in order to create a target amplitude field in mid-air. Secondly, we use the algorithm to analyse the impact of spatial, amplitude and phase emission resolution on the resulting acoustic field, thus providing engineering insights towards array design. For example, we show an onset of diminishing returns for smaller than a quarter-wavelength sized emitters and a phase and amplitude resolution of eight and four divisions per period, respectively. Lastly, we present a hardware platform for the generation of acoustic holograms. The array is integrated in a single board composed of 256 emitters operating at 40 kHz. We hope that the results and procedures described within this paper enable researchers to build their own ultrasonic arrays and explore novel applications of ultrasonic holograms.

Keywords: acoustic hologram algorithm; open ultrasonic array; acoustic tweezers

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1. Introduction

The ability to produce dynamic ultrasonic fields with target shapes is of fundamental importance in ultrasonic imaging [1], nondestructive testing [2,3], and high-intensity focused ultrasound HIFU therapy [4]. When operating in air, there are numerous emerging applications that require the generation of acoustic fields with certain shapes, such as non-contact tactile feedback [5–7], volumetric displays [8,9], parametric audio generation [10,11], and the contactless manipulation of objects [12–16].

In recent years, optical holographic methods have been adapted to acoustics [13,16–18], opening the possibility of generating arbitrary acoustic fields that can be controlled in real time. Acoustic holography is normally achieved using either passive metamaterial structures [17,19,20] or an array of ultrasonic transducers [13,16,21]. Metamaterial structures have the main advantage of allowing for the generation of acoustic fields with a higher spatial resolution, but they cannot dynamically change the field. In contrast, phased arrays do not have this limitation, since the emission phase and amplitude of each transducer can be controlled by a computer, allowing to change the acoustic field in real time. This capability of phased arrays is encapsulated in commercially available platforms, e.g., Ultraleap, Bristol, UK; Pixie Dust Tech., Tokyo, Japan; SonicEnergy, California, USA, each of which provides technology development and commercialisation towards specific target market solutions. Despite the numerous scientific advancements made in both industry and academia, there is currently no unifying hardware platform that can flexibly support exploratory research in acoustic holography applications.

In this paper, we present SonicSurface, a low-cost open hardware array for generating arbitrary acoustic fields in mid-air. We also present an algorithm for calculating the emission amplitude and phase for each transducer in order to create a target amplitude field at a certain distance from the array. Additionally, we offer a comparison of the accuracy of the generated fields depending on the size of the ultrasonic emitters as well as their phase and amplitude resolution. This paper is accompanied by video instructions, available at www.upnalab.com (accessed on 20 February 2021), Do-it-Yourself. Given the low-cost and the use of off-the-shelf components, we hope that researchers can build and use these ultrasonic arrays for their own experiments. We also note the companies commercializing ultrasonic phased arrays offer proprietary solutions that are certified for their use in various commercial applications.

2. Related Work

Our review of related work gives an overview of projects that designed and built ultrasonic arrays that typically operate at 40 kHz. Additionally, we provide a review of algorithms for creating an arbitrary pressure field.

An ultrasonic phased array consists of a collection of elements that can transmit or receive ultrasonic waves with specific time delays (phases offsets) and amplitudes. This technology enables the generation of arbitrary pressure fields by controlling the phases and amplitudes of each emitter. Moreover, it provides an interesting setup for a wide spectrum of novel applications, such as mid-air displays [22], wireless power transfer [23], acoustic imaging [24], or delivering food through acoustic levitation [25], to mention a few.

Iwamoto et al. first demonstrated ultrasonic mid-air haptic feedback [26], who developed a prototype consisting of 12 annular channels with a total of 91 ultrasound transducers in a hexagonal arrangement, a single focal point could be refocused along the central axis perpendicular to the array. Shinoda's group [27–30] developed a more sophisticated system that was capable of controlling individually 249 transducers, being able to focus at different 3D positions in space, their boards have the capability to be chained to operate as a larger array system. Carter et al. [6] developed a phased array that can produce multi-point haptic feedback. Ultraleap (Bristol, UK) is a company that commercializes ultrasonic phased arrays for haptic applications related to automotive [31], digital signage [32], and AR/VR [33] applications. The company has also been exploring the effects on humans of high intensity ultrasound exposure [34] and has been releasing multiple prototypes that explore optimized array designs [35,36]. For example, transducer array in a Fibonacci spiral arrangement can suppress unwanted secondary focal points [37]. Pixie Dust Technologies (Tokyo, Japan) provides a parametric speaker [10] and an acoustic levitator [38] based on ultrasound phased arrays. The parametric prototype array has 269 transducers populating a circular array, $\pi/32$ phase resolution, and can be refreshed at 1 kHz. Their levitator prototype has four orthogonally placed phased arrays with 285 transducers with a phase resolution of $\pi/8$ and it is updated at 1 kHz. These ultrasound phased arrays have a fast update rate, high-power output, and sufficient phase and amplitude resolution; however, they are comparatively expensive, the software is closed, and the hardware cannot be easily modified.

Some researchers have developed open platforms of acoustic phased arrays operating at 40 kHz in air. These platforms allow developers to create their own low-cost array [39–41]. For example, TinyLev [42] is a single-axis acoustic levitator that uses two ultrasonic arrays facing each other, reducing the number of independent channels by arranging transducers within the same distance to the trapping positions. Hirayama et al. [9] presented an acoustic levitator display with two opposed arrays that was capable of creating and modulating a large number of focal points at high speeds (20 kHz update rate) for delivering tactile feedback and parametric audio at the same time. While some part of the code is public, the hardware was not provided. Other projects have released both the hardware and software. For example, Ultraino [41] is a multi-purpose phased array that is accompanied by a platform that helps designers to build small phased arrays. The hardware is based on an Arduino MEGA microcontroller and provides 64 channels with $\pi/5$ phase resolution. Furthermore, multiple boards can be chained together, expanding the number of individual controlled channels. The software is capable of customising phased array arrangements and visualising the pressure field in real-time. Despite the advantage of being a low-cost platform, the operating voltage is limited, reaching a large number of channels is cumbersome, and the transducers need to be wired to the boards. This last part gives some flexibility, but it makes the setups complicated to build, even when just flat geometries are required.

A more detailed review of the available ultrasonic phased arrays can be found in [40]. We reckon that the presented hardware, SonicSurface, provides the most affordable and simple flat phased-array. More importantly, within this paper, we provide an algorithm that is capable of generating arbitrary acoustic fields using SonicSurface or other arrays that provide phase control.

Acoustic holography [43] involves obtaining the near field of a radiating surface by taking measurements on the far field. It is a fundamental technique in health structure monitoring or mechanical vibration analysis. During the last years, a new trend in acoustic holograms has emerged [13,16–18], which is defined as the application of techniques, previously used in optics, to obtain target acoustic fields of different shapes by engineering the amplitude and phase of an array of emitters or an emission modulating surface.

From an algorithmic point of view, researchers first implemented single-point algorithms [5,26] or single traps with different shapes [13]. Later, multi focal-point algorithms [16,44,45] enabled creating high-amplitude points at independent positions. For example, Plasencia et al. [46] proposed a method for optimizing the phases and amplitudes of the acoustic field, obtaining higher-quality points than previous phase-optimization approaches.

Other strategies used a phase modulation plate on top of a flat radiating piston. Melde et al., used an iterative algorithm [17] in order to calculate the required phase modulation to create a target field at a given distance; they employed a static 3D printed modulator that encoded the phases for reconstructing the target hologram. Brown et al. [47] introduced a second holographic plate to modulate both phase and amplitude surface.

These algorithms assume a high-resolution modulation plate with almost pixel-like shape for each point that modulates the field. Differently, here we introduce a modification on the previous algorithms to obtain target amplitude fields using discrete ultrasonic arrays that are made of circular emitters.

3. Hardware Design

SonicSurface is a phased array consisting of 256 transducers emitting at 40 kHz. The transducers are arranged in a 16 × 16 grid and built on a single integrated printed circuit board (PCB). On one side of the PCB, ultrasonic emitters are soldered, whereas, on the other side, the field-programmable gate array (FPGA) (EP4CE6E22C8N—ALTERA IV Core Board, Waveshare), shift registers (74HC595, TI), drivers (MIC4127 from MT), and decoupling capacitors (ceramic 50V 0.1 µF) are mounted. The signals for each emitter are generated by the FPGA. The shift registers demultiplex each digital line coming from the FPGA into eight channels, and the drivers boost the voltage of the channels from logic voltage to the supplied power voltage (up to 20 peak-to-peak voltage (Vp-p)). A block diagram can be seen in Figure 1.

The calculation of the phases and amplitudes to be emitted is performed on an external computer and then sent to the FPGA via Serial Universal asynchronous receiver-transmitter (UART) protocol at 203,400 bauds. A double buffer has been implemented in the FPGA to generate the signals uninterruptedly [48]; one of the buffers stores emission patterns coming from the computer, whereas the second buffer is the one that is used by the FPGA to continuously generate the emission signals, a command from the computer swaps the buffers at once. This method avoids latency and waiting issues. Different versions of the firmware are available for the FPGA to support phase and amplitude control, or amplitude modulation of the 40 kHz main signal.

The protocol used to communicate with the FPGA is presented in Table 1; 1 byte specifies commands or emission patterns. If the byte value is larger than 127, it is a command; otherwise, it represents an emission phase offset or amplitude, depending on the mode. By default, the FPGA has a resolution of 32 divisions per period, so numbers from 0 to 31 represent phases from 0 to 2π, 32 represents no emission. Receiving a value of 254 indicates that new phases are going to be sent, the read pointer of the buffer is set to channel 0; afterwards, each phase sent will be assigned into the current read pointer and the pointer increased by one. The command 253 indicates swapping of the buffers. Other commands are: 252, to toggle amplitude modulation at 200 Hz for haptic feedback applications; 252 indicates that instead of phases, amplitudes are going to be sent. From 192 to 196, indicates the board number to activate (being 192 board number 1), in the case that multiple boards were chained together.

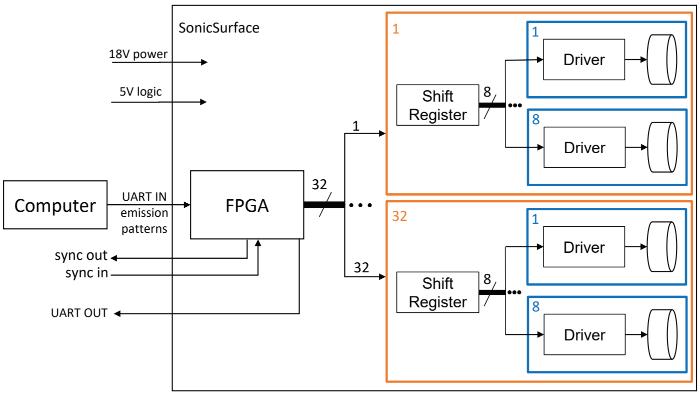

Figure 1. Schematic of the SonicSurface ultrasonic array. A field-programmable gate array (FPGA) receives the phases to be emitted from a computer, they are stored on a double buffer and constantly output. The FPGA multiplexes 8 channels into one line so that only 32 output pins are needed. There are 32 blocks of shift registers, being able to drive a total of 256 emitters.

The FPGA can generate 256 square-wave signals at 40 kHz. Each of the signals supports a phase delay control of 32 divisions per period or $\pi/16$ radians, the amplitude can be modulated with up to 16 divisions. A multiplexing scheme strategy was employed for reducing the number of needed output pins and, thus, reduce the price of the FPGA. Packs of eight channels are multiplexed into one digital line. Later, this line is demultiplexed back into eight channels while using the shift registers. Figure 2 illustrates the channel multiplexation scheme from the FPGA and circuit implementation.

Table 1. Communication protocol commands.

BYTE	Command	Action
0XXX XXXX	Set phases or amplitudes	Sets the phase or amplitude for the current channel and moves the pointer to the next channel
1111 1110	Start receiving phases	Sets the current channel to the first one and set that values will represent phases
1111 1101	Swap buffer	Swaps the emission and read buffer
1111 1100	Toggle modulation	A modulation of 200 Hz on the amplitude
1111 1100	Amplitude mode	Sets the current channel to the first one and set that values will represent amplitudes

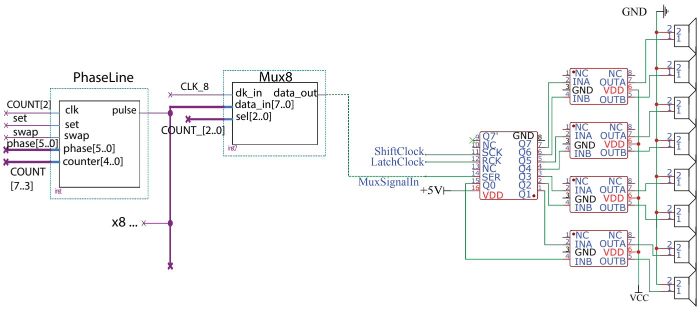

Figure 2. At the left, the FPGA blocks in charge of generating the signals are presented, 8 phaseLine blocks (signal generators) are multiplexed into one digital line to reduce the required number of output pins. At the right, the circuit schematic represents a shift register that demultiplexes the signal into 8 channels that get amplified by four dual Metal–oxide–semiconductor field-effect transistor (MOSFET) drivers and fed into the ultrasonic emitters.

The shift and the latch clock are generated by the FPGA. The shift clock controls when the shift registers shift data in, the latch clock determines when the data that were shifted should be output. The shift clock operates at 10.24 MHz (8 multiplexed channels $\times$ 40 kHz $\times$ 32 divisions per period), whereas the latch clock operates at 1.28 MHz (40 kHz $\times$ 32 divisions per period). The number of divisions per period (i.e., the resolution in phase or amplitude) could be doubled to 64, but the shift clock would operate slightly above 20 MHz, which would require better filtering and traces on the PCB.

Once the digital signal for each channel has been demultiplexed, it is amplified from 5 V up to 20 V using a dual Metal–oxide–semiconductor field-effect transistor (MOSFET) driver (e.g., TC4427a or MIC4127 from MT). After testing different electronic components for amplifying the signals (e.g., L293D or BJT transistors), MOSFET drivers were found to efficiently drive the ultrasonic transducers. Dual Mosfet Drivers can amplify two channels and have a small footprint; larger components would not fit on the integrated board. Subsequently, the output of the drivers is fed into the ultrasonic emitters (a comparison of suitable transducers can be found in the supplementary information of TinyLev [42]). Given the narrowband nature of the emitters, it is possible to use a half-square wave to drive them without generating a significant amount of harmonics [41]. This technique is widely employed for airborne ultrasonic phased arrays, because generating a digital square signal is less complex than creating an analog sinusoidal signal, they are also easier to amplify.

We present two models of the ultrasonic array. In the first one, the electronic components (i.e., shift registers, drivers, and decoupling capacitors) are surface mounted device (SMD) and the ultrasonic emitters have a diameter of 10 mm (Figure 3). The second model uses emitters of 16 mm diameter and through-hole (TH) components (Figure 4). The first model is more compact and faster to assemble if SMD equipment is available (e.g., stencils, solder paste, and a reflow oven). The TH model is larger and it takes more time to assemble, but it can be done with entry level electronics equipment (i.e., a soldering iron). Throughout the paper, we focus our experiments on the SMD board, since we think that it will be employed more often in the scientific community.

The program synthesized for the FPGA delegates the phase calculations on an external computer, thereby the cost of the board itself can be kept low. A UART reader block gets the bytes coming from the external computer [49]. A distributor block stores the current channel and sets the phases on the 256 signal generator blocks, each generator block outputs a digital signal of 40 kHz. Each generator block stores two phases, the one to be emitted and the previously read phase. The generator blocks have an internal amplitude counter that represents the number of divisions that the output should be HIGH, there is a global counter (from 0 to 31) that reaches all of the blocks, when the phase of a generator block coincides with the global counter, the internal amplitude counter is set to the target amplitude. The generator blocks have a dataline of five bits to read phases or amplitudes when the line setPhase or setAmp goes high. It also has a swap line, which swaps the phases/amplitudes when it goes high; this is to implement the double buffer. Eight generator blocks are grouped into a multiplexer, giving a total of 32 multiplexed lines that are output from the FPGA, as well as the shift and latch clocks. There are six auxiliary general-purpose inputs/outputs (GPIOs) (we have denominated them from A to F) that can be operated, defined, and implemented by the user. For example, B is used as the UART input, D is used as sync out (internal 40 kHz reference), E can be used as sync in (40 kHz signal to synchronize the global counter), and A can be used as a UART out; C and F are free for custom applications. Figure 5 shows the block diagram of the FPGA firmware.

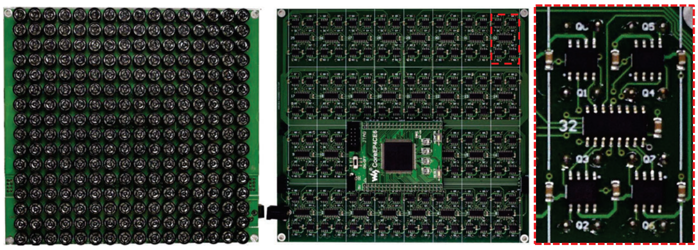

Figure 3. Board with surface mounted devices and emitters of 10 mm diameter. (**left**) Top view of the Sonic surface where 16 × 16 ultrasonic emitters can be seen. At the sides there are connectors for power, Universal asynchronous receiver-transmitter (UART) in, grounds, sync out and sync in. (**center**) bottom view where the shift register blocks can be seen with the FPGA on top. (**right**) closer view on a shift register block where a shift register demultiplexes a digital line into eight signals that are fed to four dual-drivers and then into eight ultrasonic emitters.

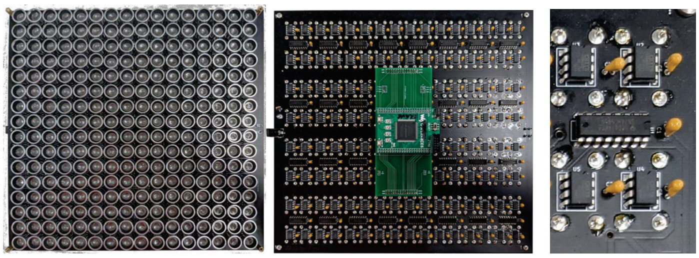

Figure 4. Ultrasonic array built with Through-hole components and emitters of 16 mm diameter. (**Left**) transducers of 16 mm diameter soldered on the printed circuit board (PCB). (**Center**) back of the board with the shift registers, drivers and decoupling capacitors. The FPGA board is connected through an expander board. (**Right**) detailed view of a shift register block.

The UART Reader and Distributor blocks operate with the internal clock, the generator blocks and multiplexers operate with a clock that is synchronized with the sync in signal. Thereby, when multiple boards operate together, the emission waves have exactly the same frequency. If the emission clocks were not synchronized, traveling waves would be created [41], making the generation of static fields impossible. A master board has its sync out connected to its sync in, slave boards take the sync signal from the master board.

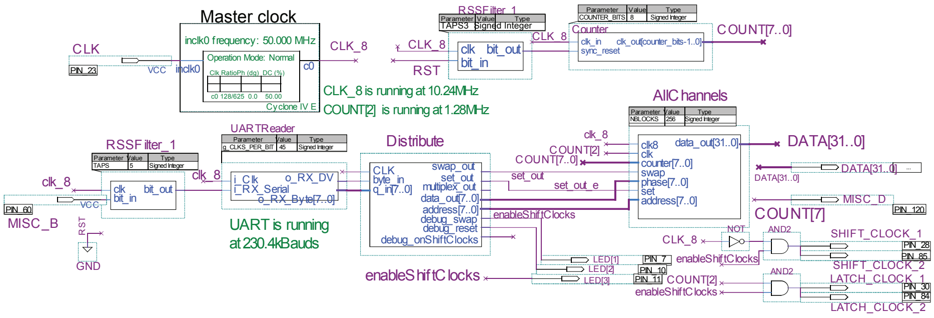

Figure 5. Block diagram of the code that is synthesized in the FPGA. On the top-left, the MasterClock is a phase-locked loop (PLL) to transform the internal 50 MHz clock into a 10.24 MHz clock named CLK_8. At the top-right, there is a global counter that acts as a frequency divider of CLK_8: COUNT[7] sets at 40 kHz and is output as the reference signal on MISC_D; COUNT[2] is the latch clock. If the board acts as a slave, the counter is synchronized with a 40 kHz external signal filtered by a RSS filter. On the bottom left, the UART input is filtered, read, and sent to the distributor. The distributor updates the emission phases of the generator blocks. AllChannels contain 256 generator blocks that connect to 32 Multiplexers of eight channels each. The generator blocks and multiplexers are timed by the outputs of the global counter. At the bottom-right, the multiplexed data channels as well as the latch and shift clocks are output.

The presented hardware has been optimized for an operating frequency of 40 kHz. This is the most common frequency for airborne ultrasonic phased arrays [9,38,41,42], operating at higher frequencies is not straightforward. On the one hand, the multiplexation of signals is used to reduce the required traces on the PCB and pins on the FPGA, our current system requires just a two-layer PCB and 40 GPIOs of the FPGA. However, this multiplexation leads to a 10.24 MHz shift clock. Increasing the frequency or phase resolution would require a higher clock frequency, which is beyond what is recommended for a simple PCB or the specs of the shift registers. On the other hand, commercially available transducers that operate at higher frequencies (e.g., 100 kHz or 400 kHz from MultiComp) are 10 mm in diameter and, thus, emit a very narrow beam. The emission from an array of these emitters would not interfere between each other and, thus, would not be suitable for the techniques presented here or phased-array techniques in general.

4. Algorithm

The algorithm that was developed by Melde et al. [17] is a modification of the Gerchberg–Saxton algorithm [50]. It calculates the phase modulation necessary at each point in the emitter plane in order to obtain a target amplitude field at the desired distance. The issue is that the algorithm is designed to produce modulation profiles that are almost continuous with more than 100 × 100 elements that are smaller than half-wavelength. However, available airborne ultrasonic arrays have a resolution of 16 × 16 or 24 × 24 at most, with element sizes that are larger than the wavelength and a circular shape instead of a square. We introduced a modification on this algorithm to consider the discrete nature of ultrasonic arrays and their lower number of elements when compared to passive modulators.

The proposed algorithm is an iterative approach with four steps per iteration, as described in Figure 6. The FOCUS library was employed for the forward propagation and the backpropagation of the emission and target field slices [51].

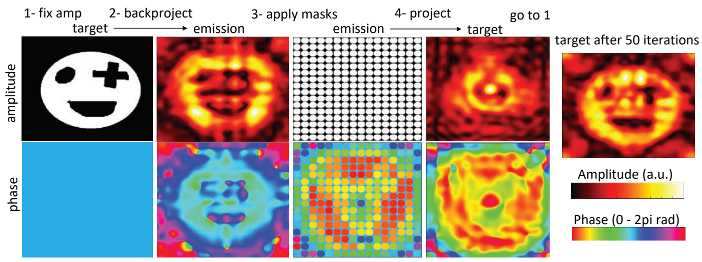

Figure 6. Iterative algorithm to determine the emission phases and amplitudes for an array of emitters. Step (1) fix the amplitude into the target slice, the phase is not modified. Step (2) Backproject the target into the emission. Step (3) Apply on the emission slice a discretization on phase, amplitude, and spatial resolution, as well as the mask with the shape of the emitters. Step (4) Project the emission into the target. After 50 iterations of steps 1 to 4, the target amplitude is shown at the left.

5. Results

5.1. Comparison between Simulations and Experiments

The experimental setup of Figure 7 was used to measure the acoustic pressure distribution generated by the array in order to compare the emitted experimental amplitude slices with the simulated ones. In this setup, an ultrasonic receiver (MA40S4S, Murata) is attached to the head of a delta stage (Anycubic Kossel) and the emitter array sits on its bed. A Matlab script communicates with the delta stage and it moves the receiver to different positions on a grid of 16 $\times$ 16 cm with 2.5 mm spacing. At each measuring point, the computer reads the peak-to-peak voltage that was captured by the oscilloscope (Hantek 6074BE). The voltage is linearly proportional to the amplitude and, thus, can be directly translated to amplitude in arbitrary units (a.u.). The computer sends the emission phases to the array through the UART protocol and it controls the stage using the G-Code protocol. Figure 8 shows the obtained experimental amplitude slices, which are in reasonable qualitative agreement with the simulation slices, except for the Brazilian flag pattern.

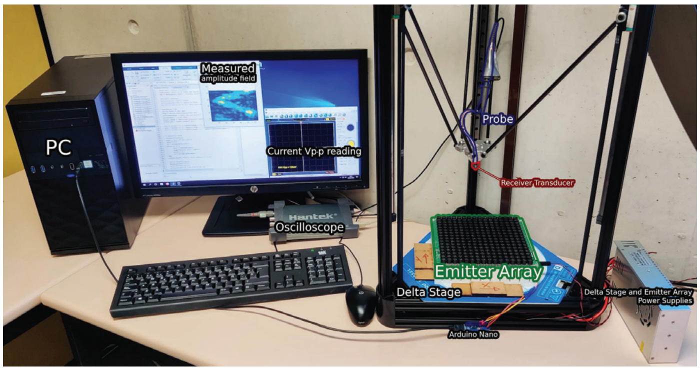

Figure 7. Experimental Setup used to scan the emitted amplitude slice.

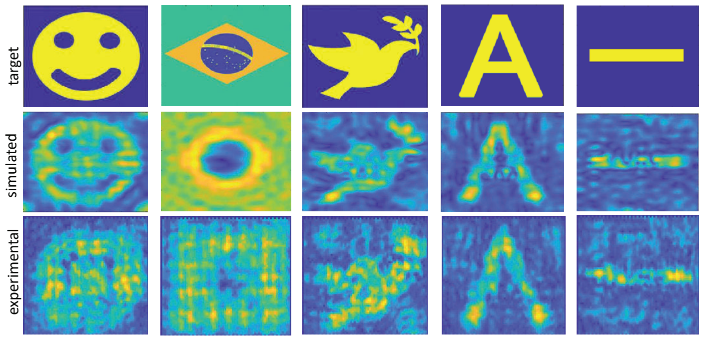

Figure 8. Amplitude slices obtained for different patterns, plotted using the function imagesc of Matlab. The first row is the target, the second one is the simulated slice, and the third row is the experimental measurement.

5.2. Effect of Phase, Amplitude, and Spatial Resolution

We carried out multiple simulations using the algorithm that is described in Section 4 with different parameters for emitter size, phase emission resolution and amplitude emission resolution. All of the target amplitude fields were generated 16 cm above the array, since we tested that, at that distance, the best results were obtained. The default simulation parameters are those from the SMD board, i.e., *emitterSize* = 10 mm, *phaseResolution* = 32, and no amplitude modulation. One parameter was varied at a time and the mean square error (MSE) of the obtained imaged was obtained. The results can be seen in Figure 9.

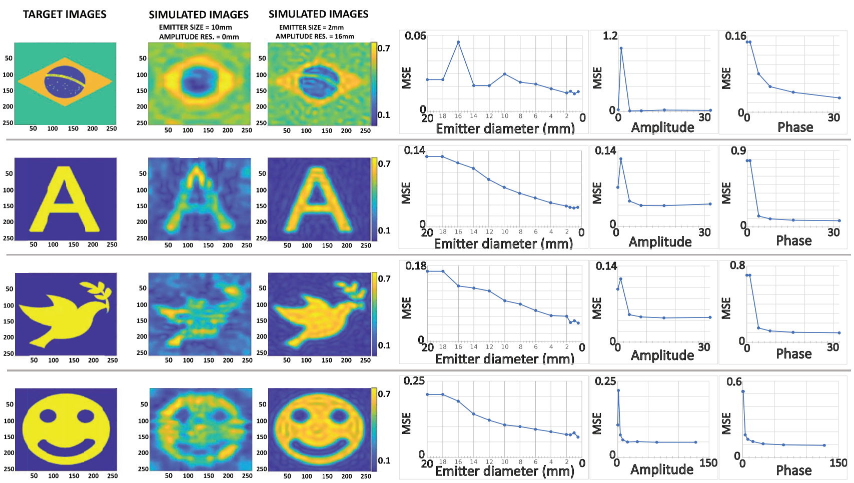

Figure 9. Simulated amplitude fields at 16 cm from the array for different target patterns and array parameters. (First column) target amplitude field. (Second column) obtained amplitude field when the emitter array is the surface mounted device (SMD) board presented in the paper, i.e., *emitterSize* = 10 mm (transducer diameter), *phaseResolution* = 32 and no amplitude modulation. (Third column) obtained amplitude fields with an array with *emitterSize* = 2 mm, *phaseResolution* = 32 and *amplitudeResolution* = 16. (Fourth column) mean square error (MSE) as the emitter size decreases. (Fifth column) MSE as phase resolution increases, *emitterSize* = 10 mm. (Sixth column) MSE as the amplitude resolution increases, *emitterSize* = 10 mm.

The patterns employed were: the flag of Brazil (non-binary image), the letter A, a Dove, and a smiley face. In general, it can be seen that as the emitter size decreases (i.e., more spatial resolution), the quality of the images improves. It is important to note that significant reductions of MSE are obtained, even when emitters get smaller than half-wavelength (4.3 mm), and that no further improvement is obtained below 2 mm (1/4 of the wavelength); this is different from the generation of regular focal points that do not increase its amplitude once the emitters are reduced below half-wavelength size [13]. The phase resolution significantly improves the pattern quality, but quickly plateaus when the phase resolution reaches eight divisions per period; this is in accordance with the simulations performed for simple focal points [41]. For amplitude resolution, it is clear that having amplitude modulation reduces the MSE by half even when only four different amplitudes can be emitted. In summary, the sweet-spot is obtained with a phase resolution of eight divisions per period and amplitude resolution of four divisions; the MSE improves as the emitters get smaller (i.e., more spatial resolution), but no improvement is found once the emitter size reaches quarter-wavelength.

These findings could be specific to the patterns that were selected in the study and to our setup characteristics (e.g., wavelength, number of emitters or distance to the target slice); however, the code was made public, so that other researchers could run simulations for their specific setups (e.g., operating in water or with static metamaterials).

6. Conclusions

In recent years, Acoustic holography has found numerous applications and has advanced rapidly due to the adaptation of methods found in the optics community. In this paper, we have attempted to advance, test, and unify algorithms and hardware used for acoustic mid-air holography. Namely, we have described a novel iterative algorithm that calculates the emission phases and amplitudes for an array of emitters that can be used to generate a desired target amplitude field. To our knowledge, this is the first algorithm capable of determining the amplitude and emission phases for discrete arrays comprised of finite sized emitters. We have then used this algorithm to investigate the effects of increased phase, amplitude and spatial resolution in the obtained amplitude field. Our analysis demonstrates that diminishing returns are observed at some point on-wards. Meaning that depending on the application requirements there is no need to use expensive hardware or that the computations can be accelerated by further discretizing the solution domain. Finally, to support the growth of the acoustic holography research community, we have described an open hardware platform named SonicSurface which is an affordable FPGA-based ultrasound phased array. Two different models for the array of emitters have been provided (SMD and TH), so that researchers from different fields and backgrounds can customise these further for their own experimental requirements. We hope that the algorithm and hardware presented in this paper facilitates further research on the field of ultrasonic arrays and enables novel applications of crafted amplitude fields.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

FPGA	A field-programmable gate array
PLL	Phase-locked loop
HCI	Human-Computer Interaction
HIFU	High-intensity focused ultrasound
3D	Three-dimensional
Hz	Hertz is the derived unit of frequency in the International System of Units (SI)
kHz	Kilohertz
MHz	Megahertz
PCB	Printed circuit board
UART	Universal asynchronous receiver-transmitter
PLL	Phased locked loop
PWM	Pulse width modulation
I/O	Input and Output
GPIOs	A general-purpose inputs/outputs
V	Voltage
MOSFET	Metal–oxide–semiconductor field-effect transistor
SMD	Surface mounted device
TH	Through-hole
MSE	Mean square error
MT	Mounted
Vp-p	Peak-to-peak voltage
a.u.	Arbitrary unity
mm	Millimetre
cm	Centimetre
rad	Radian
uF	Microfarad

References

1. Macovski, A. Ultrasonic imaging using arrays. *Proc. IEEE* **1979**, *67*, 484–495. [CrossRef]
2. Drinkwater, B.W.; Wilcox, P.D. Ultrasonic arrays for non-destructive evaluation: A review. *NDT E Int.* **2006**, *39*, 525–541. [CrossRef]
3. Movahed, A.; Waschkies, T.; Rabe, U. Air Ultrasonic Signal Localization with a Beamforming Microphone Array. *Adv. Acoust. Vib.* **2019**, *2019*, 7691645. [CrossRef]
4. Bailey, M.R.; Khokhlova, V.A.; Sapozhnikov, O.A.; Kargl, S.G.; Crum, L.A. Physical mechanisms of the therapeutic effect of ultrasound (a review). *Acoust. Phys.* **2003**, *49*, 369–388. [CrossRef]
5. Hoshi, T.; Takahashi, M.; Iwamoto, T.; Shinoda, H. Noncontact tactile display based on radiation pressure of airborne ultrasound. *IEEE Trans. Haptics* **2010**, *3*, 155–165. [CrossRef] [PubMed]
6. Carter, T.; Seah, S.A.; Long, B.; Drinkwater, B.; Subramanian, S. UltraHaptics: Multi-point mid-air haptic feedback for touch surfaces. In Proceedings of the UIST 2013—26th Annual ACM Symposium on User Interface Software and Technology, St. Andrews, UK, 8–11 October 2013; pp. 505–514. [CrossRef]
7. Frier, W.; Pittera, D.; Ablart, D.; Obrist, M.; Subramanian, S. Sampling Strategy for Ultrasonic Mid-Air Haptics. In *CHI '19: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*; Association for Computing Machinery: New York, NY, USA, 2019; pp. 1–11. [CrossRef]
8. Fushimi, T.; Marzo, A.; Drinkwater, B.W.; Hill, T.L. Acoustophoretic volumetric displays using a fast-moving levitated particle. *Appl. Phys. Lett.* **2019**, *115*, 064101. [CrossRef]
9. Hirayama, R.; Martinez Plasencia, D.; Masuda, N.; Subramanian, S. A volumetric display for visual, tactile and audio presentation using acoustic trapping. *Nature* **2019**, *575*, 320–323. [CrossRef] [PubMed]
10. Ochiai, Y.; Hoshi, T.; Suzuki, I., Holographic Whisper: Rendering Audible Sound Spots in Three-Dimensional Space by Focusing Ultrasonic Waves. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*; Association for Computing Machinery: New York, NY, USA, 2017; pp. 4314–4325.
11. Bourland, A.C.; Gorman, P.; McIntosh, J.; Marzo, A. Project telepathy. *Interactions* **2018**, *25*, 16–17. [CrossRef]
12. Hoshi, T.; Ochiai, Y.; Rekimoto, J. Three-dimensional noncontact manipulation by opposite ultrasonic phased arrays. *Jpn. J. Appl. Phys.* **2014**, *53*, 07KE07. [CrossRef]
13. Marzo, A.; Seah, S.A.; Drinkwater, B.W.; Sahoo, D.R.; Long, B.; Subramanian, S. Holographic acoustic elements for manipulation of levitated objects. *Nat. Commun.* **2015**, *6*, 1–7. [CrossRef] [PubMed]

14. Watanabe, A.; Hasegawa, K.; Abe, Y. Contactless fluid manipulation in air: Droplet coalescence and active mixing by acoustic levitation. *Sci. Rep.* **2018**, *8*, 10221. [CrossRef] [PubMed]
15. Andrade, M.A.B.; Camargo, T.S.A.; Marzo, A. Automatic contactless injection, transportation, merging, and ejection of droplets with a multifocal point acoustic levitator. *Rev. Sci. Instrum.* **2018**, *89*, 125105. [CrossRef]
16. Marzo, A.; Drinkwater, B.W. Holographic acoustic tweezers. *Proc. Natl. Acad. Sci. USA* **2019**, *116*, 84–89. [CrossRef]
17. Melde, K.; Mark, A.G.; Qiu, T.; Fischer, P. Holograms for acoustics. *Nature* **2016**, *537*, 518–522. [CrossRef]
18. Zhang, J.; Tian, Y.; Cheng, Y.; Liu, X. Acoustic holography using composite metasurfaces. *Appl. Phys. Lett.* **2020**, *116*, 030501. [CrossRef]
19. Memoli, G.; Caleap, M.; Asakawa, M.; Sahoo, D.R.; Drinkwater, B.W.; Subramanian, S. Metamaterial bricks and quantization of meta-surfaces. *Nat. Commun.* **2017**, *8*, 14608. [CrossRef] [PubMed]
20. Polychronopoulos, S.; Memoli, G. Acoustic levitation with optimized reflective metamaterials. *Sci. Rep.* **2020**, *10*, 4254. [CrossRef] [PubMed]
21. Morales, R.; Marzo, A.; Subramanian, S.; Martínez, D. LeviProps: Animating Levitated Optimized Fabric Structures Using Holographic Acoustic Tweezers. In *UIST '19: Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*; Association for Computing Machinery: New York, NY, USA, 2019; pp. 651–661. [CrossRef]
22. Norasikin, M.A.; Martinez-Plasencia, D.; Memoli, G.; Subramanian, S. SonicSpray: A Technique to Reconfigure Permeable Mid-Air Displays. In *ISS '19: Proceedings of the 2019 ACM International Conference on Interactive Surfaces and Spaces*; Association for Computing Machinery: New York, NY, USA, 2019; pp. 113–122. [CrossRef]
23. Morales González, R.; Marzo, A.; Freeman, E.; Frier, W.; Georgiou, O. UltraPower: Powering Tangible & Wearable Devices with Focused Ultrasound. In *TEI '21: Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction*; Association for Computing Machinery: New York, NY, USA, 2021; [CrossRef]
24. Harput, S.; Bozkurt, A.; Yamaner, F.Y. Ultrasonic phased array device for real-time acoustic imaging in air. In Proceedings of the 2008 IEEE Ultrasonics Symposium, Beijing, China, 2–5 November 2008; pp. 619–622. [CrossRef]
25. Vi, C.T.; Marzo, A.; Ablart, D.; Memoli, G.; Subramanian, S.; Drinkwater, B.; Obrist, M. TastyFloats : A Contactless Food Delivery System. In Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces, Brighton, UK, 17–20 October 2017; pp. 161–170. [CrossRef]
26. Iwamoto, T.; Tatezono, M.; Shinoda, H. Non-contact method for producing tactile sensation using airborne ultrasound. In *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications*; Springer: Berlin/Heidelberg, Germany, 2008; Volume 5024, pp. 504–513. [CrossRef]
27. Inoue, S.; Makino, Y.; Shinoda, H. Scalable Architecture for Airborne Ultrasound Tactile Display. In *Haptic Interaction*; Hasegawa, S., Konyo, M., Kyung, K.U., Nojima, T., Kajimoto, H., Eds.; Springer: Singapore, 2018; pp. 99–103.
28. Suzuki, S.; Takahashi, R.; Nakajima, M.; Hasegawa, K.; Makino, Y.; Shinoda, H. Midair Haptic Display to Human Upper Body. In Proceedings of the 2018 57th Annual Conference of the Society of Instrument and Control Engineers of Japan (SICE), Nara, Japan, 11–14 September 2018; pp. 848–853. [CrossRef]
29. Morisaki, T.; Mori, R.; Mori, R.; Makino, Y.; Itoh, Y.; Yamakawa, Y.; Shinoda, H. Hopping-Pong: Changing Trajectory of Moving Object Using Computational Ultrasound Force. In *ISS '19: Proceedings of the 2019 ACM International Conference on Interactive Surfaces and Spaces*; Association for Computing Machinery: New York, NY, USA, 2019; pp. 123–133. [CrossRef]
30. Ito, M.; Kokumai, Y.; Shinoda, H. Midair Click of Dual-Layer Haptic Button. In Proceedings of the 2019 IEEE World Haptics Conference (WHC), Tokyo, Japan, 9–12 July 2019; pp. 349–352. [CrossRef]
31. Large, D.R.; Harrington, K.; Burnett G.; Georgiou O. Feel the noise: Mid-air ultrasound haptics as a novel human-vehicle interaction paradigm. *J. Appl. Ergon.* **2019**, *81*, 102909. [CrossRef] [PubMed]
32. Limerick, H.; Hayden, R.; Beattie, D.; Georgiou, O. User Engagement for Mid-Air Haptic Interactions with Digital Signage. In *PerDis '19: Proceedings of the 8th ACM International Symposium on Pervasive Displays*; Association for Computing Machinery: New York, NY, USA, 2019; pp. 1–7. [CrossRef]
33. Martinez, J.; Griffiths, D.; Biscione, V.; Georgiou, O. Touchless Haptic Feedback for Supernatural VR Experiences. In Proceedings of the Conference on Virtual Reality and 3D User Interfaces (VR), Reutlingen, Germany, 18–22 March 2018; pp. 629–630. [CrossRef]
34. Carcagno, S.; Di Battista, A.; Plack, C. Effects of High-Intensity Airborne Ultrasound Exposure on Behavioural and Electrophysiological Measures of Auditory Function. *Acta Acust. United Acust.* **2017**, *105*, 1610-1928. [CrossRef]
35. Shakeri, G.; Freeman, E.; Frier, W.; Iodice, M.; Long, B.; Georgiou, O.; Andersson, C. Three-in-One: Levitation, Parametric Audio, and Mid-Air Haptic Feedback. In *CHI EA '19: Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems*; Association for Computing Machinery: New York, NY, USA, 2019; pp. 1–4. [CrossRef]
36. Morales González, R.; Freeman, E.; Georgiou, O. Levi-Loop: A Mid-Air Gesture Controlled Levitating Particle Game. In *CHI EA '20: Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems*; Association for Computing Machinery: New York, NY, USA, 2020; pp. 1–4. [CrossRef]
37. Price, A.; Long, B. Fibonacci Spiral Arranged Ultrasound Phased Array for Mid-Air Haptics. In Proceedings of the 2018 IEEE International Ultrasonics Symposium (IUS), Kobe, Japan, 22–25 October 2018; [CrossRef]
38. Ochiai, Y.; Hoshi, T.; Rekimoto, J. Pixie Dust: Graphics Generated by Levitated and Animated Objects in Computational Acoustic-Potential Field. *ACM Trans. Graph.* **2014**, *33*. [CrossRef]

39. Strobino, L. Acoustic levitation on SoC FPGA (DE0-Nano-SoC). In Proceedings of the 2019 IEEE International Ultrasonics Symposium (IUS), Glasgow, UK, 6–9 October 2019.
40. Zehnter, S.; Ament, C. A Modular FPGA-based Phased Array System for Ultrasonic Levitation with MATLAB. In Proceedings of the 2019 IEEE International Ultrasonics Symposium (IUS), Glasgow, UK, 6–9 October 2019; pp. 654–658. [CrossRef]
41. Marzo, A.; Corkett, T.; Drinkwater, B.W. Ultraino: An open phased-array system for narrowband airborne ultrasound transmission. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **2017**, *65*, 102–111. [CrossRef] [PubMed]
42. Marzo, A.; Barnes, A.; Drinkwater, B.W. TinyLev: A multi-emitter single-axis acoustic levitator. *Rev. Sci. Instrum.* **2017**, *88*. [CrossRef] [PubMed]
43. Maynard, J.D.; Williams, E.G.; Lee, Y. Nearfield acoustic holography: I. Theory of generalized holography and the development of NAH. *J. Acoust. Soc. Am.* **1985**, *78*, 1395–1413. [CrossRef]
44. Long, B.; Seah, S.A.; Carter, T.; Subramanian, S. Rendering Volumetric Haptic Shapes in Mid-Air Using Ultrasound. *ACM Trans. Graph.* **2014**, *33*. doi:10.1145/2661229.2661257. [CrossRef]
45. Fushimi, T.; Yamamoto, K.; Ochiai, Y. Acoustic Hologram Optimisation Using Automatic Differentiation. *arXiv* **2020**, arXiv:2012.02431.
46. Plasencia, D.M.; Hirayama, R.; Montano-Murillo, R.; Subramanian, S. GS-PAT: High-Speed Multi-Point Sound-Fields for Phased Arrays of Transducers. *ACM Trans. Graph.* **2020**, *39*. [CrossRef]
47. Brown, M.D. Phase and amplitude modulation with acoustic holograms. *Appl. Phys. Lett.* **2019**, *115*, 053701. [CrossRef]
48. Sedcole, P.; Blodget, B.; Becker, T.; Anderson, J.; Lysaght, P. Modular dynamic reconfiguration in Virtex FPGAs. *IEE Proc. Comput. Digit. Tech.* **2006**, *153*, 157–164. [CrossRef]
49. Kim, J.; You, K.; Choe, S.H.; Choi, H. Wireless Ultrasound Surgical System with Enhanced Power and Amplitude Performances. *Sensors* **2020**, *20*. [CrossRef] [PubMed]
50. Gerchberg, R.W. A practical algorithm for the determination of phase from image and diffraction plane pictures. *Optik* **1972**, *35*, 237–246.
51. FOCUS. Michigan State University. Available online: https://www.egr.msu.edu/~fultras-web/ (accessed on 20 February 2021).

2.2 LeviPrint: Contactless Fabrication using Full Acoustic Trapping of Elongated Parts.

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Abstract:	LeviPrint is a system for assembling objects in a contactless manner using acoustic levitation. We explore a set of optimum acoustic fields that enables full trapping in position and orientation of elongated objects such as sticks. We then evaluate the capabilities of different ultrasonic levitators to dynamically manipulate these elongated objects. The combination of novel optimization algorithms and levitators enable the manipulation of sticks, beads and droplets to fabricate complex objects. A system prototype composed of a robot arm and a levitator is tested for different fabrication processes. We highlight the reduction of cross-contamination and the capability of building on top of objects from different angles as well as inside closed spaces. We hope that this technique inspires novel fabrication techniques and that reaches fields such as microfabrication of electromechanical components or even in-vivo additive manufacturing.
Attached Media:	Abstract video: https://youtu.be/9eHmmhpYXdQ (5min long) In-depth Explanation Video: https://drive.google.com/file/d/1kMDPLwFqIzgLdgbZ1o5Fwtf-mVu20wG0 (14min long)

LeviPrint: Contactless Fabrication using Full Acoustic Trapping of Elongated Parts.

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ABSTRACT

LeviPrint is a system for assembling objects in a contactless manner using acoustic levitation. We explore a set of optimum acoustic fields that enables full trapping in position and orientation of elongated objects such as sticks. We then evaluate the capabilities of different ultrasonic levitators to dynamically manipulate these elongated objects. The combination of novel optimization algorithms and levitators enable the manipulation of sticks, beads and droplets to fabricate complex objects. A system prototype composed of a robot arm and a levitator is tested for different fabrication processes. We highlight the reduction of cross-contamination and the capability of building on top of objects from different angles as well as inside closed spaces. We hope that this technique inspires novel fabrication techniques and that reaches fields such as microfabrication of electromechanical components or even in-vivo additive manufacturing.

CCS CONCEPTS

• **Hardware** → *Emerging architectures*; • **Applied computing** → *Computer-aided design*.

KEYWORDS

acoustic levitation, additive manufacturing, contactless manipulation, robot arm, end-effector

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1 INTRODUCTION

Fabrication in the form of assembly or additive manufacturing has evolved considerably due to its combination with computer systems, novel actuators and end-effectors. Additive manufacturing has been booming since the last decade, it will not only be used to fabricate objects by the Maker community but also in the aeronautical, automobile, and medical sector for prosthetic as well as tissue engineering. Manufacturing is usually complemented with assembly, which is the placement of the parts that compose the final object, a common example is the pick&place of electronic components on a printed circuit board (PCB).

Across ordinary assembly and manufacturing techniques, a common characteristic is that the parts or materials that are manipulated or dispensed are in direct contact with the machine. Consequently, special equipment is required to manipulate small or fragile components, and the handling of liquids, powders or hot materials is challenging. Furthermore, contact-based processes inherently lead to cross-contamination, so when dangerous materials or bio-materials are employed, it is necessary to have multiple manipulators or sterilise them between the changes of materials.

We propose to use acoustic manipulation as a contactless way of distributing materials in additive manufacturing as well as placing and orientating parts in assembly processes. Thereby, it is possible to manipulate small and fragile parts as well as liquids or powders, bringing more versatility to the processes. There is less cross-contamination since the manipulator does not touch the parts or material. Moreover, it enables manufacturing scenarios not achievable with traditional 3D printing, such as threading through cavities or adding to the manufactured item on any direction.

Levitation and manipulation of small particles and droplets have been achieved before but never combined in a full prototype for contactless fabrication. Furthermore, there is no existing work on how to trap in position and orientation elongated objects, this would open new possibilities in contactless manufacturing since beams, sticks or girders are vital for the rapid fabrication of robust and lightweight structures.

In this article, we introduce *LeviPrint* a method to generate acoustic fields that fully trap small particles, droplets and, more importantly, manipulate and reorient elongated bodies such as sticks. Also we present a fully working system to fabricate 3D structures using contactless manipulation. The novel contributions are:

- *A method to optimally trap a stick.* We analyze different acoustic fields in terms of their capability to trap in position and orientation an elongated object.
- *Levitators capabilities.* A study of the capabilities for dynamic orientation of elongated objects inside different acoustic levitators.
- *A Contactless Fabrication System.* An integration of an acoustic levitator, mechanical translator and droplet injector to realize a working prototype.

In section 2, we analyze the existing research regarding the capabilities and uses of acoustic levitation for fabrication. Section 3 summarizes the main models employed to simulate the acoustic field generated by phased arrays and the forces that they exert on objects. In section 4, we evaluate different methods to generate acoustic fields to fully trap a stick. Section 5 presents the dynamic manipulation capabilities of various levitators using the selected method. In section 6, we combine the insights from the previous sections to build a prototype that enables contactless fabrication mixing liquids, particles and sticks. In the next section (7), we showcase some of the structures build with the system. Finally, in section 8, we discuss limitations and future work.

2 RELATED WORK

In this section, we review the manipulation capabilities of ultrasound and its uses in fabrication. We note that acoustic levitation still lacks the capability of moving and orienting thin elongated objects larger than the wavelength of sound. Also, integrated prototypes that combine the required processes for fabrication (injection, manipulation and fusing mechanism) have not been developed.

2.1 Fabrication: Assembly and Additive Manufacturing

Assembly can be defined as the process of picking the parts that compose an object and placing them with the correct orientation and position. This process can be observed at multiple scales; a crane will position the girders for a building [Shapiro and Shapiro 1988], robot arms will position components of a car [Marvel et al. 2018] and pick&place machines will pick electronic components and place them on a PCB [Baby et al. 2017].

Additive manufacturing is defined as adding material layer by layer into a final object. This is opposed to carving or milling, in which parts from a block of material are removed to create the final object. Multiple innovations have been added to additive manufacturing to enable multiple colors, the use of less support structure, better layer distribution or non-planar 3d-printing [Dai et al. 2018; Etienne et al. 2019; Hornus et al. 2020; Song et al. 2019]. However, these techniques rely on direct contact between the dispenser (e.g., nozzle) and the objects that are being built. We reckon that acoustic manipulation could be employed to create a contactless system.

2.2 Acoustic Manipulation

Acoustic Manipulation has the potential to become a fundamental tool in contactless processing [Foresti et al. 2013], given: the wide range of particles that can be manipulated for a given operating frequency (from the micrometre to the centimeter scale), materials (plastic, metal or liquids), relative-high strength (larger ratio of input power to radiation force) when compared with optical trapping, and non-damaging effects on the trapped samples [Marzo et al. 2017].

Particles inside an acoustic field are subjected to radiation forces [Bruus 2012; Gor'kov 1962; Karlsen and Bruus 2015], it is possible to design the fields so that these forces converge from all directions into a point in which the particles get trapped [Brandt 2001]. In the most basic configuration, an emitter opposed to a reflector creates a standing wave and particles are trapped at its nodes [Whymark 1975]. More complex arrangements allow for dynamic control of the trapped particles.

The acoustic field can be dynamically modified by adjusting the phase or amplitude of the emitters, this allows to move particles in 3D using 4 opposed arrays [Ochiai et al. 2014], this was simplified to two-opposed arrays [Omirou et al. 2015] and later to a single array by using acoustic tractor beams [Marzo et al. 2015]. However, acoustic tractor beams have trapping forces which are 8 times weaker than regular standing waves [Marzo 2020], limiting its applications. With the introduction of holographic methods, it was possible to acoustically levitate multiple particles independently [Marzo and Drinkwater 2019; Plasencia et al. 2020].

In most levitation methods, the particles are smaller than half of the wavelength of the employed sound frequency [Zang et al. 2017]. Near-field levitation allows to levitate larger particles very close to the acoustic emitter [Andrade et al. 2017]. Also, virtual vortices [Marzo et al. 2018a] and other exotic fields [Inoue et al. 2019] can levitate larger-than-wavelength objects, but with limited force and no dynamic capabilities. We do not consider levitation of solid large objects (larger than the wavelength) particularly useful for fabrication since they are not stable, occlude too much the acoustic field, and do not allow for complex designs with fine pieces.

A more interesting manipulation capability for fabrication would be the control of the orientation of elongated objects. We note that many fabricated items use beams, sticks or girders as building primitives for the fast creation of strong and light structures. Ultrasonic arrays are capable of 2D translation and rotation along one axis of toothpicks [Foresti et al. 2013]. Sub-wavelength asymmetric particles can be fully locked [Cox et al. 2018] and controllably rotated when enclosed inside a sphere of emitters [Helander et al. 2020] but not translated. However, there is no existing technique to fully trap an elongated object enabling its reorientation and its repositioning. Consequently, we propose different novel methods (Section 4) to fully trap a stick in 6DoF and we compare them with a traditional tweezers method [Marzo and Drinkwater 2019]. This would allow a contactless system to employ segments as a building primitive.

2.3 Acoustic Fabrication

Using levitated particles as graphic representations is an emerging field [Fushimi et al. 2019; Marzo and Drinkwater 2019; Ochiai et al. 2014; Suzuki et al. 2021] but the use of acoustic levitation in fabrication has not been that thoroughly explored. Acoustic Manipulation has been used to pattern cells [Collins et al. 2015], aerosols and small particles [Shapiro et al. 2021] in simple 2D patterns. Melde et al.[K et al. 2016] used a static holographic plate to form more complex 2D patterns of particles that were fused together [K et al. 2018]. In these methods, the fabrication result is a 2D pattern that gets formed as a whole because small particles follow the distribution of the acoustic field. We classify this as 2D printing and not 3D fabrication.

Primitives such as beads, threads, and fabrics have been levitated [Fender et al. 2021; Morales et al. 2019]. However, in all these cases, spherical particles were used as levitated buoys in which acoustically transparent fabric was attached. This limits the materials, shapes, rigidity and in general the possibility of having an additive process.

Automatic injection of droplets inside a levitation system has been shown [Andrade et al. 2018], also a static levitator was attached to a robot arm to translate sub-wavelength particles in a contactless way [Röthlisberger et al. 2021]. However, no system integrates insertion, manipulation and fusing of droplets or sub-wavelength particles; moreover, there is no possibility of working with elongated parts. One patent from Boing (United States) [Harkness and Goldschmid 2018] and another from Neurotechnology Ultrasound (Lithuania) [Putkis 2018] present the idea of a contactless manufacturing systems, yet no full realization is shown, they present the concept.

Optical tweezers have been used to manipulate micrometric spheres to create microstructures [Sinclair et al. 2004]. A prototype was capable of moving spherical particles and stacking them together using biotin [Kirkham et al. 2015]. However, optical tweezers are limited to micrometric sizes. We note that the methods from optics are not trivially adapted to acoustic manipulation because in optics, a focus on the particle is sufficient for trapping whereas in acoustics more complex structured fields are required [Marzo and Drinkwater 2019].

The working methods presented in Section 4 to fully trap and rotate sticks are novel contributions, there is no previous work describing and showing a method to fully trap an elongated object.

3 MODELS

In this section, we define the models employed in this work and the common physical definitions that will be used throughout it.

3.1 The Emitted Complex Acoustic Field

The piston model is employed [O'Neil 1949] to calculate the complex acoustic field generated by a single emitter that has a radiating part in the shape of a piston vibrating at a single frequency. In the complex pressure, the magnitude represents the amplitude and the angle, the phase. An ultrasonic phased array is formed by multiple emitters operating at the same frequency and varying their amplitude and phase in a controlled way. The total field generated by an array of n emitters is the addition of their emitted fields:

$$P(\boldsymbol{x}) = \sum_{i=1}^{n} \frac{P_0 J_0 (kr \sin\theta_i)}{d_i} e^{i(\varphi_i + kd_i)}, \tag{1}$$

where P_0 is the amplitude power of the transducer, defined by its efficiency and driving voltage amplitude. J_0 is the Bessel function of order zero. $k = 2\pi/\lambda$ is the wavenumber and λ is the wavelength. r is the radius of the piston, d_i is the distance from the emitter i to the point $\boldsymbol{x}$ in space. θ_i is the angle between the normal of the emitter and the transducer to point $\boldsymbol{x}$ vector.

This models is commonly used and implemented in various frameworks [Marzo et al. 2018b], it is designed to work in open space where there are no large obstacles in the field. In this paper, the trapped particles and structures being built do not affect significantly the acoustic field since they are not fully solid. An analysis of the effect of occlusions on the trapping force can be find in Supplementary Information 1.

3.2 Potential, Radiation Forces and Stiffness

The Gor'kov potential approximates the radiation forces exerted on a small sphere that is inside an arbitrary acoustic field. It can be defined in terms of the complex acoustic pressure p and its spatial derivatives p_x, p_y and p_z. The Gor'kov potential U is given by:

$$\begin{aligned} U &= K_1 \left(|p|^2\right) - K_2 \left(|p_x|^2 + |p_y|^2 + |p_z|^2\right) \\ K_1 &= \frac{1}{4} V \left(\frac{1}{c_0^2 \rho_0} - \frac{1}{c_\mathrm{p}^2 \rho_\mathrm{p}}\right) \\ K_2 &= \frac{3}{4} V \left(\frac{\rho_0 - \rho_\mathrm{p}}{\omega^2 \rho_0 \left(\rho_0 + 2\rho_\mathrm{p}\right)}\right). \end{aligned} \tag{2}$$

The volume of the spherical particle is V, ω is the angular frequency of the emitted waves, and c and ρ are the speed of sound and the density, respectively. Their subindex 0 and p refer to the propagation medium and the particle material.

The lower the potential is at a position, the stronger the object will be trapped there. In general, the potential can be visualized as a heightmap and thus minima in the field represent wells where the particles will roll in and get trapped. The radiation force acting on a particle can be obtained from the gradient of the potential:

$$\mathrm{F} = -\nabla U. \tag{3}$$

Another measure of strength of a trapping position is the positional stiffness, which represents how converging the forces are at that position. The Laplacian operator (convergence of the gradient) can be applied to the potential to get a mathematical representation of the stiffness.

$$stiffness = \nabla^2 U = U_{xx} + U_{yy} + U_{zz}, \tag{4}$$

where $U_{aa} = \frac{\partial^2 U}{\partial a^2}$ and $a = x, y, z$ are the Cartesian axes. Large positive values of stiffness represent large converging forces.

3.3 Torques and Rotational Stiffness on Elongated Objects

In Supplementary Information 2, we show that the torque and forces acting on a stick can be approximated as the summation of the forces or torques acting on constituent spheres. Potential, forces and stiffness are linear functions of each other, therefore our sphere decomposition approximation can be applied to them. We performed a converging analysis to determine that decomposing the stick into small spheres separated by $\lambda/8$ is sufficient.

When the acoustic field acts on a stick, there is a torque that will affect the orientation. We calculate the torque as the addition of the torques exerted on each constituent sphere. The torque from a sphere is the cross product between the force on that sphere and the vector that joins the sphere to the center of mass of the object:

$$\boldsymbol{\tau} = \mathbf{r} \times \mathbf{F}, \quad (5)$$

where $\mathbf{r}$ is the positional vector from the location where the force is applied and $\mathbf{F}$ is the force acting on that part of the object. The rotational stiffness can be obtained by differentiating the torque on small rotations of the stick.

3.4 Summary

Potential, Force, Positional Stiffness, Torque and Rotational Stiffness will be used throughout the paper to characterize the trapping on an object. These properties were calculated on the simulations but only the most informative ones will be reported. Potential provides a basic measurement, the lower the better, it is not dimensional and gives information both for translation and orientation trapping. Forces should be analyzed along different positions of the objects, since the forces at the trap are 0 and push towards the trap, i.e., they become positive when the objects shifts towards negative positions and vice-versa. Positional stiffness represents the trapping force convergence with a single value, the higher the better, however it does not provide topological information such as the reach of the trap. Torque and rotational stiffness have similar features to force and positional stiffness respectively but acting on orientation instead of position.

4 FULLY TRAPPING A STICK

In this section, we derive and analyze algorithms that generate an acoustic field capable of fully trapping a stick inside an acoustic field. The stick has to be trapped in position (3 Dof) and orientation (3 DoF). All methods were evaluated attending to their trapping performance in position and orientation.

We analyzed levitators with different geometries (Fig. 1), they were composed of ultrasonic emitters of 1 cm diameter with the following parameters for Eq. 1: r = 4.5 mm and P_0 = 2.4, which correspond to a real existing emitter (e.g., model MA40S4S - Murata). The levitators were selected between the most common geometries in the literature for airborne acoustic levitation. Fixed two-opposed inspired by TinyLev [Marzo et al. 2017], two-opposed arrays of 16x16 emitters separated by 23 cm as in [Marzo and Drinkwater 2019; Morales et al. 2019; Suzuki et al. 2021], four orthogonal arrays in a cube formation as in [Ochiai et al. 2014]. We also tried with variations of the cube in the shape of a triangle, cylinder and sphere.

The trapping algorithms will determine the emission phases of the levitators in order to generate a field that traps the stick. The generated fields for the two-opposed levitator can be seen in Fig. 2, similar results were obtained for the other levitators. Similarly, others were designed and evaluated, we just selected the 4 most representative and effective ones. The methods are:

- **Trap at Center:** It is the trivial method of creating a standing wave focused at the center of the stick. It is the default method for trapping sub-wavelength particles. We do not expect it to be effective on a stick but the resulting forces and torques can be used as a baseline for comparison with the other methods.
- **Traps at Sides:** Two trapping nodes are generated at both sides of the stick. A modified Iterative Backpropagation (IBP) [Marzo and Drinkwater 2019] algorithm is employed to maximize amplitude in 2 pairs of focal points above and below the stick, with a phase difference of π is forced between the first points of each pair. Thereby, high-amplitude is generated above and below the stick with low-amplitude at the stick. Whilst Marzo and Drinkwater [Marzo and Drinkwater 2019] optimized trapping strength on individual particles, this method traps an elongated body by creating two traps at its sides. The traps were offset 2.5mm towards the stick center, this was the optimum offset in terms of stiffness (see Supplementary Information 3).
- **Minimum Potential:** Employs an optimizer to find the emission phases that minimize the Gork'ov potential along the stick. If we simplify to 2D, this can be seen as digging a potential well with the shape of the object that should be trapped. A quasi-newton optimizer is employed with gradients approximated using finite differences. The parameters were the default ones from Matlab R2019 fminunc function (except, TolFun=0.0025, TolX=eps, MaxIters=30). The result can be interpreted as a strong trap at the center of the stick and two smaller ones at the sides. The target function can be expressed as:

  $$SumGorkov(\varphi_1, \ldots, \varphi_N) = \sum_{i=1}^{P} gorkovAt(\boldsymbol{pos(i)})$$

  Where φ_n is the emission phase of the n transducer, P is the number of points that form the stick, pos is their position, and $gorkovAt$ is the Gork'ov potential at that point (Eq. 2).
- **Minimum Weighted Potential:** Similar to the previous method (Minimum Potential) but the 4 terms appearing in Gork'ov potential (Eq. 2) were weighted using the factors 0.09 for p, 15.01 for px, 8.34 for py and 7.66 for pz. These weights were obtained from the *Traps at Sides* method. The results in Figure 2.c shows that the method tries to fit as many traps as possible along the stick.

The forces and torques acting on a stick under the fields generated by the different methods can be seen in Fig. 3. The stick was 30 mm length, 2 mm width and 1 mm height and placed at the center of the levitator. Similar results were obtained for sticks between 2 wavelengths (1.6 cm) and a a length of 8 cm.

All the forces and torques but the Trap a center are converging since the force is 0 at the neutral position or angle, but become positive if the position or angle gets negative, and vice-versa. The steepness of the curves at the neutral position or angle, characterize the strength of the trap.

The most promising methods are Traps at Sides (TrapsAtSides) and Minimum Potential (MinPot), the rest of the methods were weaker on all of the axes, both in position and rotation. The trap at center (traditional standing wave) does not have the capability to trap along the x-position and the x-torque was marginal. The MinPot algorithm produces fields that are ∼ 10% stronger in force-Y, force-Z and torque-X, however TrapsAtSides is ∼ 25% stronger on force-X, torque-Y, and torque-Z.

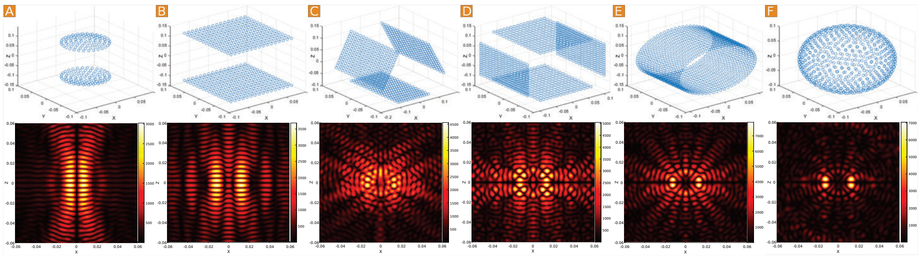

Figure 1: Different simulated levitator geometries and a vertical slice of the pressure field that they generate when applying the TrapsAtSides method on a thin stick of 30 mm. A) Two-opposed fixed levitator. B) Two-opposed Levitator. C) Triangle levitator. D) Cube. E) Cylinder. F) Sphere.

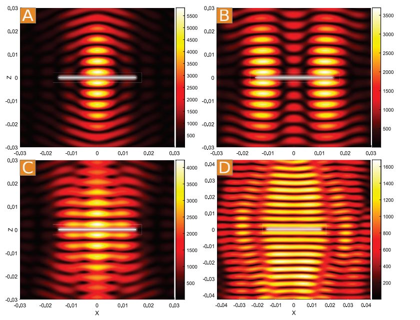

Figure 2: Amplitude fields around a 30 mm stick for different trapping methods on the Two-opposed levitator. A) Trap at center, B) Traps at sides (2.5mm inward offset) C) Minimum Potential, D) Minimum Weighted Potential.

TrapsAtSides provides the overall stronger trapping forces and torques. We also note that the fields obtained in TrapsAtSides can be generated by a fixed-levitator without phase control (Fig. 4) and is applicable to sticks of different lengths since the trapping positions are relative to the ends of the stick. Furthermore, it is based on an iterative method (IBP) and is computationally faster than the other methods based on traditional optimization.

We note that the problem of fully trapping a stick is multi-variable and required expert knowledge to analyze the results of the different methods: e.g., the forces and torques in Figure 3, potentials in 5, and stiffness in Supplementary Information 4.

5 MANIPULATION CAPABILITIES OF THE LEVITATORS

In the previous section, we have selected the TrapsAtSides method for generating fields that trap a stick in position and orientation. In this section we will analyze the capabilities of the levitators presented in Fig. 6 to orientate the sticks by changing their emission phases. For each levitator, a stick of 30 mm length, 2 mm width and 1 mm height was placed at the center. Then, it was rotated along each axis applying the trapping method at each step and calculating the potential on the stick.

The potentials while rotating (Fig. 5) indicate that all arrangements can rotate the stick around the Z-axis. The two-opposed levitator provides a good balance between manipulation capabilities and being open at the sides, it can rotate a stick around the Z-axis and in Y-axis with a limited angle ∼ 30 degrees. The cube arrangement provides full rotations around the Z- and Y-axis, being able to orient the sticks as needed in the piece, this is crucial to fabricate vertical structures and shorings, it just lacks the capability to fully rotate the stick around itself. The cylinder was not superior than the cube, it is more complex to fabricate and less uniform on the potentials along the rotations. The triangle arrangement is not a good alternative since it has less working volume than the cube and less manipulation capabilities. The sphere can orientate the stick around any axis with uniform potential but it is cumbersome to use in a fabrication system. Similar conclusions were derived from analyzing the positional and rotational stiffnes (See Supplementary Information 4).

6 SYSTEM PROTOTYPES

In this section, we combine the trapping and manipulation capabilities of an acoustic levitator with a mechanical manipulator that complements the levitator. Thereby, the manipulation of the stick is performed by the dynamic levitator in some DoFs whereas other DoFs are covered by the mechanical manipulator. We note that this control strategy can be easily integrated into the kinematic chains of most control software.

In section 5, we obtained the manipulation capabilities of different levitators, we have constructed the 3 most promising levitators 6 to experimentally realize the manipulations. The levitators were built using MA40S4S (Murata) emitters which are 1 cm in diameter and made of plastic, its parameters for Eq. 1 are r = 4.5 mm and P_0 = 2.4 for a 15 Voltage peak-to-peak (Vpp) square excitation signal.

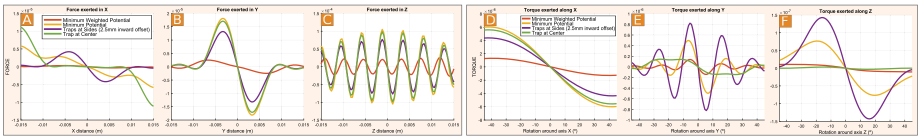

Figure 3: Forces and torques exerted on a stick by the field generated by different methods: Minimum weighted potential, minimum Potential, Trap at side and Trap at center. A) Forces exerted in the X-Axis. B) Forces exerted in the Y-Axis. C) Forces exerted in the Z-Axis. D) Torque exerted in the X-Axis. E). Torque exerted in the Y-Axis. F) Torque exerted in the Z-Axis.

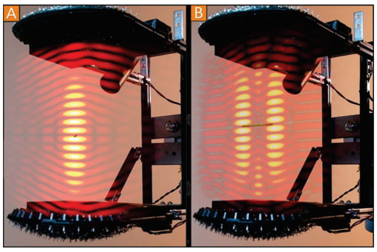

Figure 4: Pressure fields generated by a fixed-levitator. A) a standing wave creates a trap for holding a single sub-wavelength particle when the emitters are driven with the same signal. B) TrapsAtSides are generated when a halve of the emitters is driven with an inverse polarity signal (π phase), this field can fully trap a stick.

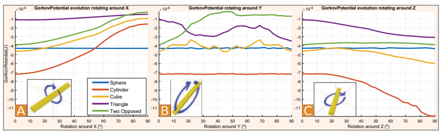

Figure 5: Gor'kov potential on a stick inside different levitators applying the TrapsAtSides method as it rotates around a A) x-axis, B) y-axis, and C) z-axis. The stick is 30 mm long, 2 mm wide and 1 mm height.

For larger operating voltages, P_0 scales linearly with the Vpp. The bowl design is based on TinyLev [Marzo et al. 2017]. The flat arrays are based on SonicSurface [Morales et al. 2021].

The basic operation of the fabrication prototypes is as follows. An acoustically transparent foundation is placed at the center of the working volume before starting the fabrication process, the foundation is the initial part where other parts or matter will be added. The system starts by trapping with the levitator a droplet of glue dispensed by a syringe pump. Then, the droplet is levitated into the position where the next piece is going to be added. The system picks sticks or particles from an acoustically-transparent

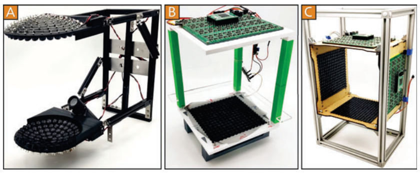

Figure 6: Constructed levitators. A) a fixed single-axis levitator with bowl geometry. B) two-opposed flat phased-arrays. C) four orthogonal flat arrays in a cube structure.

repository and positions them in contact with the previously placed glue, UV light is applied to cure the glue. This process is repeated for all the parts.

The main prototype is a fixed two-opposed levitator attached to a 7-DoF robot arm, a secondary prototype made of a a cube levitator mounted on a translation stage was tested, but the first prototype was easier to operate.

6.1 Two-opposed Fixed Levitator + Robot Arm

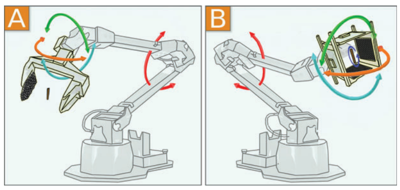

Figure 7: Examples of levitators attached to a robotic arm to complement or boost their missing manipulation DoFs. A) Fixed single-axis levitator with bowl geometry. B) Four orthogonal flat arrays in a cube structure.

A 7-DoF robotic arm (UR-3) is attached to a fixed two-opposed levitator (see Fig. 7.C). The fixed levitator is composed of two spherical arrays of 60 emitters each, with 4 concentric rings. It generates a field that traps the stick, using the Traps At Sides method from Section 4, see Fig. 4. A dynamic two-opposed levitator could also be used to add more DoFs to the levitator but for this system it was decided that the levitator would only be in charge of trapping and the robot arm would provide the manipulation DoFs. Alternatively, the fixed single-axis levitator can be held by a human to manually perform the steps involved in LeviPrint: trapping, releasing, translating, orientating and rotation.

6.2 Cube Levitator + Mechanical Stage

A cube levitator was attached to a translation stage. The levitator can orientate the stick to have the desired alignment as well as providing limited translation capabilities. The cube was attached to a mechanical translation stage that could provide larger ranges in the translation DoFs.

7 FABRICATION RESULTS

We illustrate the capabilities of *LeviPrint* by combining various building primitives such as sticks, beads and droplets to fabricate robust, lightweight and complex structures.

7.1 Basic Joints

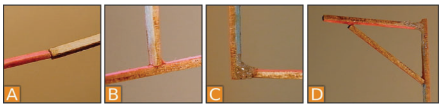

Figure 8: Types of joints between sticks. A) Butt joint: Two sticks are connected end to end forming a longer segment. B) L-joint: Two sticks are connected end to end at 90 degrees, the angle can be adjusted, more glue should be used since the contact surface is small. C) T-joint. D) Mitered joint: An L-joint reinforced with a third stick connecting the L at 45 degrees.

Joining sticks together is the main novel capability of *LeviPrint*. For doing so, a droplet of glue is levitated into the main object at the place where the next stick will be placed. The stick is then levitate to come in contact with the glue. UV light is applied to cure the glue. The types of joints can be seen in Fig. 8. We note that also beads can be used to connect sticks.

7.2 Fabricating with Particles

Instead of using sticks, only particles (a.k.a beads) are joined together using glue between them. The use of sub-wavelength spherical particles as the building parts enables more flexible designs in terms of shapes since they can be connected from anywhere. However, the process is longer since more parts are needed for the same length when compared to sticks, also the final result is denser and not necessarily stronger (Fig. 9.A).

7.3 Fabricating with UV Resin

UV-resin droplets can be used for manufacturing objects with free-form shapes. Droplets are repeatedly moved into its target position and cured until the final objects is formed. The droplets have a dish shape because of the pressure of the standing wave, the droplet can be oriented so that it is aligned with the building direction. We have manufactured a loop of 1cm diameter (see Fig. 9.B).

7.4 Complex Objects

The methods presented in the previous subsections can be combined to build more complex objects. We built a cube using orthogonally placed sticks via L joints, we also built a bridge connecting two separated metallic meshes, using different joints to provide a stronger structure (see Figs. 9.C and 9.E).

7.5 Adding on Top of Other Objects

Sticks, particles and droplets can be levitated on top of existing solid objects if they are approach from certain angles. The solid object cannot be directly located between the levitated part and the arrays since it would block a significant amount of the field. However, the solid object can be located in front of the levitated part without significantly disrupting the field. We showcase the addition of parts into a spherical object in Fig. 9.F.

7.6 Building Inside a Container

Fabric, meshes and sponges are acoustically translucent to the ultrasound field. Therefore, *LeviPrint* can fabricate inside containers made of these material, from the outside. In Fig. 9.D, we fabricate a boat inside a metallic mesh bottle. The sticks and glue are introduced inside the bottle through a small aperture at the side. In airborne Leviprint, the materials of the container are limited but if *LeviPrint* would be adapted to operate in aqueous media, it could assemble microscopic objects in cell-culture media and perhaps even inside living beings (See 9.D).

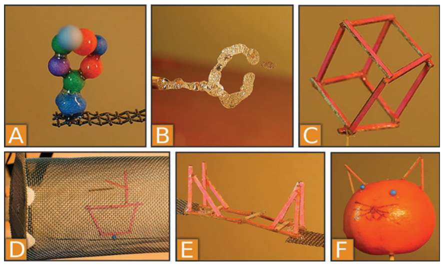

Figure 9: Fabricated items. A) Particles joined together to build a loop. B) Glue droplets being levitated to its final position to be cured for building a loop. C) Twelve orthogonally placed sticks via L-joints to build a cube. D) A stick being levitated inside a container towards its final position. E) Fifteen sticks joined via butt joints, L joints and miter butt joints to form a bridge. F) Adding multiple primitives at different angles into a solid spherical object.

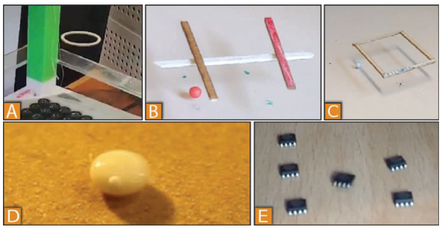

Figure 10: Another primitives that have been successfully levitated using stick. A) A circle was hold in mid-air using the two-opposed levitator. B) An airplane created by three sticks, using an array on top of a reflective surface. C) a levitated square. D) droplet of milk on a hydrophobic surface. E) electronic components Soic8 levitating over a table.

8 DISCUSSION

The individual steps involved in the results were conducted by a robot arm and an automatized software. The robot arm is programmed to perform the required movements to grab and place each primitive. However, for practicality reasons, on some occasions there was human intervention. We highlight that all the actions that were carried out manually could also have been performed by the programmed robotic arm, droplet dispenser and UV lamp.

Apart from sticks, we tested other primitives such as circles, squares, triangles and crosses. For these primitives, TrapsAtSides was not directly applicable and we employed the MinPot method. These primitives were levitated but we did not explore them since they can be composed with the basic primitives (see Fig.10. A-C).

The levitators presented here were based on various arrays facing each other. However, the developed methods are also applicable when a single array is placed on top of an acoustically reflective surface. The DoFs are limited to 1 DoF rotation and 2D translations at a plane located a a quarter wavelength above the surface. Printed circuit boards or functionalized substrates can be used as surfaces (see Fig.10.D and E).

Given that the fabricated structures are made of thin segments such as sticks, beads or cured glue, the fabricated object does not cause a significant disruption on the acoustic field since its "fill rate" is quite low (i.e., it is like a wireframe object). However, if complete solid objects were manufactured, we foresee two strategies that should be followed. First, the order in which the parts are added should be planned so that they approach the object from an operative angle that does not block significantly the ultrasound emitted from the arrays. As future work, it would also be possible to consider reflections caused by the object.

The emitters were driven at 70% of their maximum power so denser materials could be employed if a non-prototype system with extra cooling and electronics to handle more voltage was designed. The prototypes operated in air at 40 kHz, thus the wavelength λ=8.6mm determines the scale of the objects that can be manipulated, long sticks give flexibility in this regard. We reckon that decreasing the frequency to work with larger objects is not a feasible research direction; however, operating in water-based media at Mhz range would enable to control micrometric bio-structures on cell-friendly cultures and even in-vivo.

The maximum weight for sticks is that of 8 cm length of balsa wood (16 mg). The system can recover from external perturbations like shaking of the robot arm or weak wind since Acoustic levitation has converging forces and torques [Marzo et al. 2015]. The typical positioning accuracy is around 0.2 mm for levitating system operating at 40 kHz in air [Marzo et al. 2015], but moving into smaller wavelengths would increase this accuracy to the micrometres range [K et al. 2018]. Translation speeds vary from 1 cm/s [Marzo et al. 2015] to 8 m/s [Hirayama et al. 2019] for lighter particles, in our system the sticks were translated at up to 4 cm/s. We note that these limits are system-specific, systems operating at higher voltage, with less separation or working in water-based solutions instead of air would trap more weight, move faster or provide more accuracy.

9 CONCLUSION

LeviPrint is a technique for fabricating objects in a contactless way using acoustic levitation on primitives such as beads, sticks and droplets. We have presented an optimum acoustic field to trap elongated parts. Afterwards, we analyzed the capabilities of different levitators to allow dynamic manipulation of the stick by changing the emission phases. We designed a levitator integrated with a robotic arm to enable contactless fabrication of complex objects. We hope that the presented methods help other researchers to use acoustic contactless fabrication in other fields such as bioengineering or micro-fabricated machines, and in general that it broadens our concept of additive manufacturing.

ACKNOWLEDGMENTS

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REFERENCES

Marco AB Andrade, Thales SA Camargo, and Asier Marzo. 2018. Automatic contactless injection, transportation, merging, and ejection of droplets with a multifocal point acoustic levitator. *Review of Scientific Instruments* 89, 12 (2018), 125105.
Marco AB Andrade, Fábio TA Okina, Anne L Bernassau, and Julio C Adamowski. 2017. Acoustic levitation of an object larger than the acoustic wavelength. *The Journal of the Acoustical Society of America* 141, 6 (2017), 4148–4154.
Ashly Baby, Chinnu Augustine, Chinnu Thampi, Maria George, Abhilash AP, and Philip C Jose. 2017. Pick and place robotic arm implementation using Arduino. *IOSR Journal of Electrical and Electronics Engineering* 12, 2 (2017).
E H Brandt. 2001. Suspended by sound. *Nature* 413, 6855 (2001), 474–475. https://doi.org/10.1038/35097192
Henrik Bruus. 2012. Acoustofluidics 7: The acoustic radiation force on small particles. *Lab Chip* 12 (2012), 1014–1021. Issue 6. https://doi.org/10.1039/C2LC21068A
David J Collins, Belinda Morahan, Jose Garcia-Bustos, Christian Doerig, Magdalena Plebanski, and Adrian Neild. 2015. Two-dimensional single-cell patterning with one cell per well driven by surface acoustic waves. *Nature communications* 6, 1 (2015), 1–11.
L. Cox, A. Croxford, B. W. Drinkwater, and A. Marzo. 2018. Acoustic Lock: Position and orientation trapping of non-spherical sub-wavelength particles in mid-air using a single-axis acoustic levitator. *Applied Physics Letters* 113, 5 (2018), 054101. https://doi.org/10.1063/1.5042518 arXiv:https://doi.org/10.1063/1.5042518
Chengkai Dai, Charlie CL Wang, Chenming Wu, Sylvain Lefebvre, Guoxin Fang, and Yong-Jin Liu. 2018. Support-free volume printing by multi-axis motion. *ACM Transactions on Graphics (TOG)* 37, 4 (2018), 1–14.

Jimmy Etienne, Nicolas Ray, Daniele Panozzo, Samuel Hornus, Charlie CL Wang, Jonàs Martínez, Sara McMains, Marc Alexa, Brian Wyvill, and Sylvain Lefebvre. 2019. CurviSlicer: Slightly curved slicing for 3-axis printers. *ACM Transactions on Graphics (TOG)* 38, 4 (2019), 1–11.

Andreas Rene Fender, Diego Martinez Plasencia, and Sriram Subramanian. 2021. ArticuLev: An Integrated Self-Assembly Pipeline for Articulated Multi-Bead Levitation Primitives. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. 1–12.

Daniele Foresti, Majid Nabavi, Aldo Klingauf, and Dimos Poulikakos. 2013. Acoustophoretic contactless transport and handling of matter in air. *Proceedings of the National Academy of Sciences* 110, 31 (2013), 12549–12554.

Tatsuki Fushimi, Asier Marzo, Bruce W Drinkwater, and Thomas L Hill. 2019. Acoustophoretic volumetric displays using a fast-moving levitated particle. *Applied Physics Letters* 115, 6 (2019), 064101.

Lev P. Gor'kov. 1962. On the forces acting on a small particle in an acoustical field in an ideal fluid.

William A Harkness and Josh H Goldschmid. 2018. Free-form spatial 3-D printing using part levitation. US Patent 9,908,288.

Petteri Helander, Tuomas Puranen, Antti Meriläinen, Göran Maconi, Antti Penttilä, M Gritsevich, Ivan Kassamakov, Ari Salmi, Karri Muinonen, and Edward Haeggström. 2020. Omnidirectional microscopy by ultrasonic sample control. *Applied Physics Letters* 116, 19 (2020), 194101.

Ryuji Hirayama, Diego Martinez Plasencia, Nobuyuki Masuda, and Sriram Subramanian. 2019. A volumetric display for visual, tactile and audio presentation using acoustic trapping. *Nature* 575, 7782 (2019), 320–323. https://doi.org/10.1038/s41586-019-1739-5

Samuel Hornus, Tim Kuipers, Olivier Devillers, Monique Teillaud, Jonàs Martínez, Marc Glisse, Sylvain Lazard, and Sylvain Lefebvre. 2020. Variable-width contouring for Additive Manufacturing. *ACM Transactions on Graphics (TOG)* 39, 4 (2020), 131–1.

Seki Inoue, Shinichi Mogami, Tomohiro Ichiyama, Akihito Noda, Yasutoshi Makino, and Hiroyuki Shinoda. 2019. Acoustical boundary hologram for macroscopic rigid-body levitation. *The Journal of the Acoustical Society of America* 145, 1 (2019), 328–337.

Melde K, Mark AG, Qiu T, and Fischer P. 2016. Holograms for acoustics. *Nature*, 518–22.

Melde K, Choi E, Wu Z, Palagi S, and Fischer P Qiu T. 2018. Acoustic Fabrication via the Assembly and Fusion of Particles. *Adv Mater.*

Jonas T. Karlsen and Henrik Bruus. 2015. Forces acting on a small particle in an acoustical field in a thermoviscous fluid. *Phys. Rev. E* 92 (Oct 2015), 043010. Issue 4. https://doi.org/10.1103/PhysRevE.92.043010

Glen R Kirkham, Emily Britchford, Thomas Upton, James Ware, Graham M Gibson, Yannick Devaud, Martin Ehrbar, Miles Padgett, Stephanie Allen, Lee D Buttery, et al. 2015. Precision assembly of complex cellular microenvironments using holographic optical tweezers. *Scientific reports* 5, 1 (2015), 1–7.

Jeremy A Marvel, Roger Bostelman, and Joe Falco. 2018. Multi-robot assembly strategies and metrics. *ACM Computing Surveys (CSUR)* 51, 1 (2018), 1–32.

Asier Marzo. 2020. Standing Waves for Acoustic Levitation. In *Acoustic Levitation*. Springer, 11–26.

Asier Marzo, Adrian Barnes, and Bruce W. Drinkwater. 2017. TinyLev: A multi-emitter single-axis acoustic levitator. *Review of Scientific Instruments* 88, 8 (2017), 085105. https://doi.org/10.1063/1.4989995 arXiv:https://doi.org/10.1063/1.4989995

Asier Marzo, Mihai Caleap, and Bruce W Drinkwater. 2018a. Acoustic virtual vortices with tunable orbital angular momentum for trapping of mie particles. *Physical review letters* 120, 4 (2018), 044301.

Asier Marzo, Tom Corkett, and Bruce W. Drinkwater. 2018b. Ultraino: An Open Phased-Array System for Narrowband Airborne Ultrasound Transmission. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* 65, 1 (2018), 102–111. https://doi.org/10.1109/TUFFC.2017.2769399

Asier Marzo and Bruce W. Drinkwater. 2019. Holographic acoustic tweezers. *Proceedings of the National Academy of Sciences* 116, 1 (2019), 84–89. https://doi.org/10.1073/pnas.1813047115 arXiv:https://www.pnas.org/content/116/1/84.full.pdf

Asier Marzo, Sue Ann Seah, Bruce W Drinkwater, Benjamin Sahoo, and Sriram Subramanian. 2015. Holographic acoustic elements for manipulation of levitated objects. *Nature communications* 6, 1 (2015), 1–7.

Rafael Morales, Iñigo Ezcurdia, Josu Irisarri, Marco A. B. Andrade, and Asier Marzo. 2021. Generating Airborne Ultrasonic Amplitude Patterns Using an Open Hardware Phased Array. *Applied Sciences* 11, 7 (2021). https://doi.org/10.3390/app11072981

Rafael Morales, Asier Marzo, Sriram Subramanian, and Diego Martínez. 2019. LeviProps: Animating levitated optimized fabric structures using holographic acoustic tweezers. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*. 651–661.

Yoichi Ochiai, Takayuki Hoshi, and Jun Rekimoto. 2014. Pixie Dust: Graphics Generated by Levitated and Animated Objects in Computational Acoustic-Potential Field. *ACM Trans. Graph.* 33, 4, Article 85 (jul 2014), 13 pages. https://doi.org/10.1145/2601097.2601118

Themis Omirou, Asier Marzo, Sue Ann Seah, and Sriram Subramanian. 2015. LeviPath: Modular Acoustic Levitation for 3D Path Visualisations. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI '15)*. Association for Computing Machinery, New York, NY, USA, 309–312. https://doi.org/10.1145/2702123.2702333

HoT O'Neil. 1949. Theory of focusing radiators. *The Journal of the Acoustical Society of America* 21, 5 (1949), 516–526.

Diego Martinez Plasencia, Ryuji Hirayama, Roberto Montano-Murillo, and Sriram Subramanian. 2020. GS-PAT: High-Speed Multi-Point Sound-Fields for Phased Arrays of Transducers. *ACM Trans. Graph.* 39, 4, Article 138 (jul 2020), 12 pages. https://doi.org/10.1145/3386569.3392492

Osvaldas Putkis. 2018. Contactless manipulation apparatus, assembly method and 3d printing. US Patent App. 15/765,126.

Marc Röthlisberger, Marcel Schuck, Laurenz Kulmer, and Johann W Kolar. 2021. Contactless Picking of Objects Using an Acoustic Gripper. In *Actuators*, Vol. 10. Multidisciplinary Digital Publishing Institute, 70.

Jenna M. Shapiro, Bruce W. Drinkwater, Adam W. Perriman, and Mike Fraser. 2021. Sonolithography: In-Air Ultrasonic Particulate and Droplet Manipulation for Multiscale Surface Patterning. *Advanced Materials Technologies* 6, 3 (2021), 2000689. https://doi.org/10.1002/admt.202000689 arXiv:https://onlinelibrary.wiley.com/doi/pdf/10.1002/admt.202000689

Lawrence K Shapiro and Howard I Shapiro. 1988. Construction cranes. *Scientific American* 258, 3 (1988), 72–79.

Gavin Sinclair, Pamela Jordan, Johannes Courtial, Miles Padgett, Jon Cooper, and Zsolt John Laczik. 2004. Assembly of 3-dimensional structures using programmable holographic optical tweezers. *Optics Express* 12, 22 (2004), 5475–5480.

Haichuan Song, Jonàs Martínez, Pierre Bedell, Noemie Vennin, and Sylvain Lefebvre. 2019. Colored fused filament fabrication. *ACM Transactions on Graphics (TOG)* 38, 5 (2019), 1–11.

Shun Suzuki, Seki Inoue, Masahiro Fujiwara, Yasutoshi Makino, and Hiroyuki Shinoda. 2021. AUTD3: Scalable Airborne Ultrasound Tactile Display. *IEEE Transactions on Haptics* 14, 4 (2021), 740–749. https://doi.org/10.1109/TOH.2021.3069976

RR Whymark. 1975. Acoustic field positioning for containerless processing. *Ultrasonics* 13, 6 (1975), 251–261.

Duyang Zang, Kejun Lin, Lin Li, Zhen Chen, Xiaoguang Li, and Xingguo Geng. 2017. Acoustic levitation of soap bubbles in air: Beyond the half-wavelength limit of sound. *Applied Physics Letters* 110, 12 (2017), 121602.

2.3 UNDER REVIEW - Enhanced Spatial Resolution of Amplitude Patterns using Time-Multiplexed Virtual Acoustic Fields

Title:	*Enhanced Spatial Resolution of Amplitude Patterns using Time-Multiplexed Virtual Acoustic Fields*
Publication:	Manuscript submitted for publication
Authors:	Sonia Elizondo, Iñigo Ezcurdia, Jaime Goñi, Mikel Galar, Asier Marzo
Abstract:	Ultrasonic fields can push particles, generate heat, be felt by humans, or affect the blood-brain barrier amongst many other effects. Consequently, generating fields with custom amplitude patterns is of major interest. Phased-arrays can create dynamic patterns but they lack spatial resolution due to the complexity and cost of having a high density of emitters; on the other hand, passive modulators have high-spatial resolution but produce a static pattern. Here, we show that multiple averaged amplitude fields generated with phased-arrays have more spatial resolution than a single emission field. We optimise the non-linear problem of decomposing a target amplitude field into multiple fields considering the limitations of the phased array. The presented technique, improves the spatial resolution without having to replace existing equipment, having the potential to improve bio-printing, haptic devices or ultrasonic medical treatments.

Enhanced Spatial Resolution of Amplitude Patterns using Time-Multiplexed Virtual Acoustic Fields

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ABSTRACT

Ultrasonic fields can push and levitate particles, heat up materials, induce contactless tactile stimuli or affect the blood-brain barrier. Phased-arrays can create dynamic amplitude patterns but their resolution may be insufficient due to the limited density of emitters. On the other hand, passive modulators can provide high-spatial resolution patterns, but only static patterns can be generated. Here, we show and evaluate how the average of multiple time-multiplexed amplitude fields improves the resolution of the obtained patterns when compared with the traditional single-emission method. We optimise the non-linear problem of decomposing a target amplitude field into multiple fields considering the limitations of the phased-array. The presented technique improves the spatial resolution for existing setups without modifying or replacing the equipment. Furthermore, it can also improve future upcoming phased-arrays of more resolution, having the potential to improve bio-printing, haptic devices or ultrasonic medical treatments.

Introduction

Custom acoustic fields are vital for particle[1,2], aerosol[3] or cell[4] patterning; as well as for ablation of tumours[5], Alzheimer treatment[6] or tactile perception[7]. Consequently, being able to generate fields with custom patterns can significantly advance the fields of bio-printing, medical ultrasound or parallel particle manipulation.

Acoustic fields can be dynamically shaped to specific patterns by using phased-arrays composed of various emitters with controllable amplitude and phases[8,9]. These arrays can generate different amplitude fields by electronically adjusting the signal of each emitter, but the resulting fields lack spatial resolution given the limited number of emitters, which usually do not fulfil the Rayleigh criterion (smaller than $\lambda/2$). Using a phased-array to generate amplitude patterns has been achieved by adapting the Gerchberg–Saxton algorithm to consider the limited number of emitters that current devices have[8] or by optimising the emissions of each emitter to match target patterns[9]. However, the obtained patterns were limited in resolution given the low number of emitters (16×16 elements of 1.16λ in size, or 20×20 elements). Available phased-arrays with enough power for patterning or manipulation usually have this resolution.

On the other hand, passive phase modulators can be manufactured with high-spatial resolution[1,2,10–12] but they are static and generate only one pattern. These passive structures can modulate impinging waves to obtain high-resolution patterns[1], but they are static and one plate is needed per target pattern. Some improvements allow to produce different fields when the modulator is impinged by different frequencies[13], but the number is limited to 2 or 3 fixed patterns.

Combinations of phased arrays and passive modulators provide some flexibility over the static patterns. Cox et al.[14] used this combination for focusing along the vertical direction a trap generated with the array and enhanced its trapping performance on a single-particle. Athanassiadis et al.[15] were able to code 10 patterns in stack passive modulators. These patterns were projected when impinged by one of the 10 different emitters that were behind the modulator, yet only a fixed amount of patterns were encoded in the modulator with some loss in their resolution.

Time-multiplexation consists in rapidly switching the emitted fields. Time-multiplexation has been explored for particle manipulation by switching between 2 modes in a microfluidic channel[16] to control the horizontal position of the particles. Virtual vortices[17] are pairs of vortices that rapidly switch their topological charge to cancel their orbital angular momentum and stably trap particles larger than the wavelength. Rapidly switching between a standing-wave and a twin-trap led to an acoustic lock[18], a trap that holds sub-wavelength asymmetric objects in position and orientation. Three different predefined fields can be switched quickly to combine their radiation forces in particle manipulation[19]. However, all of these applications are focused on controlling the forces at specific points to trap particles, and cannot generate complex 2D patterns. Furthermore, the emitted multiplexed fields were predefined by the researchers, not obtained through decomposition or optimisation.

Here, we present a technique to calculate multiple fields that can be emitted by an array that when averaged in amplitude, result in a virtual field that has more spatial resolution than any single-emission field that can be produced with the same array. To achieve this, we optimise the non-linear problem of decomposing a target amplitude field into multiple fields that can be emitted with a phased-array. When the amplitude of these fields is averaged, they approximate the target field. This technique improves the resolution of the produced amplitude fields without the need of modifying existing hardware, being applicable to existing systems, and also to upcoming higher resolution arrays.

The target amplitude field is a real 2D matrix, which is flattened into a 1D vector named $TargetField$. On the other hand, $VirtualField$ is the averaged amplitude from the multiplexed fields, i.e., $VirtualField = (mag(F_1) + ... + mag(F_m))/m$. Where F_j is a complex field (flattened as well) that can be obtained by the matrix multiplication of the emitter vector T_j by the propagators matrix P, that is $F_j = T_jP$ where $j = 1..m$ for the different multiplexed fields. Note that the propagators P remain the same for all the multiplexed fields since the emitters and the field points do not change position.

P can be pre-calculated for each pair of emitters and points in the field, using for example the Piston Model[20] $p = P_0 \frac{D(\theta)}{d} e^{i(kd)}$ where P_0 is the power constant of the emitter, d is the distance between the centre of the emitter and the point in the field, $k = 2\pi/\lambda$ is the wavenumber, while λ is the wavelength; $D(\theta)$ is the directivity of the emitter and depends on the angle θ between the emitter normal and the point. The directivity function of a vibrating piston source can be expressed as $D(\theta) = 2J_1(ka \sin\theta)/ka \sin\theta$, where J_1 is a first order Bessel function of the first kind and a is the radius of the piston. The field that an emitter generates at the point is $f = tp$, where t is the emitter complex representation of amplitude and phase; and p is the propagator from the emitter to the point. The emitter emission is encoded as $t = amp \quad e^{ik\varphi}$ where amp is the emission amplitude and φ is the emitting phase.

As such, the target function to minimise is the mean squared error between the $VirtualField$ and the $TargetField$ as a function of the emissions for each of the multiplexed fields $O(E_1, ..., E_m) = MSE(VirtualField, TargetField)$. Other loss functions were tested (See Supplementary Figure 1) but MSE provided the best general results. In Figure 1, we show a single-emission field, virtual field and multiplexed fields for the same target field. It can be seen that the decomposition of a virtual field is not trivial. These examples are from the circular array described in the next section.

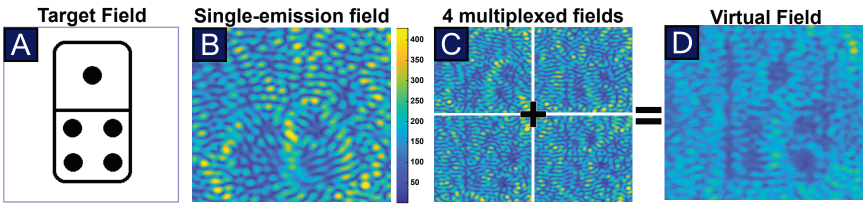

Figure 1. A) Target Field. B) Single-emission field. C) Four multiplexed fields. D) Virtual Field resulting from averaging the amplitude of the multiplexed fields. All fields represent amplitudes and are simulations for the Circular array.

Results

Both for simulations and experiments, we selected two ultrasonic arrays. Firstly, a circular array with 64 emitters of 1.6 cm (1.9 λ) diameter divided into two overlapping circumferences of 32 emitters each. The radius of the array was 12 cm (14λ). Secondly, a squared array of 16×16 emitters of 1 cm (1.16λ) diameter. The array had 16 cm of side (18.6 λ). The fields were generated 20 cm above the squared array ($TargetField$ of 10cm$\times$10cm) and at the centre of the circular array ($TargetField$ of 10cm$\times$10cm). The arrays are shown in Figure 2. The operating frequency is 40 kHz and as such the wavelength in air is approximately 8.46 mm. These arrays were selected as a representation of devices employed for particle manipulation[21] and patterning[3]. We note that other geometries and sizes exist in the literature. In the discussion section, virtual fields for higher-resolution arrays are simulated.

Different target patterns were tested: latin alphabet symbols, digits and basic geometries. We report in the main paper a representative subset: letter A, as a symbol made of straight lines; an inverted domino piece, as an inverted image with straight edges and holes; the pi symbol, as a symbol with curved strokes; a star, as a simple target with straight lines and varying thickness; and a Trojan helmet, as a combination of thick and curved strokes with small gaps between them. A complete set of the tested patterns is attached as supplementary data. Also, in the discussion, we show target patterns generated with simulated arrays that have a denser distribution of emitters, up to the Rayleigh limit.

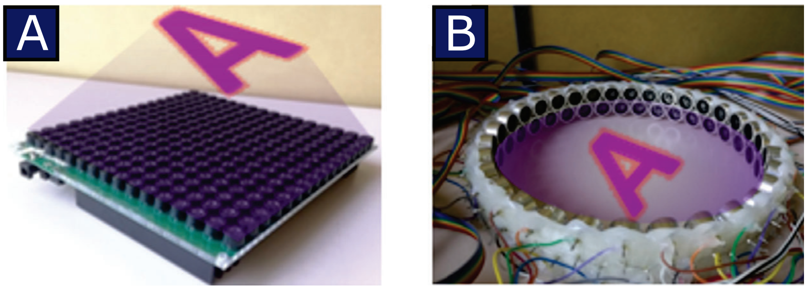

Figure 2. Phased-arrays: A) Squared array of 16 × 16 emitters of 1 cm diameter. B) Circular array of 64 emitters of 1.6cm diameter. The array has a 12 cm radius.

Simulations

We used a quasi-newton gradient-descent optimizer (fminunc function from Matlab R2019b) with numerical approximation of the gradient and default parameters. In general, 40 iterations were enough to converge into a solution.

For each of the target patterns, we calculated $VirtualFields$ composed of 1 to 16 multiplexed fields. The target patterns were 10cm×10cm, discretised in fields of 256 × 256 points. Figure 3 shows the simulated $VirtualFields$ for different target patterns grouped by array geometry.

There is a significant improvement in the definition of the virtual fields when using 2 multiplexed fields, instead of just a single field. Beyond 4 multiplexed fields, the improvement is less significant. This becomes evident when comparing 1 and 2 fields with 4 and 16 multiplexed fields, being even more noticeable for the squared array.

The reduction of the Mean Squared Error (MSE) as the number of multiplexed fields increases is shown in Figure 4 for both circular array and squared array. The graphs show two different sets of lines: a solid one, representing the normalised MSE decrease as we increase the density of emitters; and a dashed set, which is the MSE evolution as the virtual fields are composed of more multiplexed fields.

The MSE error drops sharply when using a 2-fields multiplexation as it was also seen in the obtained patterns. In some cases, using Virtual Fields offer a larger improvement than increasing the density of emitters. See Figure 4. For example, for the 'Trojan helmet' pattern, a circular array would need to double its emitters to obtain a result as well-defined as the multiplexing technique does with 6 multiplexations; and with a squared array the quality of a virtual field is not even matched with double the number of transducers. In all cases, using virtual fields improves the resolution, except for the basic star pattern in the squared array, which already has enough resolution with a single-emission. The domino pattern in the circular array is the most significant example of how virtual fields improve the resolution of the obtained field.

Scanned Fields

The ultrasonic arrays were used to emit the resulting patterns obtained in the simulations for the different number of multiplexations, so that the virtual field could be experimentally scanned. The arrays were powered with 10 V and a computer sent the emission for each of the multiplexed fields. Fields were switched at 100 Hz and the reported value is the RMS averaged over 5 ms.

Figure 5 shows the experimental amplitude slices of the virtual fields, which are in reasonable agreement with the simulated slices seen in Figure 3. For both single and multiplexed fields, some details are lost between the simulated and the scanned fields. We attribute this to reflections from the scanning head, as well as phase and amplitude variations of the emitters from the phased-arrays.

Thermal Patterns

Thermal patterns generated on a piece of fabric are shown in Figure 6. A squared array was placed 20 cm above a neoprene piece of fabric for 20 seconds. Two target patterns were tested, with a single-emission field and with virtual fields composed of 4 and 16 multiplexing fields switched at 0.5Hz . It is worth mentioning that the variation between the coldest and hottest points are similar using single-emission or virtual fields. Thus, no power loss was observable, only an increase on the spatial resolution. The patterns definition and resolution increases when adding more multiplexed fields.

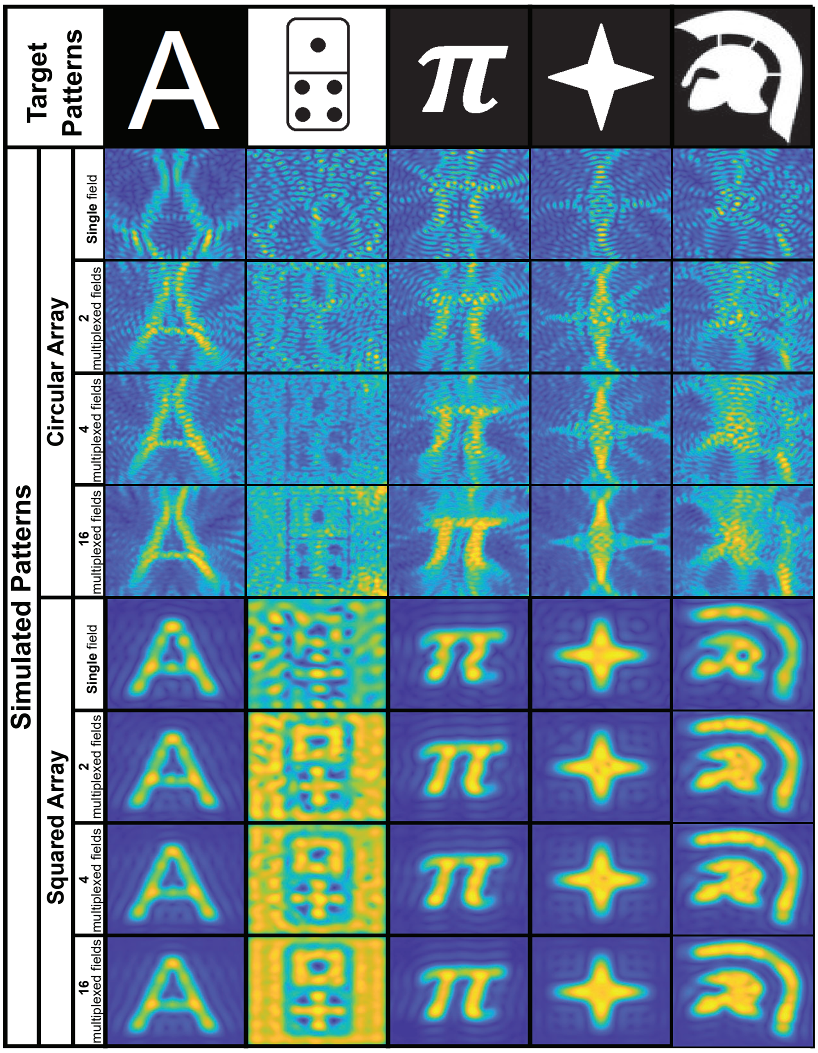

Figure 3. Virtual fields calculated for 5 target patterns, for different number of multiplexed fields, for the circular and the squared array. Amplitude scale bars for circular array are [0, 300] Pa and for squared array are [0, 450] Pa. Fields are 10cm×10cm which at 40 kHz in air represent $11.62 \times 11.62\lambda$.

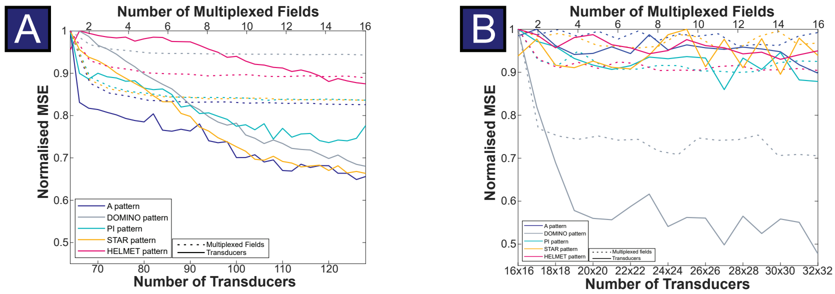

Figure 4. Evolution of the normalised MSE of virtual fields compared with increasing the density of emitters for (A) a circular array and (B) a squared array. The upper X-axis shows the number of time-multiplexed fields in use (dashed line) and the lower one shows the number of emitters (solid line).

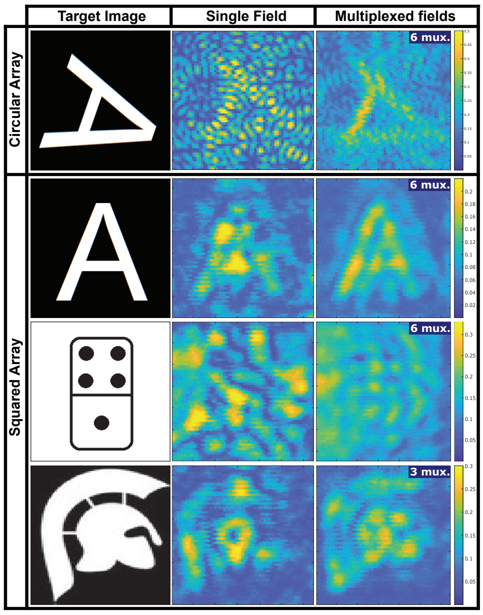

Figure 5. Experimental scans of 3 patterns for a single field, and 3 or 6 multiplexed fields on the circular and square arrays.

Discussion

Depending on the target application, the system will react as if the average of the effects of the multiplexed fields is acting on the system. For example, a particle inside switching acoustic fields will perceive the average of the forces resulting from each field. Acoustic levitation in mid-air requires a switching frequency of 1 kHz[17] whereas manipulation in water requires less frequency[16]. For thermal patterns, we switched the fields at 0.5 Hz, but faster speeds will be required if heat dissipation

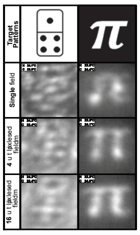

Figure 6. Thermal images obtained for domino and pi-symbol target patterns. The single-emission field result is compared to virtual fields composed of 4 and 16 fields from the squared array.

is large. For aerosol patterning (Supplementary Figure 2), a multiplexation speed of 1 Hz produced a clean average between the patterns. Multiplexation speeds beyond 1 kHz will result in power loss since the emitters require some time to transition between different fields (Supplementary Information XX).

Most common commercially available[?] and DIY[?] phased-arrays have emitter densities similar to the ones used in these experiments. Nonetheless, imaging arrays have higher densities of emitters and in the future, it is to be expected to have high-power high-density phased-arrays; for example in novel HIFU therapies, currently performed with static modulators[22]. In Figure XX, we show that virtual fields still improve the resolution of the amplitude fields when the arrays have a high density of emitters, even beyond the Rayleigh criterion.

To compare and evaluate the resolution improvement of Virtual Fields with the current acoustic field techniques, we use the current commonly used optimisation of a single-emission field[9] as a baseline. In Supplementary Figure 3, we show that optimising for single-emission is the current best technique, which is also similar to adapted spectral methods[8]. Virtual Fields improve the resolution beyond these state-of-the-art algorithms.

Spatial-multiplexation can be employed in a similar way to time-multiplexation for increasing the resolution. It would consist in rotating or moving the arrays as they emit different patterns. In our simulations (see Supplementary Figure 4 and Figure 5) both time-multiplexation and spatial-multiplexation obtained similar improvements. We conducted the experiments with time-multiplexation since it is easier to implement, as the arrays do not need to be moved or rotated at high-speed, therefore requiring no modifications in existing hardware. Furthermore, with time-multiplexation, the fields can be switched faster and thus be applicable to more domains.

We have presented a technique to improve the resolution of acoustic amplitude patterns with no need for hardware modifications. This technique has been explored for representative arrays commonly used for dynamic patterning and levitation; namely, a squared array of 16×16 emitters, and a circular array of 12cm radius and 64 emitters. Amplitude Virtual Fields obtained by time-multiplexation have been presented in simulations and compared to the alternative of increasing the density of the emitters. Virtual Fields have also been experimentally evaluated by scanning the fields and by capturing thermal patterns created with them. This technique improves the resolution of the produced amplitude fields without modifying the hardware, and also works for upcoming high-resolution arrays. Thus, it can provide benefits in the fields of bio-printing, medical ultrasound or parallel particle manipulation.

Methods

Ultrasonic arrays

The squared ultrasonic array is based in the design of SonicSurface[8] using MSO-P1040H07T (Manorshi) emitters operating at 40kHz and of 1 cm diameter, P_0=0.13 VppPa/m a=5mm. The amplifiers were MOSFET drivers MIC4127 (Microchip) and the signals were generated by an FPGA (P4CE6E22C8N—ALTERA IV Core Board, Waveshare). The phases were sent from a PC using UART protocol at 500 kbauds, and had 32 divisions per period resolution.

The circular array was based on the hardware from Ultraino[23], it employed MSO-A1640H10T (Manorshi) emitters operating at 40kHz and 16mm diameter, P_0=0.36 VppPa/m a=6mm. The drivers were TC4427A (microchip) and the signals were generated by an Arduino Mega 2560 Rev3 with a resolution of 10 divisions per period. The phases were sent from a PC using UART protocol at 115200 bauds, and with an internal memory for 32 phase sets that could be emitted for specific number of periods.

Scanning setup

To scan the fields, the setups shown in Figure 7 were used. These setups measure slices of the acoustic pressure distribution generated by the arrays. The squared array is placed directly on the bed. The circular array is suspended parallel to the bed at a fixed height. An ultrasonic receiver (MANORSHI 16mm MSO-A1640H10T) is attached to the head of a delta stage (Anycubic Kossel). This receiver has a diameter of 16mm. A PLA 3D-printed 1.5mm diameter wide conical aperture tip is attached to the ultrasonic receiver to achieve a narrower acquisition aperture. A Matlab script communicates with the delta stage and moves the receiver to different positions with 1.5mm spacing on a 96 × 96 mm grid for the square array and on a 85 × 85 mm grid for the circle array. At each measuring point, the computer takes a signal sample captured by an oscilloscope (RedPitaya STEMLab 125-10), and calculates the signal's root mean square (RMS). The signal acquisition is configured to capture all the multiplexed fields. These RMS values can be translated to amplitude in arbitrary units (a.u). The computer sends the emission phases of the multiplexed field to the arrays through the UART protocol, and it controls the stage using the G-CODE protocol.

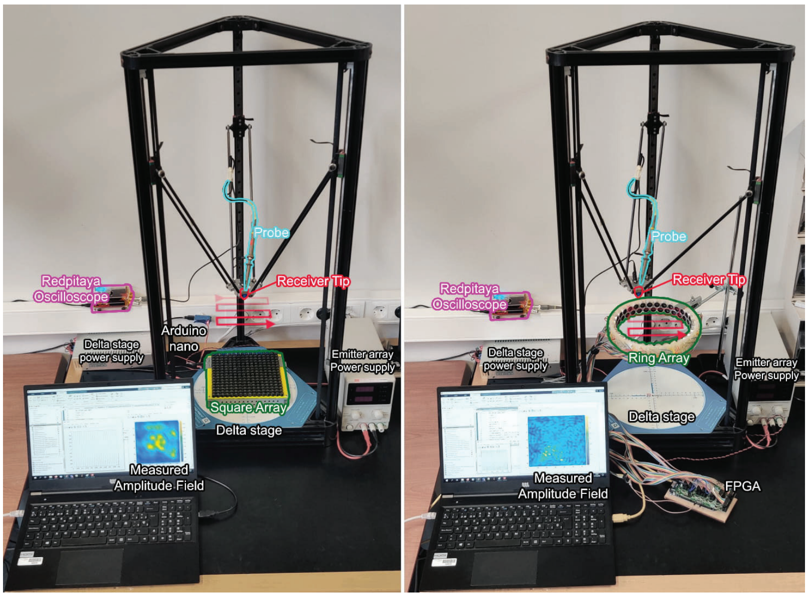

Figure 7. Setup for the scanning of the acoustic patterns, both for the circular and squared arrays.

Thermal patterns

A FLIR A655sc thermal camera was used. The square phased-array was placed above a black neoprene piece of fabric, which was resting on an adjustable z-stage. The array was connected to a power supply at 12V and to a computer that sent the patterns to the array. The thermal camera was standing on a tripod next to the table, and it was pointing at the fabric.

Data Availability

Data generated or analysed for this research are included in the published article and its supplementary information files.

References

1. Melde, K., Mark, A. G., Qiu, T. & Fischer, P. Holograms for acoustics. *Nature* **537**, 518–522 (2016).
2. Melde, K. *et al.* Compact holographic sound fields enable rapid one-step assembly of matter in 3d. *Sci. Adv.* **9**, eadf6182 (2023).

3. Shapiro, J. M., Drinkwater, B. W., Perriman, A. W. & Fraser, M. Sonolithography: In-air ultrasonic particulate and droplet manipulation for multiscale surface patterning. *Adv. Mater. Technol.* **6**, 2000689 (2021).
4. Ma, Z. *et al.* Acoustic holographic cell patterning in a biocompatible hydrogel. *Adv. Mater.* **32**, 1904181 (2020).
5. Andrés, D., Vappou, J., Jiménez, N. & Camarena, F. Thermal holographic patterns for ultrasound hyperthermia. *Appl. Phys. Lett.* **120**, 084102 (2022).
6. Lipsman, N. *et al.* Blood–brain barrier opening in alzheimer's disease using mr-guided focused ultrasound. *Nat. communications* **9**, 2336 (2018).
7. Gavrilov, L., Tsirulnikov, E. & Davies, I. a. I. Application of focused ultrasound for the stimulation of neural structures. *Ultrasound medicine & biology* **22**, 179–192 (1996).
8. Morales, R., Ezcurdia, I., Irisarri, J., Andrade, M. A. & Marzo, A. Generating airborne ultrasonic amplitude patterns using an open hardware phased array. *Appl. Sci.* **11**, 2981 (2021).
9. Iablonskyi, D. *et al.* Tailored acoustic holograms with phased arrays. In *2022 IEEE International Ultrasonics Symposium (IUS)*, 1–3 (IEEE, 2022).
10. Memoli, G. *et al.* Metamaterial bricks and quantization of meta-surfaces. *Nat. communications* **8**, 14608 (2017).
11. Xie, Y. *et al.* Acoustic holographic rendering with two-dimensional metamaterial-based passive phased array. *Sci. reports* **6**, 35437 (2016).
12. Li, W., Lu, G. & Huang, X. Acoustic hologram of the metasurface with phased arrays via optimality criteria. *Mech. Syst. Signal Process.* **180**, 109420 (2022).
13. Brown, M. D., Cox, B. T. & Treeby, B. E. Design of multi-frequency acoustic kinoforms. *Appl. Phys. Lett.* **111**, 244101 (2017).
14. Cox, L., Melde, K., Croxford, A., Fischer, P. & Drinkwater, B. W. Acoustic hologram enhanced phased arrays for ultrasonic particle manipulation. *Phys. Rev. Appl.* **12**, 064055 (2019).
15. Athanassiadis, A. G., Schlieder, L., Melde, K., Volchkov, V. & Fischer, P. Animating sound using neurally multiplexed holograms. *The J. Acoust. Soc. Am.* **148**, 2807–2807 (2020).
16. Glynne-Jones, P., Boltryk, R. J., Harris, N. R., Cranny, A. W. & Hill, M. Mode-switching: A new technique for electronically varying the agglomeration position in an acoustic particle manipulator. *Ultrasonics* **50**, 68–75 (2010).
17. Marzo, A., Caleap, M. & Drinkwater, B. W. Acoustic virtual vortices with tunable orbital angular momentum for trapping of mie particles. *Phys. review letters* **120**, 044301 (2018).
18. Cox, L., Croxford, A., Drinkwater, B. & Marzo, A. Acoustic lock: Position and orientation trapping of non-spherical sub-wavelength particles in mid-air using a single-axis acoustic levitator. *Appl. Phys. Lett.* **113**, 054101 (2018).
19. Cox, L., Croxford, A. & Drinkwater, B. W. Dynamic patterning of microparticles with acoustic impulse control. *Sci. reports* **12**, 1–14 (2022).
20. O'Neil, H. Theory of focusing radiators. *The J. Acoust. Soc. Am.* **21**, 516–526 (1949).
21. Marzo, A. & Drinkwater, B. W. Holographic acoustic tweezers. *Proc. Natl. Acad. Sci.* **116**, 84–89 (2019).
22. Andrés, D., Jiménez, N., Benlloch, J. M. & Camarena, F. Numerical study of acoustic holograms for deep-brain targeting through the temporal bone window. *Ultrasound Medicine & Biol.* **48**, 872–886 (2022).
23. Marzo, A., Corkett, T. & Drinkwater, B. W. Ultraino: An open phased-array system for narrowband airborne ultrasound transmission. *IEEE transactions on ultrasonics, ferroelectrics, frequency control* **65**, 102–111 (2017).

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Author contributions statement

S.E. and A.M. wrote the manuscript. S.E. and I.E. conducted the experiments. S.E., A.M and J.G. made the simulations. All authors reviewed the manuscript.

Additional information

The authors declare no competing interests.

2.4 UNDER REVIEW - Microfluidic platform using focused ultrasound passing through hydrophobic meshes with jump availability

Title:	*Microfluidic platform using focused ultrasound passing through hydrophobic meshes with jump availability*
Publication:	Pre-print available at https://doi.org/10.51094/jxiv.166
Authors:	Yusuke Koroyasu, Thanh-Vinh Nguyen, Shun Sasaguri, Asier Marzo, Iñigo Ezcurdia, Yuuya Nagata, Takayuki Hoshi, Yoichi Orchiai, Tatsuki Fushimi
Abstract:	Applications in chemistry, biology, medicine, and engineering require the large-scale manipulation of a wide range of chemicals, samples, and specimens. To achieve maximum efficiency, parallel control of microlitre droplets using automated techniques is essential. Electrowetting-on-dielectric (EWOD), which manipulates droplets using the imbalance of wetting on a substrate, is the most widely employed method. However, EWOD is limited in its capability to make droplets detach from the substrate (jumping), which hinders throughput and device integration. Here, we propose a novel microfluidic system based on focused ultrasound passing through a hydrophobic mesh with droplets resting on top. A phased array dynamically creates foci to manipulate droplets of up to 300 μL. This platform offers a jump height of up to 10 cm, a 27-fold improvement over conventional EWOD systems. In addition, droplets can be merged or split by pushing them against a hydrophobic knife. We demonstrate Suzuki-Miyaura cross-coupling using our platform, showing its potential for a wide range of chemical experiments. Biofouling in our system was lower than in conventional EWOD, demonstrating its high suitability for biological experiments. Focused ultrasound allows the manipulation of both solid and liquid targets. Our platform provides a foundation for the advancement of micro-robotics, additive manufacturing, and laboratory automation.

3 Conclusions

The research presented in this thesis provides a comprehensive overview of acoustic levitation and the design and optimisation of acoustic fields and their potential for different applications, such as contactless fabrication and microfluidics.

While each compiled paper comprises its conclusion section, the contributions achieved by each piece are summarized here.

Generating Airborne Ultrasonic Amplitude Patterns Using an Open Hardware Phased Array. Presented in section 2.1.

- A novel iterative algorithm that calculates the emissions phases and amplitudes for an array of emitters has been described to generate a desired target amplitude field. To our knowledge, the present study is the first to report an algorithm capable of determining the amplitude and emission phases for discrete arrays composed of finite size emitters.

- It has been demonstrated that, depending on the application requirements, there is no need to use expensive hardware or that the computation can be accelerated by discretising the solution domain.

- An open and affordable FPGA-based hardware platform has been presented. Two models for the array of emitters (with Surface Mounted and with Through-hole components) have been introduced to facilitate customisation for experimental requirements from researchers of varying disciplines.

- These software and hardware contributions will enable researchers to build their own ultrasonic arrays and explore novel applications of ultrasonic holograms. Several research works already use these devices and algorithms to bring further their investigation [63, 68, 69, 95, 134, 154, 156, 177, 198, 247].

LeviPrint: Contactless Fabrication using Full Acoustic Trapping of Elongated Parts. Presented in section 2.2.

- Four trapping methods for sticks have been compared in terms of Gor'kov potential, force and positional stiffness and, more importantly, in terms of torque and rotational stiffness.

- An optimum acoustic field to trap elongated parts is shown.
- An study has been performed on the capabilities of different levitators to allow the dynamic manipulation of sticks by changing the emission phases.
- A levitator integrated with a robotic arm has been prototyped to enable the contactless fabrication of complex objects.
- Contactless fabrication of complex objects has been showcased using particles, sticks and UV resin. The capability of joining sticks forming basic joints, the addition on top of other objects and the building inside containers are also ground-breaking contributions of *LeviPrint*.

Enhanced Spatial Resolution of Amplitude Patterns using Time-Multiplexed Virtual Acoustic Fields. Presented in section 2.3.

- Two different multiplexation techniques have been proposed to improve the resolution of the final obtained acoustic pressure fields: Spatial Multiplexation and Time Multiplexation.
- Two different array arrangements (flat and circular) have been tested when applying non-linear optimisation algorithms to optimise their phases by decomposing a target amplitude field into multiple fields.
- Simulations and experimental scans have been conducted to prove that the proposed techniques improve the spatial resolution without hardware modifications, showing the potential to significantly improve current acoustic bioprinting and patterning, ultrasonic haptic devices and ultrasonic medical treatments.

Microfluidic platform using focused ultrasound passing through hydrophobic meshes with jump availability. Presented in section 2.4.

- A 3D digital microfluidics system is proposed based on focused ultrasound through a hydrophobic mesh.
- The proposed device's fundamental horizontal/vertical manipulation capabilities and operations, such as merging and splitting, are demonstrated using a hydrophobic knife.
- A new approach that can handle a large number of liquid droplets of different sizes ($> 40\mu L$) is proposed.

- Liquid droplets are propelled into mid-air, reaching up to 10.9cm (27 times greater than what is possible in EWOD systems). This manipulation technique generates less surface contamination than EWOD.

- This project presents four proofs-of-concept that highlight the potential applicability of the proposed device in multiple fields: Chemical Reactions, surface cleaning, AR for HCI and three-dimensional jumping into a cup.

- When compared to traditional techniques, this method's superior three-dimensional capabilities, power, parallelism and ease of use can be applied in laboratory environments, diagnostics and industry, paving the way for the development of microrobotics, additive manufacturing, and laboratory automation.

Hopefully, the results presented here will continue to facilitate the development of future designs of acoustic fields and their applications on acoustic levitation.

Additionally, in section 5, the reader will find future work ideas based on the design and use of acoustic fields. These will serve as further examples of how the compiled papers' contributions widen the perspective and the scope of the author's knowledge within the acoustics research field. Moreover, additional research ideas will also be disclosed, showing how my passions and points of view towards research have also grown and widened as a result of writing this thesis and the collaborations held during its development.

4 Conclusiones

Esta tesis ofrece una visión global de la levitación acústica y del diseño y optimización de campos acústicos y su potencial para distintas aplicaciones, como la fabricación sin contacto y la microfluídica.

Aunque cada trabajo recopilado comprende su sección de conclusiones, se resumen aquí las aportaciones realizadas por cada uno de ellos.

Generating Airborne Ultrasonic Amplitude Patterns Using an Open Hardware Phased Array. Presentado en la sección 2.1.

- Se ha descrito un novedoso algoritmo iterativo que calcula las fases y amplitudes de emisión de un array de emisores para generar un campo de amplitud objetivo deseado. Hasta donde sabemos, el presente estudio es el primero en reportar un algoritmo capaz de determinar la amplitud y las fases de emisión para arrays discretos compuestos por emisores de tamaño finito.

- Se ha demostrado que, dependiendo de los requisitos de la aplicación, no es necesario utilizar hardware costoso o que el cálculo puede acelerarse discretizando el dominio de soluciones.

- Se ha presentado una plataforma de hardware abierta y asequible basada en FPGA. Se han introducido dos modelos para la matriz de emisores (mediante componentes *Surface mounted* y mediante componentes *Through-hole*) para facilitar la personalización según los requisitos experimentales de las personas investigadoras de distintas disciplinas.

- Estas aportaciones de software y hardware permitirán a las personas investigadoras construir sus propios arrays de ultrasonido y explorar nuevas aplicaciones de los hologramas ultrasónicos. Varios trabajos científicos han hecho uso ya de estos dispositivos y algoritmos para profundizar en su investigación [63, 68, 69, 95, 134, 154, 156, 177, 198, 247].

LeviPrint: Contactless Fabrication using Full Acoustic Trapping of Elongated Parts. Presentado en la sección 2.2.

- Se han comparado cuatro métodos de atrapamiento para elementos elongados en términos de potencial de Gor'kov, fuerza y rigidez posicional y, lo que es más importante, en términos de torsión y rigidez rotacional.
- Se ha mostrado un campo acústico óptimo para atrapar piezas alargadas.
- Se ha realizado un estudio sobre las capacidades de diferentes levitadores para permitir la manipulación dinámica de palos cambiando las fases de emisión.
- Se ha prototipado un levitador integrado con un brazo robótico para permitir la fabricación sin contacto de objetos complejos.
- Se ha mostrado la fabricación sin contacto de objetos complejos utilizando partículas, varillas y resina UV. La capacidad de unir palos formando uniones básicas, la adición sobre otros objetos y la construcción en el interior de contenedores son también aportaciones pioneras de *LeviPrint*.

Enhanced Spatial Resolution of Amplitude Patterns using Time-Multiplexed Virtual Acoustic Fields. Presentado en la sección 2.3.

- Se han propuesto dos técnicas de multiplexación diferentes para mejorar la resolución de los campos de presión acústica: Multiplexación Espacial y Multiplexación Temporal.
- Se han testado dos disposiciones diferentes de array (plano y circular) al aplicar algoritmos de optimización no lineal para optimizar sus fases descomponiendo un campo de amplitud objetivo en múltiples campos.
- Se han realizado simulaciones y exploraciones experimentales para demostrar que las técnicas propuestas mejoran la resolución espacial sin modificaciones de hardware, mostrando el potencial de la propuesta para mejorar significativamente la bioimpresión, el diseño de patrones acústicos, los dispositivos hápticos ultrasónicos y los tratamientos médicos ultrasónicos.

Microfluidic platform using focused ultrasound passing through hydrophobic meshes with jump availability. Presentado en la sección 2.4.

- Se propone un sistema de microfluídica 3D basado en ultrasonidos focalizados a través de una malla hidrofóbica.
- Las capacidades y operaciones fundamentales de manipulación horizontal/vertical del dispositivo propuesto, como la fusión y la división, se demuestran utilizando una cuchilla hidrofóbica.

- Se propone un nuevo método que permite manipular un gran número de gotas de líquido de diferentes tamaños ($> 40 \mu L$).
- Las gotas de líquido se propulsan en el aire, alcanzando hasta 10,9 cm (27 veces más de lo que permiten los sistemas EWOD). Esta técnica de manipulación genera menos contaminación superficial que los sistemas EWOD.
- Este proyecto presenta cuatro aplicaciones *proof-of-concept* enfatizando el potencial del dispositivo propuesto en múltiples campos: Reacciones químicas, limpieza de superficies, AR para HCI y salto tridimensional en una taza.
- En comparación con las técnicas tradicionales, este método muestra capacidades tridimensionales superiores, su potencia, paralelismo y facilidad de uso pueden aplicarse en entornos de laboratorio, diagnóstico e industria, facilitando el desarrollo de la microrobótica, la fabricación aditiva y la automatización de laboratorios.

Espero que los resultados aquí presentados sigan facilitando el desarrollo de futuros diseños de campos acústicos y sus aplicaciones en levitación acústica.

Además, en la sección 5, el lector encontrará ideas de futuros trabajos basados en el diseño y uso de campos acústicos. Estos servirán como ejemplos adicionales de cómo las contribuciones de los artículos recopilados amplían la perspectiva y el alcance del conocimiento del autor dentro del campo de la investigación acústica. Además, también se darán a conocer ideas de investigación adicionales, mostrando cómo mis pasiones y puntos de vista hacia la investigación también han crecido y se han visto ampliado como resultado de la redacción de esta tesis y de las colaboraciones mantenidas durante su desarrollo.

5 Future Work

The current thesis has explored a range of topics related to the design of acoustic fields and has provided a comprehensive overview of the current state of knowledge and research. However, there are still many questions that remain unanswered, and future research should be conducted. Section "5.1 Further Research on Acoustic Fields" will discuss the potential avenues for future work that could be pursued to expand the current understanding of acoustic fields and build upon the knowledge presented in this study.

Other ideas, concerns and interests have been harvested during this PhD due to exploration and collaboration. Section "5.2 Other Research Projects" will cover all the other ideas the author considers worth exploring. These ideas are unrelated to the field of acoustic fields but are directly related to haptics and human-computer interaction.

5.1 Further Research on Acoustic Fields

Each paper presented in this compendium thesis presents its own *discussion* section. The reader is invited to re-check those sections to learn more about specific future work from each research project.

This section will list the essential future work proposals and explore other ideas related to the design and applications of acoustic fields.

5.1.1 Future work on "Generating Airborne Ultrasonic Amplitude Patterns Using an Open Hardware Phased Array"

One of this project's main goals was to offer an open DIY alternative to commercial phased arrays to enable researchers to build their own ultrasonic arrays and explore novel applications of ultrasonic holograms. Therefore, most proposed developments follow this path, developing further the device's capabilities and flexibility.

Using two frequency modulation (2FM) is an alternative and novel method to generate a modulated focal point that is haptically perceivable to the skin receptors [156]. The 2FM technique is based on the sum of two waves with nearby but different carrier frequencies $f_1 = f_c + \delta f$

and $f_2 = f_c - \delta f$. When these two carriers interfere, a "beat frequency" effect develops, producing the frequency $f_{beat} = |f_1 - f_2| = 2\delta f$. Including 2FM algorithms in *SonicSurface* would make the device more suitable for projects working on haptics.

Several sounds, such as clicks and beeps, or even voice and music, could be generated using parametric audio modulation techniques to modulate an audio signal to produce directional audio at a minimal cost. SonicSurface should be able to produce enough acoustic pressure to generate parametric audio, which starts to occur at approximately 135 dB PSP. It could act as a small speaker by modulating the transducers with an audio signal (either with amplitude modulation or a more sophisticated single-sideband technique).

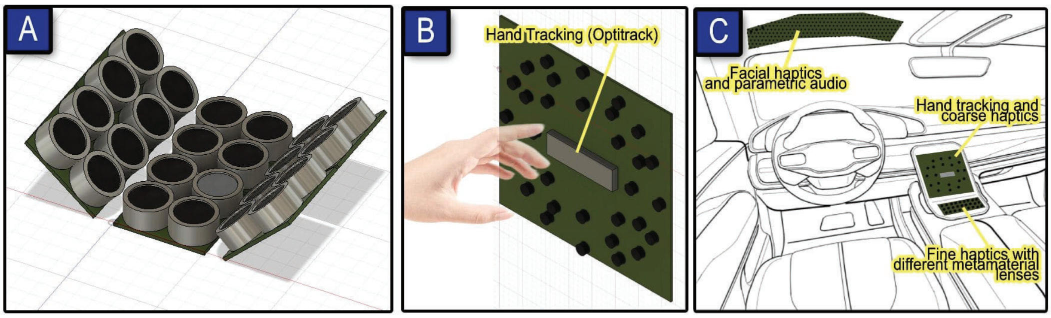

Figure 5.1: A) Six 2x2 tiles assembled into a non-flat arrangement. B) Module focused on sensing, hand-tracking and haptics. Similar to UltraButton [156]. C) Conceptualization of an ecosystem of modules used inside a car.

Hardware-wise several additions and changes could be made towards a flexible ecosystem of modular boards with different capabilities to be combined, satisfying different requirements:

- Design small 2x2 tiles, easier to assemble in non-flat shapes.
- Create different modules with different capabilities. Some modules would focus on sensing or hand tracking. Others would be focused on haptics, parametric audio, or underwater functioning.
- Prepare the modules to communicate through wireless protocols such as WIFI, LORA or Bluetooth.
- Batteries to make them portable.
- Explore the use of metamaterials as lenses to deliver complex patterns [148]. This may also enable the creation of small focal points that are impossible to create with the default array.

The combination of multiple ultrasound devices and robotic actuation for large-area mid-air haptics for VR has been already conceptualized [53]. In our future work, each small array would enable exploitation on its own but together could pave the way towards a future of "swarm" arrays.

5.1.2 Future work on "LeviPrint: Contactless Fabrication using Full Acoustic Trapping of Elongated Parts"

Leviprint has showcased the levitation of elongated elements. A straightforward next step would be the exploration of other primitives and geometries. The Traps at Sides method does not directly apply to anything but sticks, so the Minimum Potential method should be employed. While the Traps at Sides method can be used in real-time, our current approach for the Minimum Potential method requires some time and computational resources, hindering its real-time application. Therefore, alternatives to our current optimization methods should be explored, such as using Adam [105] or Diff-PAT [63] optimizers.

Given that the fabricated structures are made of thin segments such as sticks, beads or cured glue, the fabricated object does not cause a significant disruption on the acoustic field since its "fill rate" is quite low (i.e., it is like a wireframe object). However, if complete solid objects were manufactured, we foresee two strategies that should be followed. First, the order in which the parts are added should be planned so that they approach the object from an operative angle that does not significantly block the ultrasound emitted from the arrays. In future work, it would also be possible to consider reflections caused by the object. This path of action would be leveraged on recent works on acoustic holography with arbitrary scattering objects [84].

Decreasing the frequency to work with larger objects is not a feasible research direction; however, operating in water-based media at MHz range could enable biofabrication in cell-friendly cultures or even in-vivo. Although our lab lacks the expertise and the instrumental required for this research, it could be exciting to collaborate with another team willing to explore the potential biomedicine applications of Leviprint further.

5.1.3 Future work on "Enhanced Spatial Resolution of Amplitude Patterns using Time-Multiplexed Virtual Acoustic Fields"

This project has proven that multiple averaged amplitude fields generated with phased-arrays have more spatial resolution than a single emission field. To achieve that, simulations have been performed, and experimental scans of amplitude fields and projections of thermal patterns have been captured on different devices using time-multiplexed virtual acoustic fields. Spatial multiplexation is also proposed in this work. Spatial-multiplexation can be employed in a similar way to time-multiplexation for increasing the resolution. It would consist in rotating or moving the arrays as they emit different patterns on each position. In our simulations, both time- and spatial-multiplexation obtained similar improvements. Therefore, we conducted the experiments with time-multiplexation. Time-multiplexation is easier to implement since the arrays do not need to be moved or rotated therefore not requiring modifications in the hardware. However, exploring further spatial-multiplexation remains an interesting path to develop further these multiplexing techniques.

Additionally, applying these multiplexing techniques to 3D fields is yet to be explored. Other array topologies might be needed to accomplish 3D multiplexed-fields or, at least, the strategical arrangement of several 2D phased-arrays would be needed.

5.1.4 Future work on "Microfluidic platform using focused ultrasound passing through hydrophobic meshes with jump availability"

Pan et al. [176] demonstrated a superomniphobic mesh coating method that can repel a wider range of chemicals, including DMF and toluene. The mesh used by Pan et al. was less dense than that used in our study. Thus, employing a superomniphobic mesh in acoustic needles would yield a high-performance microfluidic platform in terms of the acoustic force that passes through the mesh and the supported compounds.

Additionally, we would like to explore other techniques to have more control over the trajectory of the ejected droplet or to split liquids into desired proportions without the use of a hydrophobic knife.

We are also kind about exploring the use of UV resins. Exciting the UV droplets with exotic acoustic fields would shape them to later be solidified under UV light. This could be a significant progress also in contactless additive manufacturing.

5.1.5 HaptID: Mid-air Tactile Authentication System Resilient to Shoulder-surfing Attacks

HaptID is not an evolution of any of the compiled papers for this thesis. It is a new application for ultrasound haptics that I would like to explore.

The need for secure authentication methods has become increasingly important as the ubiquitous use of online services continues to grow. Authentication is the process of verifying the identity of a user to secure access to both physical and digital resources. Authentication methods must be reliable, secure, and easy to use.

It is said that for an authentication method to be considered secure, it must combine at least two of the following [118]:

- **Something you are:** Where the user uses biometrics methods to get access control, such as fingerprints, iris scans or voice analysis.

- **Something you know:** The most common factor used, based on the user's knowledge, such as remembering a password or a PIN.

- **Something you have:** Refers to items or tokens such as smart cards or a specific device (USB key or smartphone) that the users have to physically own or have access to.

HaptID stays in a blurry frontier between the three aforementioned items.

A survey of over 500 U.K. and U.S. consumers conducted by Ultraleap was performed to assess Post-COVID-19 attitudes to touchscreens and touchless technology in interactive kiosks, and digital out-of-home [223]. Touchless interfaces could soon be present in most important public locations such as transport stations, hospitals, ATMs, restaurants, shopping malls, public restrooms, cinemas and museums. Traditional password-based authentication methods would be extremely vulnerable in these contexts.

From traditional handwritten signatures to nowadays relevant real-time facial recognition, several alternatives have been proposed to avoid identity spoofing, although most popular authentication methods as passwords or pin input, rely on visuals, enabling a malicious agent to observe and capture the interaction for posterior spoofing attempts. Besides, mid-air interactions are becoming increasingly common due to being more hygienic, removing mechanical parts, and facilitating the come-and-interact paradigm. We propose HaptID, an authentication system that provides the user tactile mid-air feedback questions; to authenticate himself, the user must recognise the stimuli and provide a previously defined hand gesture as an answer. HaptID would be robust against password stealing since only the user feels the hand part indicated by the system, and only he/she knows the associated gesture. In a first evaluation, we would analyse the ease of remembering the different gestures. Then, task completion time, success-error rate, recollection, subjective workload, and visual observation resilience would be analysed to compare this method with a traditional code method. HaptID passwords would be harder to remember, but with enough practice, they would be similarly difficult to traditional codes. This system could introduce codes in mid-air systems as a safe and hygienic alternative.

An explanatory diagram of how the authentication process would work with HaptID is shown in figure 5.2.

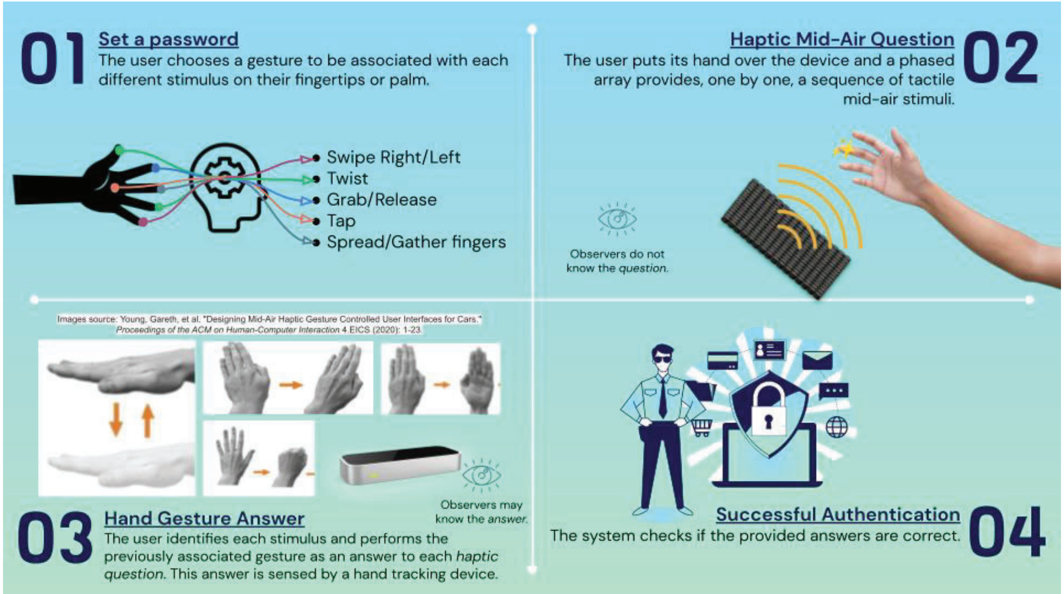

Figure 5.2: Concept diagram of HaptID authentication system.

Implementing HaptID would raise some questions that could be assessed through user studies and experiments. These studies would aim to find the optimum number of parts of the hand and gestures to map as options for users to choose their passwords. HaptID could be compared with a regular keypad to compare its efficacy and efficiency. Task Completion Time, accuracy, recall rate and Subjective Workload (NASA TLX or alternative) would be valuable metrics to gather. Additionally, it would be interesting to study two different implementation approaches for HaptID. The first one is closer to traditional PIN keypads, in which each finger would be mapped to a number chosen by the user; in this case, the user should recall this mapping and move each finger to give its answers. A second approach is where the user would have total freedom to design their gestures without mapping specific fingers to numbers.

Moreover, it could be especially interesting to answer the following questions:

- What is the ultrasound-haptic-gesture equivalent of password "12345"? Is there a specific gesture that humans commonly give as an answer to certain haptic stimuli?
- What happens when the user wants to change the HaptID password? Are the gestural answers so rigid that updating them is unfeasible, rendering them unusable for long-term authentication systems?
- Can regular audio recording break HaptID security?

As a starting point, I suggest reading the complete review of natural user interaction for authentication conducted by Sae-Bae et al. in 2019 [193] and the paper from Abdrabou et al., also published in 2019, exploring the use of gaze and gestures for shoulder-surfing resilient authentication [3]. Additionally, it would be of particular interest to examine the tactile password system proposed by Bianchi et al. in 2010 [25]. This system proposes a uni-modal haptic password method based on randomized vibration patterns.

5.2 Other Research Projects

This section will provide the opportunity to expose some of my additional interests acquired during the development of this thesis and to explore a variety of different project ideas that may be beneficial for my research career. These proposals have no association with the realm of acoustics but are linked to haptics and human-computer interaction.

5.2.1 Volumetric Displays

5.2.1.1 RealityPiercer: A Retractible Tool for Simulated Direct Interaction with Enclosed Volumetric Content and Between Realities

Volumetric displays can render True-3D graphics that provide enhanced depth perception without forcing the users to wear any device. On the other hand, direct interaction is a widespread natural way of interacting with touch screens, where we directly press a button or drag an icon; that is, the input and output spaces are aligned. However, no volumetric display supports direct interaction with the content.

RealityPiercer would be a pen-like or dagger-like tool that gives the illusion of reaching into the virtual content for an emulated direct interaction. A retractile pen is pushed against the display boundary, and the part that gets retracted is rendered inside the display, giving the illusion that the tool is reaching inside. Several works have explored this concept on 2D screens [125, 131, 160, 243], but it has never been realized in volumetric displays.

The primary interaction is to pierce into the volume with the tool to select and manipulate (rotate and translate) the 3D objects that are inside. After understanding how users operate and would like to operate the device, we could suggest higher-order applications such as volumetric data visualization or collaborative tasks [72].

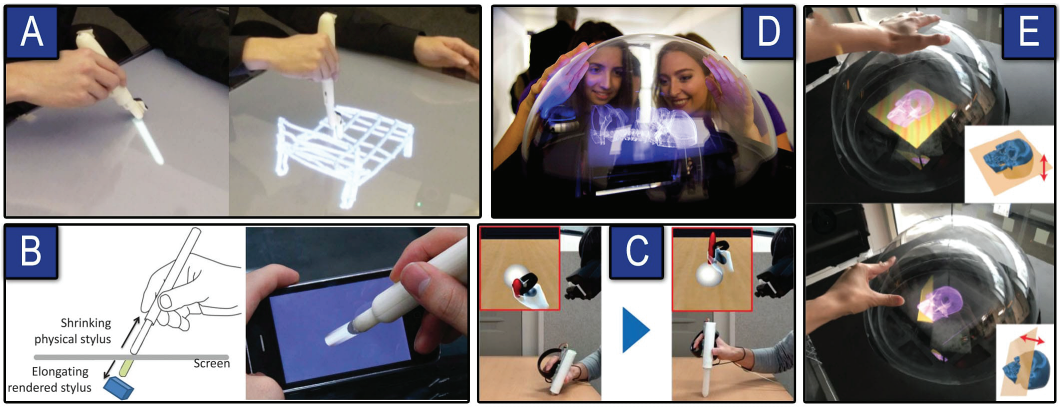

Figure 5.3: A) *Beyond* stylus used to 3D sketch inside a table. Extracted from [125]. B) *ImpAct* stylus concept and realization on a smartphone screen. Extracted from [243]. C) A stylus prototype able to provide force feedback to the user's arm for VR applications. Extracted from [98]. D) *Voxon Photonics VX1* volumetric display with its dome-shaped enclosure. Extracted from [229]. E) *InDepth* force-based interaction with volumetric content rendered in a Voxon VX1. Extracted from [251].

With *RealityPiercer*, we would like to explore the following aspects:

- **Comparison with other interaction techniques:** Compare it with other non-direct volumetric selection techniques [73], through user studies measuring TCT on docking tasks [230], or virtual assembly and 3D modelling [43].
- **Enhancing the users' capabilities without breaking the illusion of direct interaction:** The virtual part that pierces into the virtual world could be made longer than the real one, allowing the user to reach further and perform specific actions undo-able in a real-life scenario. How much can the virtual part be extended without breaking the illusion of direct interaction? Moreover, how can we augment the device capabilities with virtual end-effectors such as tweezers, blowers or syringes that only exist in the virtual world?
- **Grabbing methods:** Different applications and end-effectors will raise the question of which will be the preferred grabbing method by the users. A person applies different handles to use a fork, a pen, a broom or a syringe. Although several research works have already studied the prehensile movements of the human hand [161], identifying the most common handling techniques for interaction with volumetric content will be crucial to design *RealityPiercer* and its applications.
- **Bimanual interaction:** Grossman et al. did explore multi-finger gestural interaction with volumetric displays [74], and some bi-manual interaction techniques have already been explored with VR content [117]. Nevertheless, exploring the bi-manual interaction with vol-

umetric 3D content using *RealityPiercer* could open opportunities for novel volumetric selection and manipulation techniques.

- **Shaping the frontiers** *RealityPiercer* exploits the existing protective domes on volumetric displays that are based on fast-moving pieces. These surfaces will define the boundary between the real and the volumetric world while acting as an anchor to pivot pull-push forces. Volumetric displays, such as the Voxon Photonics VX1 [229], are usually covered by a transparent spherical dome. We hypothesize that some shapes of enclosures may be more appropriate for different applications. A cubical/prism enclosure may be optimal for data visualización or 3-dimensional selection techniques; a pyramidal one may be useful for collaborative tasks; and a cylindrical one may suit applications in which lateral visibility is required, and most of the interactions are vertical, as in museum's cabinets and store's display cases.

- **Haptics and forces acting on the users' hand:** To provide a more realistic illusion, an active version of *RealityPiercer* would offer resistance to piercing when the tip encounters an object inside the volume. The literature shows that haptic sensations have already been embedded in stylus-like devices to interact with 2D content [131, 160, 243]; exploring the perception of stiffness or texture by using vibrations [37]. How would these strategies be applied to volumetric content? Haptic stimuli may be straightforward when *piercing* orthogonally to the surface of the volumetric display, but what about sweeping or sliding movements? To create controlled friction, we suggest using an additional retractable rubber tip that could be moved in/out to modulate resistance when sliding the tip over the surface. Different frequency vibrations could also be explored to customize the resistance provided for these sliding movements. Electronic friction or electro adhesion [50, 199] and vacuum suction [92] are promissing candidates to be explored as methods to *suck* the device into the volumetric display, as a resisting force that pulls from the user's hand.

- **Piercing multiple realities:** RealityPiercer will be a portable device, so making it capable of directly interacting with different displays would be interesting. From traditional 2D screens to VR/AR/XR on binocular headsets and volumetric displays. Imagine editing a 3D mesh on your laptop, but traditional mouse and keyboard interaction do not fulfil your design needs, so you grab RealityPiercer and introduce it into your 2D screen; you directly manipulate the object, and you rotate, transform or carve it. Later, to give it a better look, you pinch the object and put the VR glasses on, and the object is there to manipulate. Afterwards, you want to discuss something about your design with several workmates, so one more time, you pinch it and drop it into the volume of a volumetric display. Here, you and your team start using several RealityPiercers to collaborate on further modifications to the

3D model. Exploring this pipeline of events between different realities could be fascinating. *RealityPiercer* could even pierce actual reality by using a pico-projector to project contents on regular surfaces such as walls, whiteboards or tables while directly interacting with or *piercing* them.

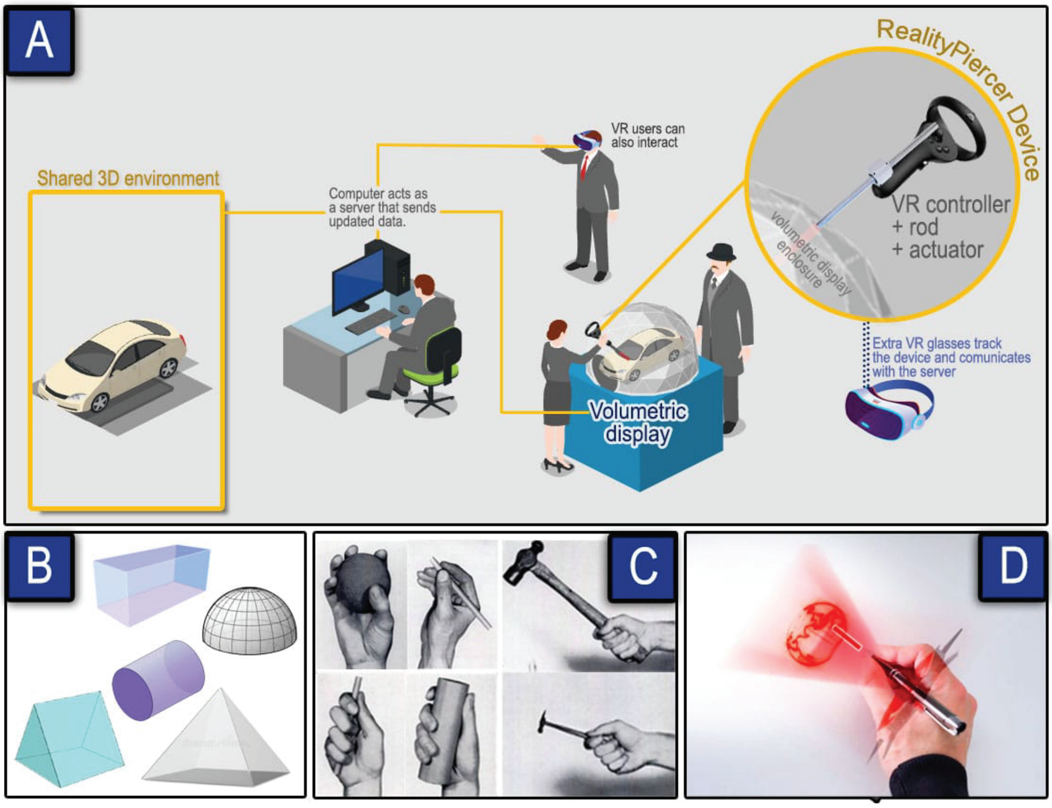

Figure 5.4: A) Working diagram of a first prototype for RealityPiercer. B) Different shapes to test as working volume enclosures. Different shapes favor different interactions. C) Power and precision grip postures. Extracted from [161]. D) Concept image of a pico projector attached to a RealityPiercer enabling the user to pierce into a wall.

5.2.1.2 Intevol: Interactions with Future Reach-Through Volumetric Displays

Displays in the shape of televisions, computer screens or phones are ever present in our education, work and entertainment. However, they do not take full advantage of our inner spatial abilities that we have to interact with the real world. True 3D displays can provide the same visual clues as the real world without forcing the users to wear devices. However, with State of the art (SoA) displays, users cannot reach inside the display volume to directly interact with the virtual objects as they would in real life. We envision a volumetric display capable of projecting true 3D virtual objects in mid-air that can be reached by the users to enable direct interaction, i.e. a reach-through volumetric display (RVD). This vision has been presented in multiple movies and books, but there has yet to be a realisation.

Three novel technologies will be developed and combined to create an RVD.

- Fast time-multiplexed acoustic fields will create virtual force fields that give shape to micro-fabricated light-scattering particles.
- Tomographic illumination will shine on the particles as a more scalable alternative to phase-based holographic.
- Volumetric tracking of the distribution of the particles will control the previous technologies in a closed-loop manner. Applications will serve as benchmarks to test novel interaction techniques and develop a framework that fills the knowledge gap for interactions with as-yet nonexistent RVDs.

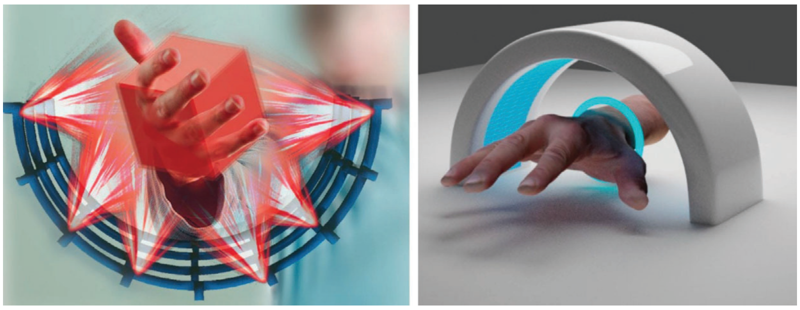

Figure 5.5: Concept of a volumetric display with Reach-through capabilities. True 3D virtual graphics can be reached to and even intertwined with existing real entities.

The *InteVol* project will have three main objectives:

- Find and develop a set of technologies that enables the realisation of Reach-through volumetric displays (RVDs) with a unique combination of acoustic force fields, microfabrication tomographic illumination and volume tracking.
- Develop novel interaction techniques for RVDs and analyse them with a new framework that will be applicable to other kinds of future displays. These interactions will be powered by machine learning, gesture recognition and natural language processing to enable a more natural and intuitive way of interacting and creating the objects rendered by RVDs.
- Analyse the effects of interacting with RVDs on our perception of virtual entities or reality. Add tactile and sound rendering capabilities to a visual RVD.

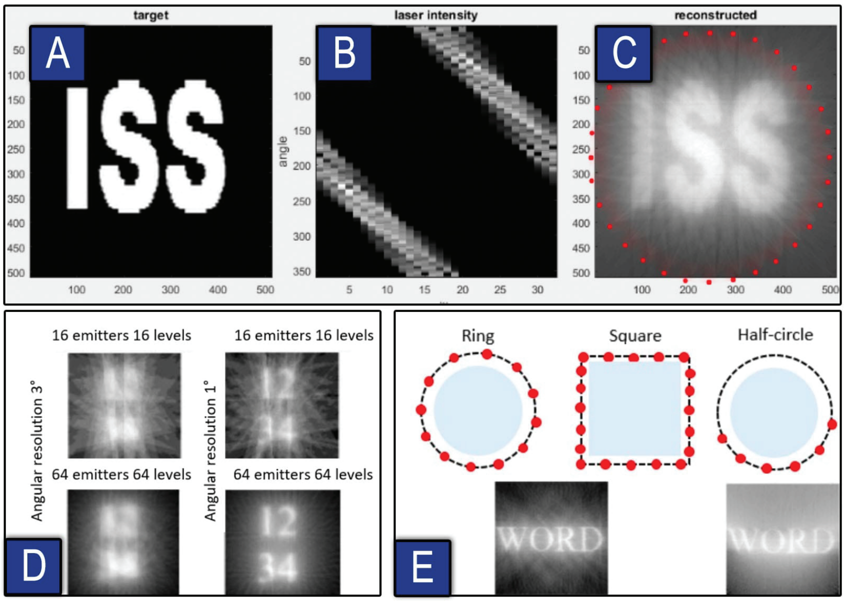

Figure 5.6: The principle behind tomographic illumination. A) A target image. B)Using a fan transformation of the Radon transform, the Cartesian image is transformed into intensities for each angle of emitters placed around the image. C) The projected 2D image where the red dots are the 1D emitters, a logarithmic mapping has been applied to model human perception of light, which is why the reconstructed image is not perceived as a sharp image. D) Projected images for different numbers of emitters, angular resolution and levels of intensity. E) Emitters geometries, it must be noted that a half-circle still projects recognizable images and would allow better access to the display and more robustness against the occlusions from the hand or other objects.

Realising this reach-through volumetric display will require a new set of technologies. We need a system capable of calculating in real time the acoustic field generated inside the display volume, even when complex reflective geometries are inside, like hands or physical objects. The particles must be levitated and controlled at ballistic speeds (>9 m/s) around and inside complex objects. More ambitiously, an alternative will be to generate an intricate 3D force field to sculpt the 3D graphics in the levitated particles that scatter visible light. This idea es portrayed in Figure 5.7. Two-photon 3d-printing microfabrication of the scatterers may be required. Internal structures of lattices would make them lighter than aerogel while being acoustically reflective so that we can manipulate them with sound. Inverse tomography would project light into the display volume, where the particles' scattered light would form a 3D image. See figure 5.6. Additionally, the distribution of the particles will be tracked in 3D by a scanning sheet of infrared light captured by a high-speed camera.

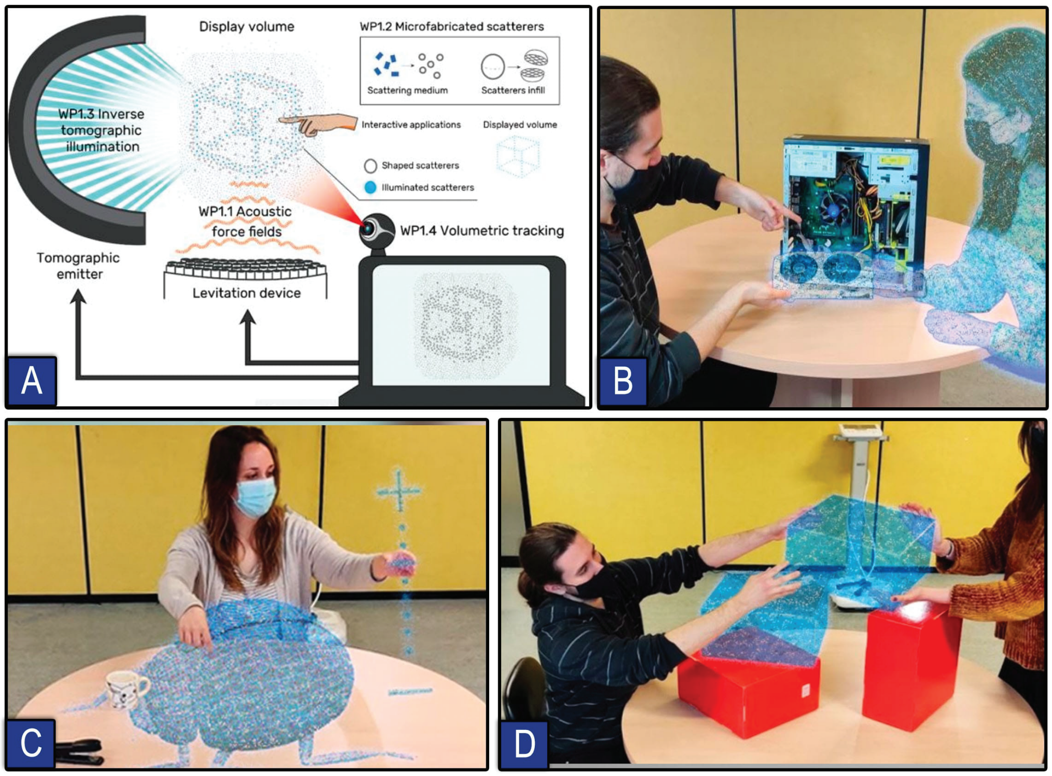

Figure 5.7: A) Integration of the technologies employed for creating an RVD. Light-scattering particles are floating inside the display volume. The acoustic force fields emitted from a phased array will dynamically shape these scatterers into the approximate shape of the rendered 3D objects. The scatterers will be microfabricated to have minimum weight and controlled light reflection characteristics. Tomographic Illumination will be used to project the fine details on the pre-shaped scatterers. A volumetric tracker composed of a high-speed camera and a scanning infrared light-sheet will obtain the scatterers' distribution to control in a close-loop manner the acoustic force fields and the illumination. B) A person receiving instructions from a remote user about how to install a graphic card, note that they do not wear any device. C) A user employs direct interaction with her left hand to control a 3D gizmo whereas with her right hand selects in which part of a virtual object this should take effect. D) Two users are collaborating to build a structure by manipulating virtual blocks on top of real blocks.

5.2.1.3 RevoHelix: An Affordable DIY Volumetric Display

While *Intevol* project aims to implement an actual volumetric reach-through display, RevoHelix aims to create a low-cost DIY fast-moving pieces volumetric display. It will take a stance as a cheaper and more accessible alternative to the current commercially available displays, enabling consumers and researchers to experiment and get introduced into this field.

Commercially available volumetric displays are scarce and expensive. Being Voxon VX1 [229] the most popular and available one, it costs $11,700 plus shipping.

Plasma-based and laser-based volumetric displays have also been explored in research [112, 113, 114, 171, 248]. However, they are still emerging technologies; they may be dangerous, experimental, small, insufficient, expensive, or inaccessible to the general public.

Some alternatives can be found online based on laser projection over fast-rotating helices [1, 242] or fast-rotating led matrices [222]. The first ones are constrained to rendering extruded figures, and the second is relatively limited in resolution or rotation speed. Some helical rotatory volumetric display patents have been filled too [67, 239].

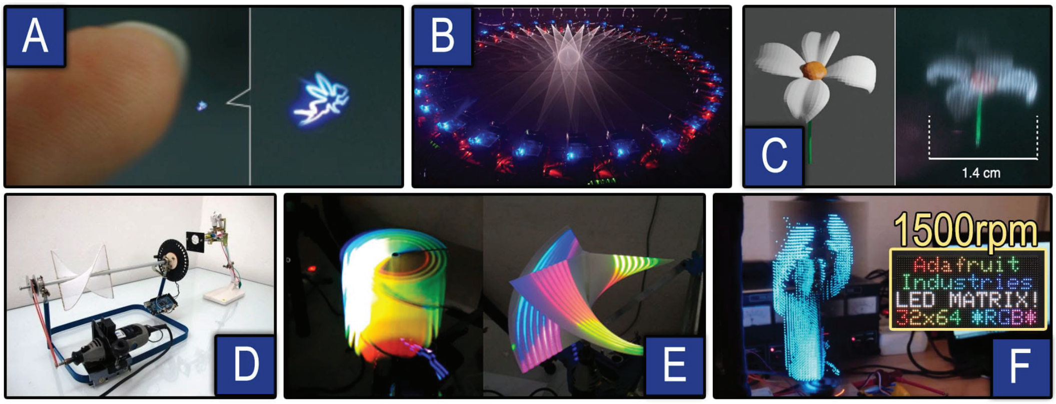

Figure 5.8: A) Aerial and volumetric graphics rendered by femtosecond lasers. Extracted from [171]. B) Inverse tomography projection of a sphere in mist. Extracted from [248]. C) Laser-excited voxels rendering a flower. Extracted from [113]. D and E) DIY helix displays based on laser projection. Extracted from [1, 242]. F) DIY composed of a 32x64 rotating led matrix. Extracted from [222].

Some research about sweep volume displays is based on ideas similar to *RevoHelix*. *FELIX 3D* [119, 120] shares the core idea of projecting over a helicoidal-shaped surface. However, a working prototype of the device has never been realised, nor code or instructions on its fabrication have been made public. Helical volumetric displays have also been proposed along retro-transmissive optics for dynamic projection mapping [107]. More recently, in 2022, invisible regions generated depending on observation angle have been examined [231].

RevoHelix would gather inspiration from all those works to offer a working inexpensive DIY volumetric display. 3D printable files and an open-source software responsible for calibrating and synchronising the projected images would be delivered.

The following aspects will be explored to provide an optimal working prototype:

- **Projection surface materials:** Check the best 3D printable materials to fabricate the projection surface. Regular thin blades of PLA or translucent PLA may be suitable. Alternatively, mix it with some reflective powder. Polishing or mirror-coating techniques could also be explored to improve the results.

- **Projection surface shape:** We note that most of the proposed helical displays consist only of one blade twisting along the 360º of the rotating axis. Dividing these 360º into more blades while maintaining rotation speed would multiply the final rendering framerate.

- **Light source:** Lasers and projectors are appropriate as light emitters. However would like to explore the use of off-the-self super-fast 240Hz or 360Hz gaming monitors as light emitters, as they are widely available and have a fantastic refresh rate while still providing a huge colour gamut.

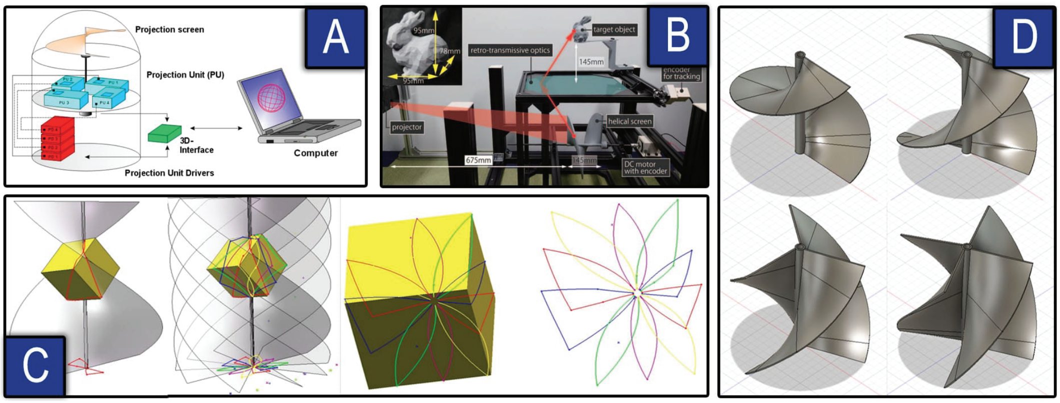

Figure 5.9: A) System architecture of the FELIX 3D Display. Extracted from [119]. B) Helical volumetric display and retro-transmissive optics combined for dynamic projection mapping. Extracted from [107]. C) Working principle of a helical rotating volumetric display. Intersection 3D curves and projected 2D images calculated each rotation 36º. Extracted from [151]. D) 3D-printable helicoids composed of one, two, three and four blades.

5.2.2 Virtual, Augmented and Mixed reality

5.2.2.1 OmniTact: Augmenting Tactile Interactions with VR Surfaces using Omnidirected Discs

OmniTact is an idea in a very early stage.

A typical way of supplying tactile feedback for virtual reality is through hand-held or wearable gadgets. However, these wearable hand-grounded devices are inherently constrained in their ability to render a world-grounded force, such as surfaces that can be touched or pushed with the user's hand. Encountered-type haptics is proposed as a substitute method to meet this requirement, providing haptic sensations through actuated physical environments by dynamically moving physical objects or altering their shape.

Examples of research exploring encountered-type haptics are: the use of servomotors and linear actuators to convey the shape being touched [87]; its more modern version mounted on omnidirectional-robots to provide both vertical and lateral kinesthetic feedback [204]; mobile shape-changing small robots [81, 212]; the use of robotic arms [16] or even drones [88] to correctly place the tangible obstacle.

Shape-changing displays often require large, heavy, and mechanically complex devices. Scaling the number of drones or small robots required for large objects is also challenging, and the opposing forces they can deliver are limited.

Figure 5.10: Examples of encountered-type haptics for VR. A) Servomotors and linear actuators. extracted from [87]. B) Robotic arm. Extracted from [16]. C) Drones. Extracted from [88]. D) Mobile robots. Extracted from [81]. E) Mobile shape-changing robots. Extracted from [204].

OmniTact goal is to provide an inexpensive tangible 2D surface for VR environments capable of presenting world-grounded forces while also rendering different textures. To achieve this, an omnidirectional conveyor table will be used to translate and rotate discs made of different materials. The users' hands will be tracked, and the appropriate required disk will be moved to the needed precision when the virtual interaction requires it. See figure 5.11. Discs can represent static passive surfaces or active moving elements. Its rotation, at different speeds, will be able to render virtually infinite-sized elements. To enrich interaction, the discs can also present controllable resistance towards the user's manipulation. Additionally, they could also be used as input devices.

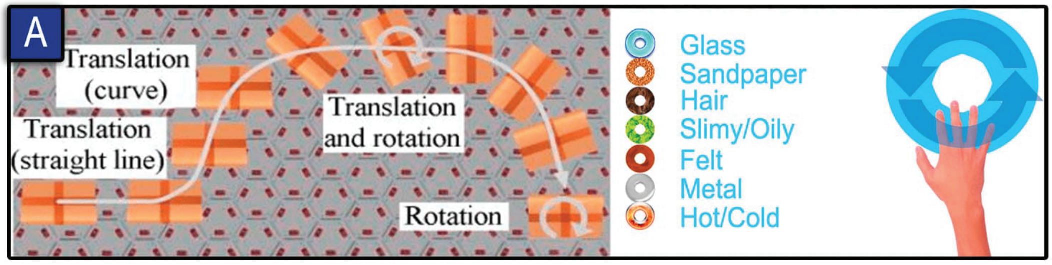

Figure 5.11: OmniTact concept. An omnidirectional conveyor table translates and rotates discs. Discs are made of different materials presenting different textures and temperatures to be touched by the user in a VR environment.

Things to be explored with *OmniTact*:

- How convincing are moving and rotating discs as dynamic tangibles?
- Exploit rotating or vibrating the discs at different speeds to convey different haptic sensations.
- What materials and textures can the discs be fabricated with to provide a wide range of options? Hair, skin, glass, plastic, sandpaper, grass, slimy, oily, felt, metal and more.
- Study also different temperatures for the discs. They could be heated/cooled down in specific places on the table.
- The discs could offer regulated resistance by locking the omnidirectional wheels in a controlled way.
- How to make it work vertically?

5.2.2.2 Virtual Chireality: Environment-based tangible surfaces for VR

This idea is just a concept in a very early stage.

With the increasing popularity of VR headsets, plenty of research has focused on adding tangibility to virtual experiences. By adding physical sensation to the experience, users can feel as if they are actually present in the virtual environment, allowing them to immerse themselves in the experience completely. As research continues to progress, virtual reality is becoming more and more realistic and is only expected to improve in the years to come.

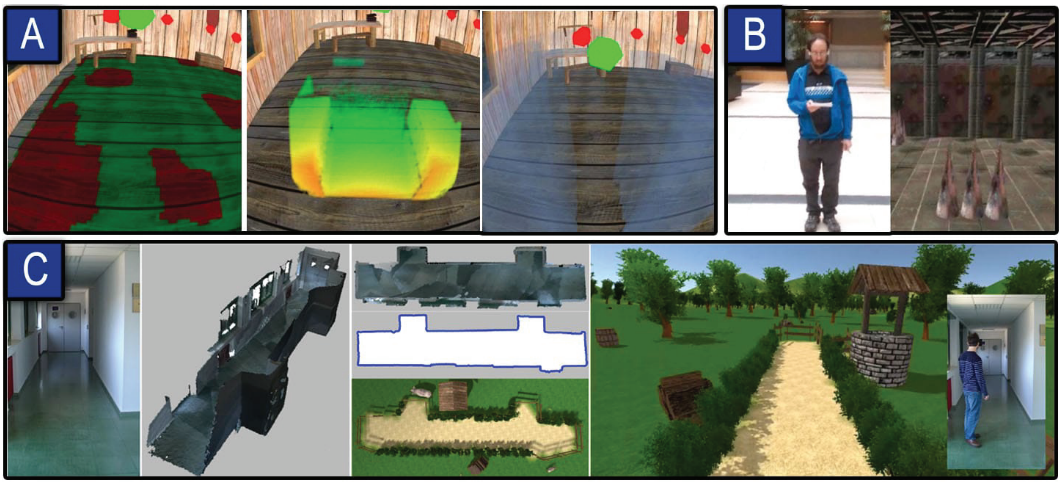

Figure 5.12: Different approaches to integrate real physical objects into virtual reality experiences. A) Semi-transparent occupancy maps overlaid on the VR environment. Extracted from [101]. B) A pedestrian being rendered as a proxy obstacle spike trap in the VR tap to avoid collisions. Extracted from [38]. C) Procedurally generated scenario to adapt its shape to the scanned real-world environment. Extracted from [206].

Different approaches can be taken to intertwine real physical elements with VR environments. Some systems opt for a mixed reality approach in which real objects are directly overlayed over the virtual content [30, 188], without a meaningful connection between them. A second approach explores a semantic connection between the physical objects and the virtual environment, embedding them inside the VR narrative, making their existence coherent within the virtual environment [39]. In these cases, objects are there to interact with them, and opposite to VR elements, they can be touched and physically interacted with. On occasions, passthrough is also used to embed visual info into the VR world [79]. A third approach can be taken, in which real-life environment elements are considered obstacles, and their presence is exploited to act as proxy elements to represent other objects in VR. This is the example of diegetic tangible objects [78], controllers designed to provide specific haptics [219], or even using the own user's hands as tangible props to interact with [179]. In this category could also fall those approaches in which the environment is scanned in search of obstacles to make the user aware of their presence. This obstacle awareness benefits those experiences where users move and roam through the environment by overlaying semitransparent occupancy maps [100, 101], or by automatically creating virtual proxy obstacles inside the VR environment [38] or procedurally generating the scenario to adapt its shape to the physical world [206].

With *VirtualChireality* we propose a novel VR movement alternative that exploits the presence and reuses the tangibility of physical obstacles and shapes present in the environment. As in many of the previously mentioned works, *VirtualChireality* will make use of RGB-D mapping [82] to obtain a virtual reconstruction of the surroundings. This environment's 3D model would then be compared with the original one extracted from the VR experience in search of similarities. After identifying those spots where virtual elements could be mapped to real physical obstacles or surfaces, the users will only be allowed to move into them. Alternatively, visual highlighting, different biased locomotion techniques or VR narratives would be proposed to encourage users to move in between and exploit those specific spots. The virtual space or the user's POV could also be imperceptibly changed between points to fit better the physical properties of the offered locations.

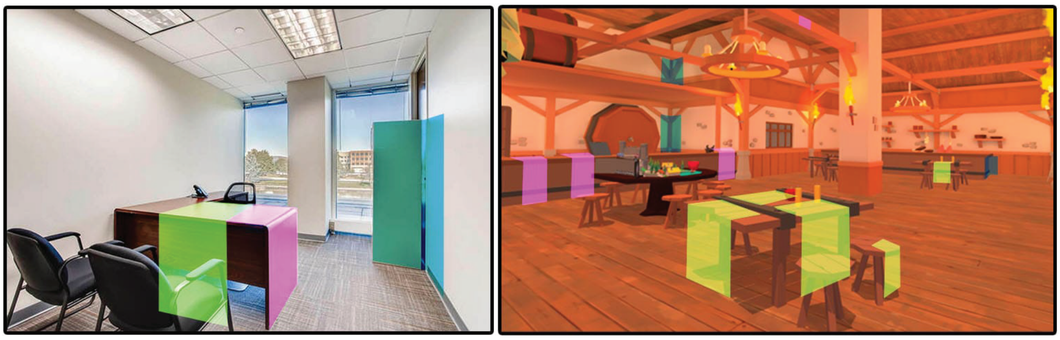

Figure 5.13: Examples of a few surfaces and shapes scanned from a regular office being mapped into different locations inside a fantasy VR tavern. Depending on the user's real-life location, it can move and interact with different virtual elements reusing the same surfaces. Note that much more shapes could be reutilised between worlds.

VirtualChirality could be used to significantly add tangibility to already existent virtual environments when used on regular home rooms, offices or labs. On top of that, rooms and spaces could be specifically designed to adapt their shapes and obstacles to the most common ones in VR experiences.

5.2.2.3 WebXRordinary: Exploring Navigation Techniques with Automatically Migrated AR/VR Websites

About 1.13 billion websites currently exist on the internet, offering an incredible amount of content to be explored. Around 43% of these sites are built using the WordPress Content Manager System. Each of these websites uses different visuals and templates to customize their users' experience, but their data and its connections rely on the same WordPress' system. Therefore, all those websites share an internal structure and taxonomies that could be exploited to adapt their visuals to different alternatives automatically.

Traditionally, websites are designed to be browsed on regular 2D screens, and innumerable amounts of work have been dedicated to studying a website's interfaces and interaction in terms of accessibility [32], usability [123], and user experience (UX) [197]. Studies have also been made to asses specific applications or areas such as websites dedicated to online banking [237], tourism [122], museums [97] or for the elderly [48].

As VR technology increases in use and popularity, we should ask how all the findings in web interfaces translate to the third dimension. Several works study the design of 3D interfaces and menus or create novel interaction techniques with them [91, 124, 152, 180]. However, these research works focus on designing and creating new experiences, often overlooking the adaptation of already existing content. *WebXRordinary* proposes the automatic adaptation of already existing WordPress-based content into 3D navigable environments. Several adaptation techniques will be proposed and evaluated regarding usability, accessibility and mental workload.

- **Point&Click with floating 2D interfaces.** This is the most direct translation from traditional 2D interfaces. The original website is rendered as a 2D floating surface, and the user can point and click anywhere to interact and navigate. Controllers with raycasting or direct hand interaction could be proposed. As it is very similar to what users already know about web browsing, this technique would be easy to learn. However, it does not exploit the possibilities of three-dimensional spaces, and we expect little to no improvement in the users' perceived usability, accessibility and UX.

- **Website as a building**. Humans are naturally adapted to navigate through 3D spaces. Visualizations of familiar spatial environments can enhance the recall of information; this strategy for memory enhancement is known as the method of loci [168]. We propose to adapt websites into 3D museum-like arranged digital tweens. Different data hierarchy levels would be adapted into different floors, rooms or art pieces. The user would roam through the website as in a real museum. Virtual spaces are not constrained to euclidean spaces and real-life restrictions; size limitations and space continuity could be ignored to explore further the wandering navigation of automatically adapted websites. We hypothesize that this technique would significantly improve the user's perception of its location and the understanding of the hierarchy levels used to categorize the website information.

- **The Matrix Armory technique**. Inspired by the famous armoury scene of the movie *The Matrix* this technique proposes the opposite of what the building one does. In this case, the users stay stationary, and the 3D representations of different web pages approach linger and go away. The user can interact with some of them before letting them go. This interaction technique may be of special interest to social media, news or e-commerce websites to improve engagement, pages visited per session and session duration.

- **Galaxies and Constellations**. Inspired by constellations and based on graph visualization, this method will create a 3D graph [226] in which the nodes are the web pages, and the lines between them are the links to travel from one node to another. Node's sizes and shapes may convey the importance and link's aesthetics may convey information on how related is the next node. The user will have a first impression of the website's size, the clustered web pages and how it all connects. Then, they can start travelling and browsing the constellation from a first-person view. This 3D twin could be especially interesting for online encyclopedias and wikis, in which data exploration, general perspective, connections, relations and hierarchy may play an important role.

These techniques, and others, should be feasible to implement for VR experiences by using WebXR [2].

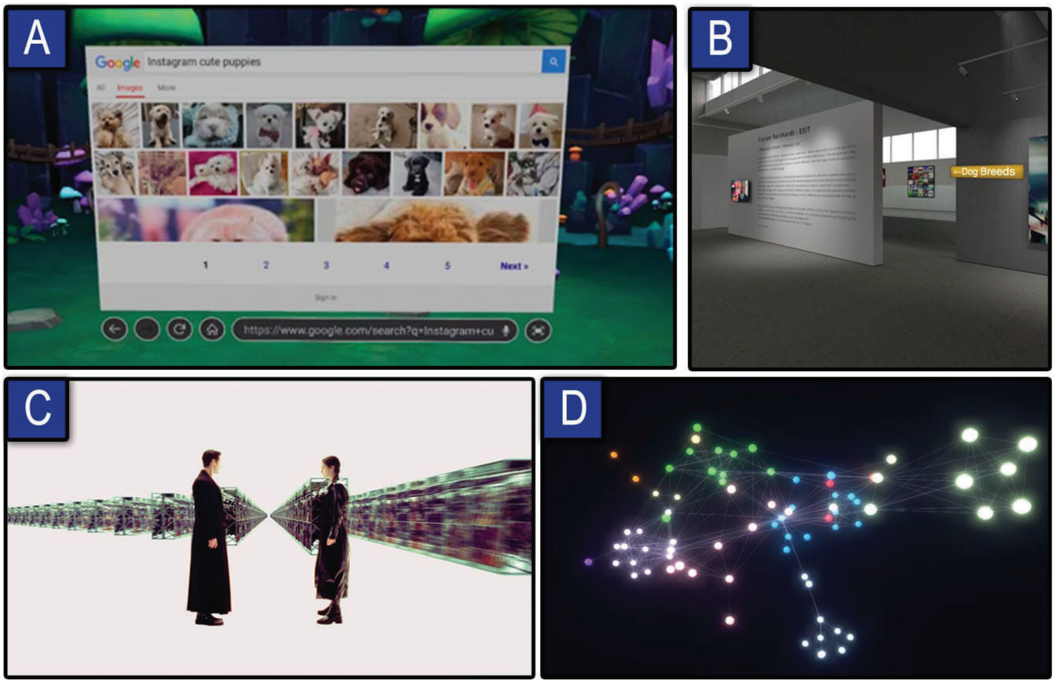

Figure 5.14: Concept ideas for the automatic adaptation of websites to three-dimensional virtual environments. A) PointClick with floating 2D interfaces. B) Website as a building. C) The Matrix Armoury. D) Galaxies and Constellations.

5.2.2.4 HunchResize: Reduced/enlarged avatar sizes based on posture for individual tasks or asymmetric interactions

This idea is in a very early stage and would require collaboration with researchers with expertise in psychology, self-perception and body ownership.

The emotional effects of body postures have been frequently studied on self-perception [207] and in the communication of attitude and status relationships [146]. Recent studies state that expansive or contractive body postures affect feelings of self-worth and impact self-esteem [109, 236]. *HunchResize* proposes using expansive and contractive body postures to enlarge or reduce the user's avatar size in the VR world. We propose two pathways to explore. First, a technical study in which we evaluate if this size change based on posture improves the interaction with small or large elements (i.e.: Exploring the tiny components of a PCB or the architectural characteristics of a skyscraper's facade). Secondly, a self-perception study on how asymmetric multi-user VR interactions affect the users' self-esteem, communication and relationships. Performing this study in VR environment enables us to modify not only the avatar size and their point of view (POV) but also their field of view (FOV), colour perception (tints, vignettes), ambient occlusion and their microphone and speaker's pitch. We hypothesise that all these size-based distortions will boost the psychological effects of body posture. *HunchResize* may be used to treat psychological disorders related to social phobia, unhealthy power dynamics in relationships or for self-esteem therapy.

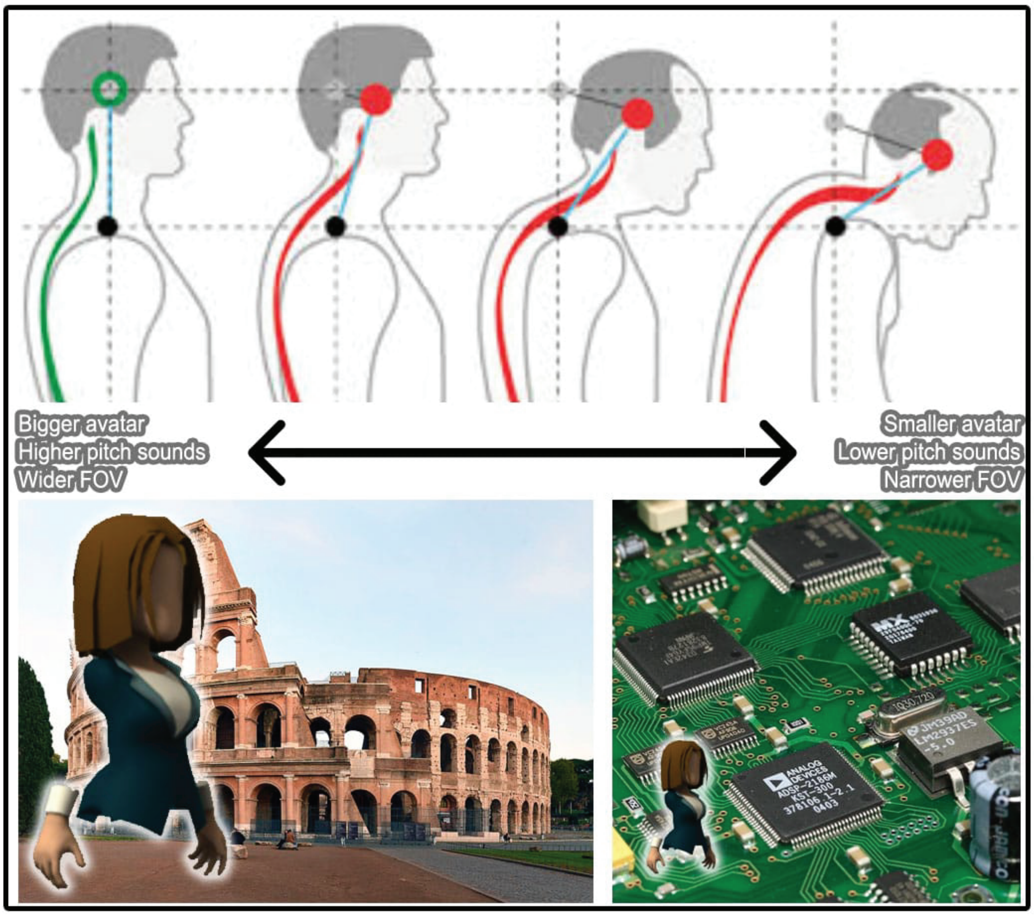

Figure 5.15: Concept idea behind *HunchResize*.

5.2.3 Other HCI Projects

5.2.3.1 GuidingHaptics: 6DoF Guiding Pulling Cues using Asymmetric Vibrations

Conventional methods of motion guidance consist in providing the users with stimuli that they have to decode, understand, map to a reaction and respond to, that is, verbal guidance, visual stimuli or vibrations in different parts of the body. Alternatively, extrinsic feedback can be applied as a guiding method, that is, the direct touch of a trainee or grabbing a mechanical or robotic arm, but they are bulky and not portable, expensive, or require the presence of an external agent, hindering the sense of agency.

Asymmetric vibrations have been recently explored to produce pulling illusions [6, 40, 45, 46, 99, 102, 132], and several works by Tanabe et. al also research this subject [213, 214, 215, 216, 217]. I tested a 2DoF prototype in SIGGRAPH, and I found it so compelling that I grew a new interest in guiding haptics. However, the devices conceived in the literature need to be revised in their capabilities to perform 3DoF translations and 3DoF rotations. With *GuidingHaptics* I would like to study further the design of pulling forces and torques via asymmetric waves.

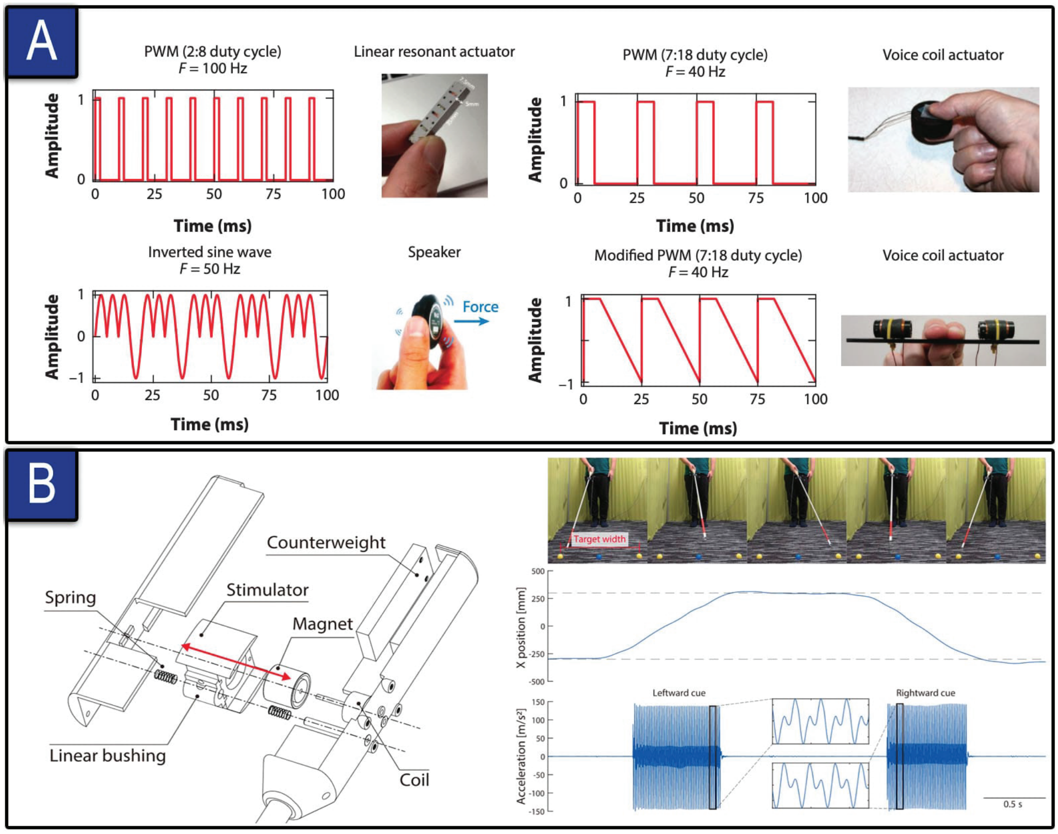

Figure 5.16: A) Examples of ungrounded asymmetric vibration systems. A Traxion system that uses a linear resonant actuator driven with a PWM signal, a voice coil driven with a PWM signal, a speaker driven with an inverted sine wave signal, and a voice coil driven with a modified PWM signal. Extracted from [44]. B) Internal configuration of an ungrounded device designed for white canes and an example of the position of the cane tip and the acceleration of vibration stimulus. Extracted from [214].

The literature states that "these asymmetric vibrations at 50 Hz are sensed by both the Meissner corpuscles and the Pacinian corpuscles. Still, the Pacinian corpuscles do not sense the direction, so the Meissner corpuscles should be the only ones responsible for the pulling illusion" [46]. But we are unsatisfied with these explanations and by the term "illusion". Asymmetric waves produce a real net force that pushes inanimate objects, so perhaps proprioception also plays a role. Using anaesthesia to numb the hand's mechanoreceptors may be an intriguing approach to further understanding the underlying mechanisms of this guiding technique.

Therefore I would like to build a working prototype that provides 6DoF translational and rotational pulling cues. To achieve this, we should explore different actuators, such as Eccentric Rotating Mass Vibration Motors (ERMs) and Linear Resonant Actuators (LRAs), regarding their guidance effectiveness, weight, size and power consumption.

In addition, I would like to suggest these user studies:

- Evaluate the consistency and strength of forces and torques the user perceives when applied on different parts of the body (hands, bows, knees, ankles, neck, back...).
- Assess the sense of agency perceived by the users under different degrees of guiding haptics and in comparison with conventional methods of motion guidance.
- Compare the mental workload of being guided by GuidingHaptics vs positional vibration vs stretching skin. Task Completion Time and Accuracy for reaching targets on a table (for example) may be measured. However, it could be more interesting to test them while multitasking with a mental task such as remembering numbers or stating the colour of written text (red blue pink).
- To study its bimanual use, having one device in each hand and checking how the user coordinates its movements. Alternatively, even try with toddlers, without training or explanation, to explore its intuitiveness.

Once the mechanism whereby the guidance effect happens is understood, its replication through contactless ultrasound, sparks or air jets may also be studied.

Applications may provide guidance for matching body postures automatically extracted from yoga videos, performing activities eyes-free or dancing with a virtual avatar.

5.2.3.2 InnerSight: Enhancing and Expanding Visual Perception via Retina Backlight Stimuli.

One should admit that this project is my idée fixe. *"Awake your spider-sense!"*

InnerSight aims to enhance and expand visual perception by stimulating the retina in unconventional ways. InnerSight will not overlay images on the user's field of view (FOV) as with AR glasses, nor will it extend visual perception by mapping new stimuli to other usually overridden senses, as audio [70] or vibrotactile [234] cues. It will excite the retina and generate non-invasive visual cues that the user will subtly perceive as notifications, guidance or warnings. If the reader, as a child, has ever put a powerful enough flashlight in their mouth, they may get a close idea of what InnerSight may deliver. A feeling close to sci-fi concepts such as Spiderman's spider-sense or low-life warnings in videogames. See figure 5.17.

Figure 5.17: Concepts that may have some resemblance to the idea of *InnerSight* stimulating the user's retina. Note that the user's vision should not be occluded.

Numerous technologies claim to extend or substitute vision, such as haptics [256], audio [181], or AR glasses or glasses with LEDs [172]. Other novel approaches have been studied, such as an electrotactile stimulator on the tongue to translate video data into tactile tongue feedback [20]. Despite their potential advantages, these methods may have drawbacks. Haptic and auditory systems do not elicit or alter visual sensations but rather create new proxy sensations in the other sensory modalities; tongue stimulators may be perceived as intrusive; other people can perceive colour-changing or flickering LEDs over the eyes; and AR screens obstruct the user's view and require significant battery power. Moreover, aligning cognition with its naturally occurring phenomenology could potentially lead to less disruptive devices and increase user adoption. *InnerSight* will provide a novel visual enhancing device that is safe, portable and available for everyone off-the-shelf. Hopefully, it may open new research opportunities in what I consider an underexplored idea: The concept of illuminating the retina not from the front but from the back or sides, with devices that are hidden to everyone but still can notify the wearer.

To realise *InnerSight* we should first answer some questions.

What kind of light should be used?. Light will be required to reach the retina without passing through the pupils, as with regular vision, but it may encounter some difficulties when travelling through flesh or bones. The behaviour of infrared light in the flesh was long ago studied [35, 76]. 630NM red light should be able to transmit through the epidermis, 660NM red light would reach the dermis, and 850NM light will travel through muscle, bone and internal tissues.

How can we reach the retina?. Assuming that we develop a technology capable of emitting the required light through flesh, we still should choose the optimum placement of such emitters. As marked in Figure 5.18, the human skull shows several cavities that may give direct access to the retina without travelling through bone. Alternatively, the palate may be thin enough [165] for light to pass through, indirectly stimulating the retina through the light scattering. Additional research could be made exploiting the Sensory Gating effect by which irrelevant stimuli are separated from meaningful ones. For example, the image of the nose does, in fact, hit the retina and is sent to the brain, but the brain decides to ignore it. What would happen if we just lit the nose, the cheeks or the eyebrows, interrupting the sensory gating?

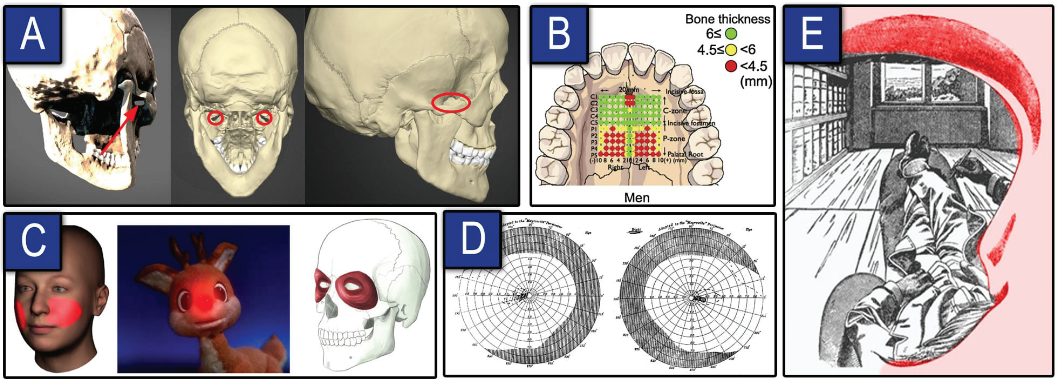

Figure 5.18: A) Apertures in the skull enable retina illumination without traversing bone. B) Palate bone thickness graph. Extracted from [165]. C) Parts of the face in our visual field that could be made to glow. D) Left and right eyes' visual field diagrams. Darked area is the nasal region and eyelids. Extracted from [178]. E) Highlighted Escher's illustration picturing how much of our visual field is occupied by our own body.

What kind of stimuli can we elicit?. Once demonstrated that we can stimulate the retina, we should examine the feasible stimuli and how to deliver them. Different configurations of the following aspects will deliver different stimuli.

- **Colors:** Most light in the visible spectrum will not reach the hypodermis [128]. A small range of red light may do it, and it would be interesting to explore if changes in colour inside that range are perceivable by the user. Alternatively, if we explore the path of making the noose, cheeks or eyebrows glow, a much wider range of colours could be employed.

- **Intensities:** What is the minimum intensity perceivable? Under what conditions? When raising the intensity to higher values, is there a threshold in which it is annoying or blinding? The staircase procedure would be used during user studies to determine the perception threshold, as in [21].

- **Frequency and patterns:** Blinking frequency, colour, length, and fade ins/outs or intensity ramps have been demonstrated to be essential in the design of notifications [110] and user's urgency perception [104].

- **Spatial Resolution:** This would be one of the most ambitious aspects of the project. We are confident this device could provide binary cues, switching the emitters on/off. Depending on how straight we can make the light to travel through flesh and how much we can reduce its scattering, low-resolution projections could be provided to the retina. This would provide more complex and richer stimuli.

- **Mono/stereo:** Unlike regular distant visual stimuli, stereoscopic vision, also known as binocular vision, can be extensively exploited when individually stimulating each eye. Binocular fusion and dichoptic cues have been recently studied with VR, and AR glasses to enhance vision [259], guide the users' attention [259], or for amblyopia therapy [244]. We hypothesise that *InnerSight* could provide dichoptic cues to hamper, improve or alter user's perception. Moreover, individually controlling the stimuli provided to each eye would also enable supplementary animation patterns to provide spatial and directional cues.

Possible applications. *InnerSight* could be used: to deliver unobtrusive notifications; as a guidance system; To enhance immersion in videogames or other experiences (health indicators, directions, spider-sense); to enhance peripheral vision and collision avoidance; or for the diagnosis and rehabilitation of visual diseases and disorders.

Other concerns. We should highlight some of the risks that could halt this project. Devices capable of generating these powerful light beams may heat up significantly, rendering them unusable as wearables on the skin or inside the mouth or the nose. Moreover, they should be sufficiently portable to be used in daily situations. The device may cause the user's face to glow, making it noticeable from the outside and perhaps leading to social stigma [75]. Additionally, ophthalmologists should be interviewed to consider a study about its long-term effects, evaluating the safety of *InnerSight*.

5.2.3.3 SnailEyes: Customizing binocular perception for awareness enhancement and on miniaturized tasks or POV simulations.

Head-mounted displays can potentially rehabilitate and enhance vision [51, 127, 185]. Most vertebrates have binocular vision, coupling both eyes' movement to decode stereoscopic depth cues. However, some animals, such as snails, chameleons or geckos, have decoupled individual control on the orientation of each eye [174].

Inspired by the snail's eyes, *SnailEeyes* proposes combining an HMD with two movable cameras to customize binocular perception for awareness enhancement, aidance on miniaturized tasks and POV simulations. See Figure 5.19.

We foresee three different categories of applications:

1. **Independent visuals**: Applications in which the cameras are uncoupled, and each eye receives an entirely different feed. See Fig 5.19.A. Studies should be done to check if surroundings awareness and obstacle awareness increase and on mental workload and visual fatigue.

2. **Coupled visuals to enhance vision**. Here, both cameras would be placed replicating our natural stereoscopic vision. See Fig 5.19.B. This could be used to aid the user in focusing on miniaturized tasks (i.e. fine surgery, soldering or figurine painting). Different lenses, focal lengths, and diaphragm apertures could also be applied for each eye to enhance normal vision. Infrared or thermal recolouring are also interesting alternatives to explore.

3. **Coupled visuals to simulate other POVs**. See Fig 5.19.C. Maintaining natural eye coupling, the POV of the user could be shifted to simulate the point of view of other individuals, such as kids, short people or tall people.

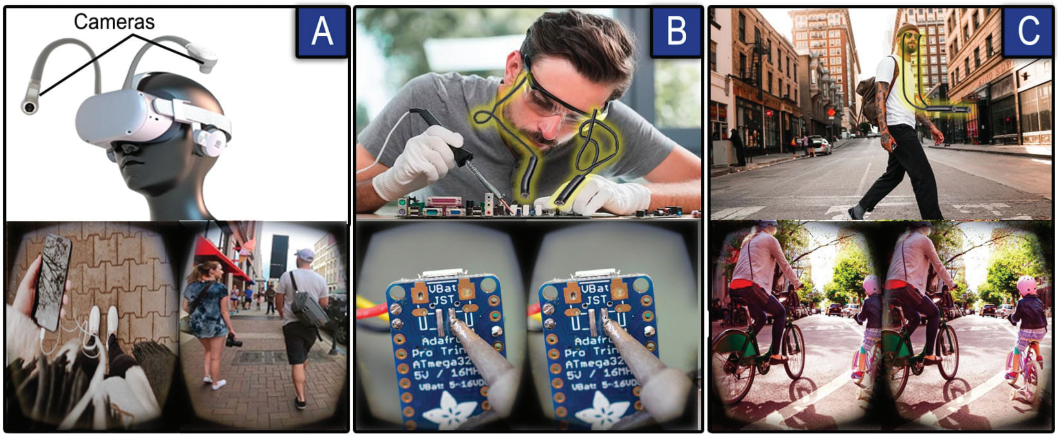

Figure 5.19: *SnailEyes* concept images. A) To received to completely different POVs on each eye. B) To help on miniaturized work, as in soldering. C) To simulate a kid's POV when walking in the street.

Part II

Annexed items

We could argue that a PhD thesis aims to extend knowledge about an important topic through research and to provide training to the PhD student to develop the competencies needed to be a sufficient researcher. The first has been proven in "Part I - Main Thesis Content".

"Part II - Annexed items" aims to provide additional evidence that the candidate has performed sufficient research, divulgation and teaching work to continue his career.

In this section, we present the participation of the candidate in the following:

- Research papers in which the candidate has played a significant role, including a summary, metrics and link access to the published work. This also includes published papers unrelated to this thesis or unpublished projects.
- Research projects in which the candidate has participated as "ayudante/colaborador de proyecto".
- Reviewing of research papers.
- Participatión on the concessión on a ERC Starting Grant
- Divulgation events, maker fairs and TV programs.
- Open access instructables.
- Teaching at Public University of Navarra.
- Student's mentoring through their Final Degree Projects.

6 Research

6.1 Published works related to this thesis

"Chapter 2 - Compiled Research Papers for this Thesis" contains all the papers directly related to the main content of this thesis.

6.2 Published works unrelated to this thesis

Participation on papers or posters not related to the main content of this thesis.

6.2.1 Effects of the use of "Tablet" devices and applications in the types of creativity of higher education students

Title:	*Effects of the use of "Tablet" devices and applications in the types of creativity of higher education students*
Access link:	https://dx.doi.org/10.21125/edulearn.2016.0562
Authors:	Oscar Ardaiz, María Teresa Sanz de Acedo, Iñigo Ezcurdia
Publication date:	2016
Venue:	8th International Conference on Education and New Learning Technologies
Abstract:	The main purpose of this project was to examine the effect of "Tablet" devices versus traditional media "pencil and paper" when performing creative tasks by higher education students. The study was conducted with a sample of 25 students from the Degree in Computer Engineering at the Public University of Navarra. Subjects were assigned randomly to the experimental group (N = 13) who worked with "Tablets" and the control group (N = 12) who performed creative tasks in "pencil and paper". The independent variable was the tablet device and applications, dependent variables were: overall creativity, narrative creativity and pictorial creativity. The procedure consisted of two distinct phases. The first intervention phase, in which the subjects in the experimental group (GE) performed individually six creative task -three verbal tasks and three drawing tasks- with "Tablets", while the control group (GC) performed the same in the format "pencil and paper". Creative tasks of the experimental group were accomplished with the assistance of software applications installed in "Tablets" with three different interaction styles: only visualization of animated objects in a two dimensional space, visualization and composition with static objects in two dimensional space, and only visualizations of animated objects in a three dimensional space. In the second evaluation phase, all subjects were examined in creativity through the Test of Creative Imagination for Adults, PIC-A (Artola, Barraca, Mosteiro, Ancillo, Poveda and Sanchez, 2012) consisting of four games, three of which measured narrative or verbal creativity while the fourth measured pictorial creativity. The results showed that using "Tablets" encouraged the creative potential of the experimental group relative to the control group. In addition, students who scored higher on creativity in narrative PIC-A performed better on verbal tasks than in drawing tasks. This type of study aims to contribute to research work in human-computer interaction, and to foster creative potential of higher education students, for whom creativity is a highly appreciated professional and social competency.

6.2.2 Content Adaptation and Depth Perception in an Affordable Multi-View Display

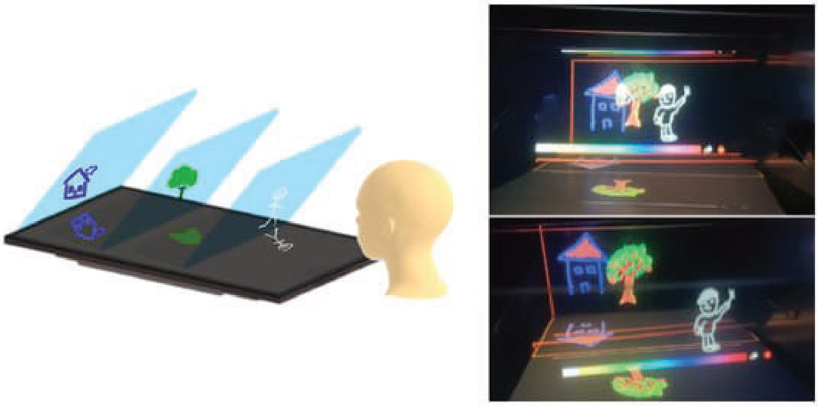

Figure 6.1: Graphical abstract of the project "Content Adaptation and Depth Perception in an Affordable Multi-View Display".

Title:	*Content Adaptation and Depth Perception in an Affordable Multi-View Display*
Access link:	https://doi.org/10.3390/app10207357
Authors:	Iñigo Ezcurdia, Adriana Arregui, Oscar Ardaiz, Amalia Ortiz, Asier Marzo
Publication date:	21 October 2020
Venue:	Applied Sciences-Basel
Impact Factor:	2.838 (Q2 in Engineering, Multidisciplinary | JCI Percentile: 64.29)
Article Views:	1352
Citations:	2
Abstract:	We present SliceView, a simple and inexpensive multi-view display made with multiple parallel translucent sheets that sit on top of a regular monitor; each sheet reflects different 2D images that are perceived cumulatively. A technical study is performed on the reflected and transmitted light for sheets of different thicknesses. A user study compares SliceView with a commercial light-field display (LookingGlass) regarding the perception of information at multiple depths. More importantly, we present automatic adaptations of existing content to SliceView: 2D layered graphics such as retro-games or painting tools, movies and subtitles, and regular 3D scenes with multiple clipping z-planes. We show that it is possible to create an inexpensive multi-view display and automatically adapt content for it; moreover, the depth perception on some tasks is superior to the one obtained in a commercial light-field display. We hope that this work stimulates more research and applications with multi-view displays.
Attached Media:	Video abstract: https://youtu.be/LZlDZgJkHtk (2min long)

6.2.3 Interactions with Digital Mountains: Tangible, Immersive and Touch Interactive Virtual Reality

Figure 6.2: Graphical abstract of the project "Interactions with Digital Mountains: Tangible, Immersive and Touch Interactive Virtual Reality".

Title:	*Interactions with Digital Mountains: Tangible, Immersive and Touch Interactive Virtual Reality*
Access link:	https://doi.org/10.1145/3380867.3426204
Authors:	Oscar Ardaiz, Asier Marzo, Ruben Baztan, Iñigo Ezcurdia
Publication date:	8 November 2020
Venue:	ISS ’20: Companion Proceedings of the 2020 Conference on Interactive Surfaces and Spaces
Impact Factor:	1.98 | Rank A - Assigned to the flagship conference, the one that is the leading in that area of discipline
Abstract:	Digitization of Earth mountains and terrains has facilitated to plan journeys, manage natural resources, and learn about the Earth from the comfort of our homes. We aim to develop new interactions on digital mountains with novel interfaces: 3D printed representation of a mountain, an immersive virtual reality visualization, and two different touch interactive interfaces for immersive virtual reality visualizations: a 3D printed mountain with touch sensors and a multitouch tablet. We show how we have built such prototypes based on digital data retrieved from a map provider, and which interactions are possible with each interaction device. We explain how we design and conduct evaluation.

6.2.4 Complex selective manipulations of thermomagnetic programmable matter

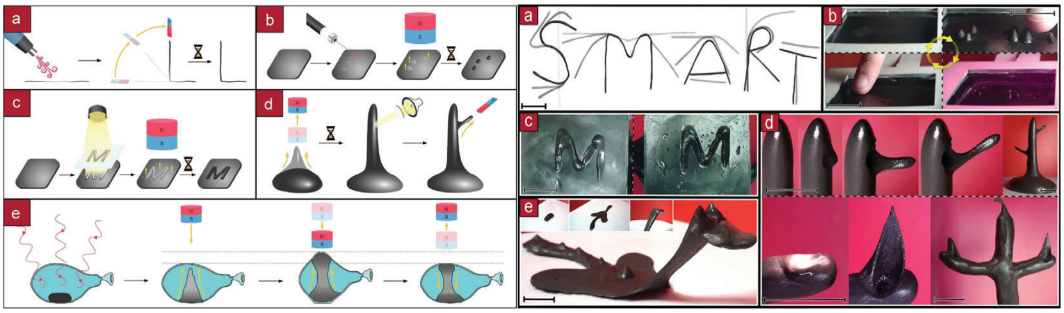

Figure 6.3: Graphical abstract of the project "Complex selective manipulations of thermomagnetic programmable matter".

Title:	*Complex selective manipulations of thermomagnetic programmable matter*
Access link:	https://doi.org/10.1038/s41598-022-24543-5
Authors:	Josu Irisarri, Iñigo Ezcurdia, Xabier Sandua, Itziar Galarreta-Rodriguez, Jose Ignacio Pérez-Landazabal
Publication date:	13 December 2022
Venue:	Scientific Reports (Nature Publishing Group)
Impact Factor:	4.997 (Q1 in Multidisciplinary Sciences | JCI Percentile: 86.30)
Article Impact:	This article is in the 98th percentile (ranked 4,860th) of the 280,687 tracked articles of a similar age in all journals and the 98th percentile (ranked 49th) of the 2,707 tracked articles of a similar age in Scientific Reports. (Source: altmetrics)
Abstract:	Programmable matter can change its shape, stiffness or other physical properties upon command. Previous work has shown contactless optically controlled matter or magnetic actuation, but the former is limited in strength and the latter in spatial resolution. Here, we show an unprecedented level of control combining light patterns and magnetic fields. A mixture of thermoplastic and ferromagnetic powder is heated up at specific locations that become malleable and are attracted by magnetic fields. These heated areas solidify on cool down, and the process can be repeated. We show complex control of 3D slabs, 2D sheets, and 1D filaments with applications in tactile displays and object manipulation. Due to the low transition temperature and the possibility of using microwave heating, the compound can be manipulated in air, water, or inside biological tissue having the potential to revolutionize biomedical devices, robotics or display technologies.
Attached Media:	Abstract video: https://youtu.be/_JP8CvIIDng (4min long)

6.2.5 Volumetric Reach-through Displays for Direct Manipulation of 3D Content

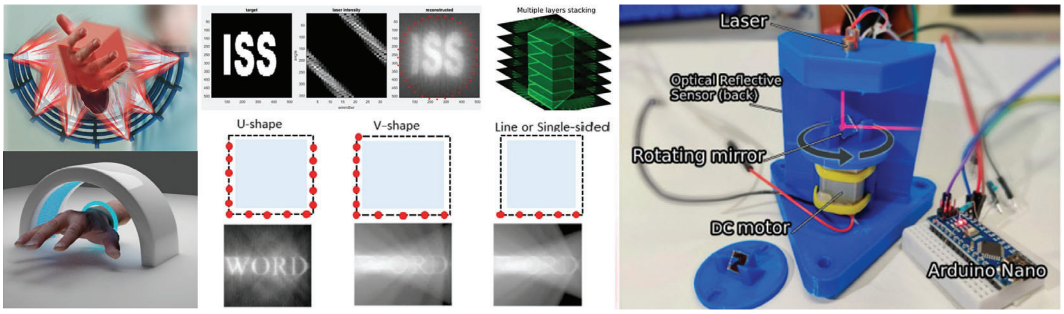

Figure 6.4: Graphical abstract of the project "Volumetric Reach-through Displays for Direct Manipulation of 3D Content".

Title:	*Volumetric Reach-through Displays for Direct Manipulation of 3D Content*
Access link:	https://doi.org/10.1145/3380867.3427410
Authors:	Iñigo Ezcurdia
Publication date:	8 November 2020
Venue:	Doctoral Symposium at ISS '20: Companion Proceedings of the 2020 Conference on Interactive Surfaces and Spaces
Impact Factor:	1.98 | Rank A - Assigned to the flagship conference, the one that is the leading in that area of discipline
Abstract:	In my PhD, I aim at developing a reach-through volumetric display where points of light are emitted from each 3d position of the display volume, and yet it allows people to introduce their hands inside to directly interact with the rendered content. Here, I present TomoLit, an inverse tomographic display, where multiple emitters project rays of different intensities for each angle, rendering a target image in mid-air. We have analysed the effect on image quality of the number of emitters, their locations, the angular resolution and the levels of intensity. We have developed a simple emitter and we are in the process of putting together multiple of them. And what I plan to do next, e.g. moving from 2D to 3D and exploring interaction techniques. The feedback obtained in this symposium will clearly dissipate some of of my doubts and guide my research career.
Attached Media:	Doctoral Symposium slides | Tomolit Video Abstract | Tomolit Poster

6.2.6 UNDER REVIEW - PiloNape: Electrostatic Artificial Piloerection for Affecting Emotional Experiences

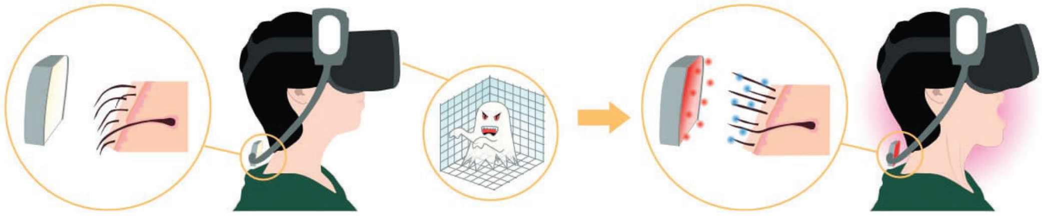

Figure 6.5: Graphical abstract of the project "PiloNape: Electrostatic Artificial Piloerection for Affecting Emotional Experiences".

Title:	*PiloNape: Electrostatic Artificial Piloerection for Affecting Emotional Experiences*
Authors:	Naroa Iriarte, Iñigo Ezcurdia, Sonia Elizondo, Josu Irisarri, Daria Hemmerling, Amalia Ortiz, Asier Marzo
Publication:	Manuscript submitted for publication.
Abstract:	Piloerection is a strong affective reaction that occurs in human beings. In this project, we induce artificial piloerection using contactless electrostatics to enhance the affective response of users when they are interacting with computer systems. Firstly, we design and compare various high-voltage generators in terms of the static charge, safety and frequency response with different electrodes as well as grounding strategies. Secondly, a psychophysics user study revealed which body parts are more sensitive to electrostatic piloerection and what adjectives are associated with them; the wrist and the nape were the most sensitive parts. Finally, we combine a generator with a head mounted display to add artificial piloerection to virtual experiences of fear. We hope that these findings allows designers to use contactless piloerection in affective experiences such as music, short movies, videogames or exhibitions.

6.3 Projects that did not end up in a publication

6.3.1 UltraGloves: Effects of Surgical Gloves on Perceived Tactile Stimuli of Ultrasonic Mid-air Feedback

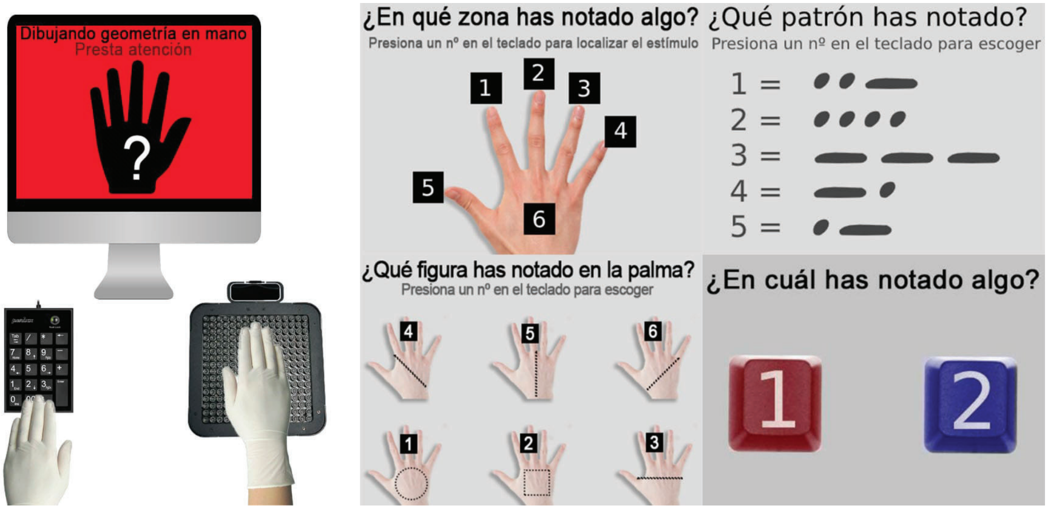

Figure 6.6: Graphical abstract of the project "UltraGloves: Effects of Surgical Gloves on Perceived Tactile Stimuli of Ultrasonic Mid-air Feedback".

Ultrasonic mid-air haptics has emerged as the main method for providing tactile feedback on the hand without needing to wear devices. Consequently, it has the potential to revolutionize virtual and augmented reality as well as tactile-guided interactions without having to look at the devices.

However, no study has analyzed the effect of wearing gloves on the perception of ultrasonic mid-air tactile feedback, even when in multiple important scenarios wearing gloves is mandatory (e.g., nurses or instrumental surgeons).

In this paper, we study the effects of wearing surgical gloves on the perception of ultrasonically induced mid-air haptic feedback on the hand. A perception threshold study reveals that the use of gloves makes our hands more sensitive to ultrasonic tactile feedback. However, the ability to differentiate different shapes gets hindered. A laser vibrometry study and matching numerical simulations reveal that this is mainly due to the larger amplitude and diffusion of the vibration in the glove. Therefore, the gloves act as a membrane that amplifies the vibration but also makes it more diffuse.

What will be the applications of this work? Training nurses and surgeons (or in general any medical specialist who wears gloves). In what sort of tasks? feedback about the position and incorrect use of instruments. Guiding their hands without them having to look at the hands.

6.4 Participation in Research Projects

The candidate has been hired and participated in the following research projects:

Project:	*Estimulación de la creatividad y la motivación intrínseca mediante un sistema informático incorporado en dispositivos "Tablet"*
Access link:	https://dx.doi.org/10.21125/edulearn.2016.0562
Principal Investigator:	María Teresa Sanz de Acedo
Position occupied:	Ayudante de proyecto
Period:	28th September 2015 to 31st July 2016
Abstract:	The main purpose of this project was to examine the effect of "Tablet" devices versus traditional media "pencil and paper" when performing creative tasks by higher education students. The study was conducted with a sample of 25 students from the Degree in Computer Engineering at the Public University of Navarra. Subjects were assigned randomly to the experimental group (N = 13) who worked with "Tablets" and the control group (N = 12) who performed creative tasks in "pencil and paper". The independent variable was the tablet device and applications, dependent variables were: overall creativity, narrative creativity and pictorial creativity. The procedure consisted of two distinct phases. The first intervention phase, in which the subjects in the experimental group (GE) performed individually six creative task -three verbal tasks and three drawing tasks- with "Tablets", while the control group (GC) performed the same in the format "pencil and paper". Creative tasks of the experimental group were accomplished with the assistance of software applications installed in “Tablets” with three different interaction styles: only visualization of animated objects in a two dimensional space, visualization and composition with static objects in two dimensional space, and only visualizations of animated objects in a three dimensional space. In the second evaluation phase, all subjects were examined in creativity through the Test of Creative Imagination for Adults, PIC-A (Artola, Barraca, Mosteiro, Ancillo, Poveda and Sanchez, 2012) consisting of four games, three of which measured narrative or verbal creativity while the fourth measured pictorial creativity. The results showed that using "Tablets" encouraged the creative potential of the experimental group relative to the control group. In addition, students who scored higher on creativity in narrative PIC-A performed better on verbal tasks than in drawing tasks. This type of study aims to contribute to research work in human-computer interaction, and to foster creative potential of higher education students, for whom creativity is a highly appreciated professional and social competency.

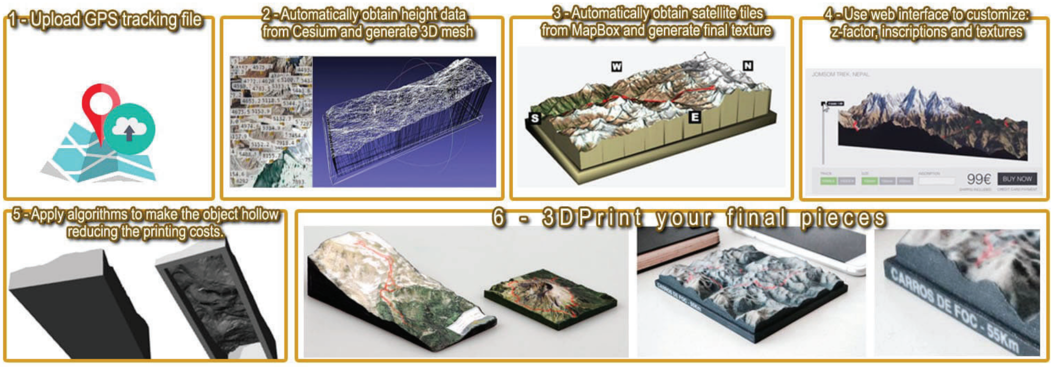

Figure 6.7: Graphical abstract of the project "Módulos API-Nicetrails y Topofab".

Project:	*Módulos API-Nicetrails y Topofab*
Acronym:	2017006143
Principal Investigator:	Oscar Ardaiz
Position occupied:	Ayudante de proyecto
Period:	16th September 2016 to 15th December 2017
Abstract:	Nicetrails is a Cloud-Based design Web App to create and fabricate 3D maps with geographical information and GPS tracks. Users can use personal Geo-tracked Experiences like biking, hiking and road trips to create physical full-color 3D-Printed objects that visualize the terrain and path taken. Professional users can use the service to fabricate models of geographical information for projects related to land planning, urban development or natural parks.
Video:	https://www.youtube.com/watch?v=ao1SXTnl6xs

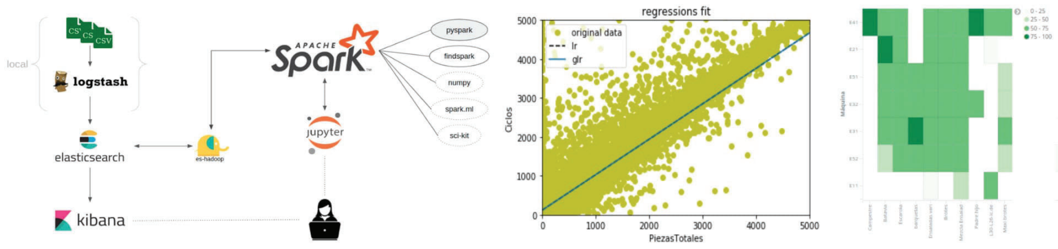

Figure 6.8: Graphical abstract of the project "Smart Talpher".

Project:	*Smart Talpher*
Acronym:	0011-1365-2017-000200
Principal Investigator:	Jesús Villadangos
Position occupied:	Colaborador de proyecto
Period:	31st October 2017 to 16th March 2019
Abstract:	Design and develop a prototype of a hardware-software Module that allows the Balancing in Real Time of Heterogeneous Productive Lines. The specific technical objectives are the following: (1) Achieve automatic adjustment in at least two parameters of the production line. (2) Provide adequate informative aid for adjustment and achieve manual adjustment on at least two parameters and also achieve automatic adjustment on at least two parameters on the production line. (3) Provide adequate informative aid for adjustment and achieve manual adjustment in at least two parameters in the automotive line. (4) Provide adequate informative aid for adjustment and achieve manual adjustment on at least two parameters on the bagging line. (5) Have your own Data Capture Service focused on adjusting machines. This is a critical element because, as the volume of data that is collected is very large, a robust data capture service is needed. (6) Treatment of data to generate data grids. We want to create a grid for each production line with all its classified data so that from there we automatically obtain the data for the adjustment. Multidimensional databases are called grids, which store their data in several dimensions and are oriented to complex queries and high performance. (7) Develop an interactive tool that allows data grid calculations for process feedback. The goal is to develop various lattices ready for process feedback. A major challenge will be to investigate whether there are common patterns between different grids, which allow for standardizing certain calculation processes. (8) Have a visualization system through Dashboards with their corresponding reports. The aim is to make it easier for the different users of the line (operators, shift manager, plant manager, quality technicians, etc.) to know the status of the line in real-time and the adjustments that are being made. In this development, it is important to choose the parameters that are displayed and also their format so that their visualization is comfortable on different devices, both on large-format screens and on a Smartphone. (9) Configure the prototype in the cloud to facilitate installation in different environments, saving costs and speeding up the installation.

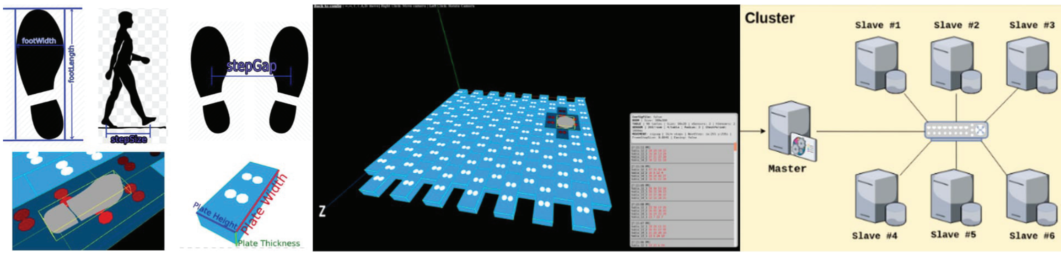

Figure 6.9: Graphical abstract of the project "Smart Thermal Floor".

Project:	*Smart Thermal Floor*
Acronym:	0011-1365-2018-000163
Principal Investigator:	Federico Fariña
Position occupied:	Colaborador de proyecto
Period:	17th March 2019 to 31st November 2019
Abstract:	Smart floor that combines localised heating and presence detection. The manufacturing process has been developed using functional printing technology on flexible plastic substrates. It is a comprehensive project because sensor data capture, data transfer and communications and remote visualisation have also been included. It has a multitude of applications in sectors such as the silver economy and energy efficiency improvement systems. Objectives: (1) Creation of simulators that allow the generation of synthetic data, similar to those generated by the pressure sensors of the underfloor heating tables. It is important that the generated data correspond to linear trajectories, just like a person walking would. It is also important that the underfloor heating tiles are still in a prototyping phase, so the data simulators must be configurable both in the dimensions of the tiles and in the position of the sensors. (2) Design and choice of the production infrastructure for the storage and exploitation of the data emitted by the tile sensors. In the event that the product reaches production, the amount of data emitted by the sensors can become enormous, so it is necessary to choose the appropriate technological components, thinking about the scalability of the solution. (3) Neighboring tile identification methods. Each tile is assigned a random id, which will be included in the data emitted by the sensors, however a priori it is not possible to know the id of the tile. In order to detect the shape of a room it is necessary to know the neighborhood of each tile.

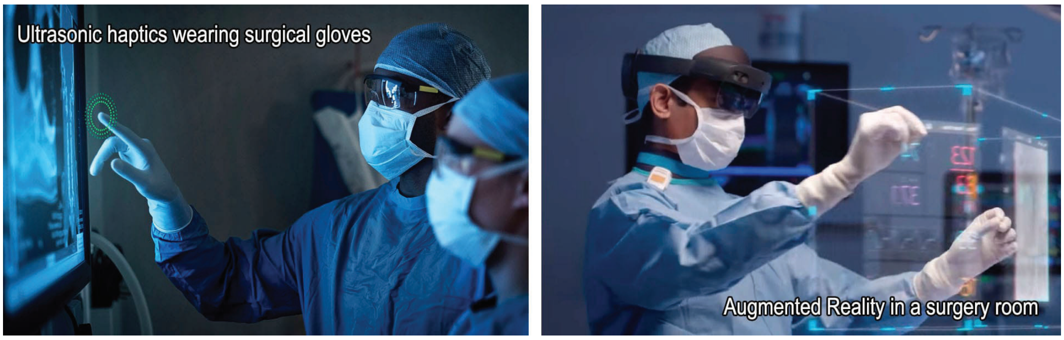

Figure 6.10: Graphical abstract of the project "Hologramas táctiles y realidad aumentada para mejorar la instrumentación quirúrgica en quirófanos".

Project:	*Hologramas táctiles y realidad aumentada para mejorar la instrumentación quirúrgica en quirófanos.*
Acronym:	0011-1365-2019-000086
Principal Investigator:	Asier Marzo
Position occupied:	Colaborador de proyecto
Period:	1st December 2019 to 30th September 2020
Abstract:	See section 6.3.1

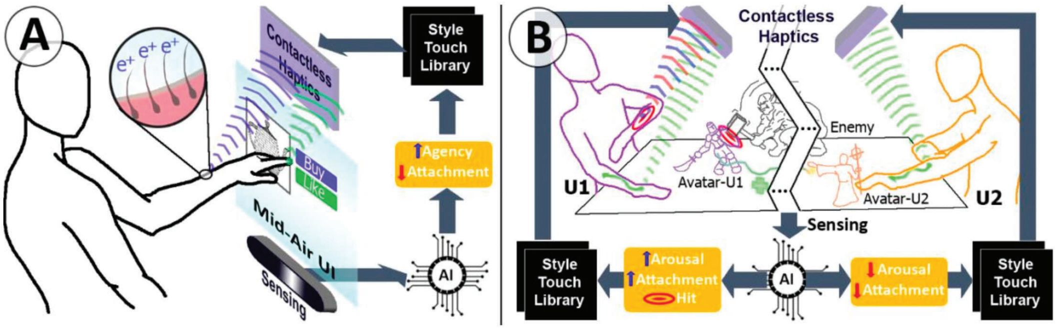

Figure 6.11: Graphical abstract of the project "TOUCHLESS Touchless Haptic Experiences with Neurocognitive AI".

Project:	*TOUCHLESS Touchless Haptic Experiences with Neurocognitive AI*
Access link:	`https://doi.org/10.3030/101017746` | `https://www.touchlessai.eu/`
Principal Investigator:	Asier Marzo
Position occupied:	Colaborador de proyecto
Period:	22nd February 2021 to present date
Abstract:	The social distancing measures introduced to restrict the spread of coronavirus and help halt the COVID-19 pandemic have made us realise just how important interpersonal physical contact is to our overall well-being, and which we are currently missing. Even though there are many advanced haptic technologies, they cannot replace tactile interaction that enables bonding physical sensation of care through the stimulation of skin receptors during touching. The EU-funded TOUCHLESS project aims to overcome that challenge through development of a next-generation touchless haptic technology. It will construct neurocognitive models and a novel AI framework to enable touchless digital inducement of the sensation of touch through the receptor response. It will also enable a soothing, affective, social and cognitive experience.

6.5 Participation on Peer-Reviewing

Peer-review is an essential academic service. I am glad to participate in this process to return the favour that other reviewers have done to me by exhaustively reviewing my work and providing knowledgeable feedback. But more importantly because I find the reviewing process very insightful. It has been a very informative experience for me, as I have been able to learn what makes a good paper and what can be improved. Also I find it to be an engaging way of staying informed about the state of the art while having the chance to exchange ideas and information with other reviewers or the authors themselves. During my PhD, I had the opportunity to collaborate with the peer-reviewing of papers presented to the following venues:

- CHI 2021 Papers Track
- CHI 2023 Papers Track

6.6 Participation on the concession of an ERC Starting Grant

The future work presented in "Section 5.2.1.2 Intevol: Interactions with Future Reach-Through Volumetric Displays" is directly connected to the concession of an ERC Starting Grant. These grants are for researchers with 2-7 years of experience since the completion of their PhD. Principal Investigators must demonstrate the ground-breaking nature, ambition and feasibility of their scientific proposal. The author of this thesis contributed with figures and feedback for the proposal presented by the principal investigator Asier Marzo. The grant for the *Intevol* has been finally accepted.

6.7 Participation in research seminars, webinars and courses

Different research works, posters and/or talks have been presented in the following seminars:

- **Title:** *Volumetric Reach-Through Displays for Direct Manipulation of 3D Content*
  - **Event:** ACM Interactive Surfaces and Spaces Conference 2020
  - **Date:** 17th January 2022
  - **Type:** Poster, presentation and paper.
  - **Poster:** https://drive.google.com/file/d/1Oa3x9q11LRgaJUTbUlCqgdPV0jfkaqBK/view?usp=share_link

  - **Paper:** https://dl.acm.org/doi/abs/10.1145/3380867.3427410

- **Title:** *Reach-Through Volumetric 3D Displays. Depth Cues and Direct Interaction.*
  - **Event:** Research seminar organized by the Departamento de Estadística Informática y Matemáticas
  - **Date:** 28th May 2021
  - **Type:** Talk/Presentation
  - **Slideshow:** https://docs.google.com/presentation/d/1W-YC1XcN185KSgQMK1vifJ1J0vwvGoQywGRxCmWcz70/edit?usp=sharing

- **Title:** *Acoustofluidics 2021: Contactless Additive Manufacturing using Acoustic Levitation with Position and Orientation Control*
  - **Event:** Acoustofluidics 2021 Conference
  - **Date:** 26th August 2021
  - **Type:** Contributed Talk at a session dedicated to Acoustic Manipulation
  - **Slideshow:** https://docs.google.com/presentation/d/1w27YPqu4BI2m8edi-X2uJHvqMy-Q9ULH/edit?usp=sharing&ouid=111991416708092003455&rtpof=true&sd=true

- **Title:** *Contactless Additive Manufacturing using Acoustic Levitation with Position and Orientation Control of Elongated Parts.*
  - **Event:** "Jornada de Internazionalización" organized by "Smart Cities: Future Trends and Challenges" institute.
  - **Date:** 17th January 2022
  - **Type:** Poster and paper.
  - **Poster:** https://drive.google.com/file/d/1n3lQqUxETkxo413ZKNiRflgK-FrU6c_r/view?usp=share_link
  - **Paper:** https://hdl.handle.net/2454/43792

An additional poster has been accepted to be presented at the "Congreso Internacional Multidisciplinar de Estudiantes de Doctorado" on the 23rd of March 2022, between the deposit of this thesis and the defence.

The author has also attended the following courses, workshops and seminars to improve his research skills:

- *"Academic Writing C1"* organized by "Centro Superior de Idiomas de la Universidad Pública de Navarra".

- *"Aspectos Básicos de la Actividad Investigadora"* organized by "la Escuela de Doctorado de la Universidad Pública de Navarra".

- *"G9 LIVE: Researcher well-being and imposter syndrome"* organized by G9 and Charlesworth Knowledge.
- *"G9 LIVE: Key skills for early researchers"* organized by G9 and Charlesworth Knowledge.
- *"G9 LIVE: Peer Review: How to do it and survive it to get your paper published"* organized by G9 and Charlesworth Knowledge.

7 Divulgation

Sharing research findings and knowledge with different audiences, such as other researchers, policymakers, practitioners, and the general public is crucial to increase the visibility and the impact of the research, fostering collaboration and knowledge exchange to build trust and accountability promoting transparency and accessibility of research.

This section summarizes the author's implication in the divulgation of his research and its involvement in sharing the findings and knowledge generated by their research with different audiences.

7.1 National TV Program "El hormiguero"

The *Leviprint* project (See the section 2.2) and other acoustic levitation exhibitions have been demonstrated in *El Hormiguero*.

"El Hormiguero" is a popular Spanish television program that has been airing since 2006. The show is hosted by Pablo Motos and Nuria Roca and features interviews with celebrities, scientific demonstrations, and comedy skits.

Figure 7.1: The author (Iñigo Ezcurdia) and his mentor (Asier Marzo) demonstrate Leviprint at the national TV program *El Hormiguero*. Accompanied by the hosts (Nuria Roca and Jorge Marrón) and the special guest (Oscar Isaac).

The scientific demonstrations on "El Hormiguero" are designed to be fun and engaging, often involving experiments that are related to the guest's area of expertise or personal interests. Overall, "El Hormiguero" has become a beloved and influential program in Spain, known for its mix of entertainment and education, as well as its ability to attract high-profile guests from a wide range of fields. Each episode of "El Hormiguero" is watched by 2 million to 3 million people on Spanish national LIVE TV.
A video with the scientific demonstration at the TV program can be found here: `https://www.youtube.com/watch?v=OxJQni-3GY4`.

7.2 Noche Europea de los Investigadores y las Investigadoras

The *Leviprint* project (See the section 2.2) and other acoustic levitation exhibitions have been demonstrated in the event *Noche Europea de los Investigadores e Investigadoras*.

Figure 7.2: Exterior shot of the event "Noche Europea de los Investigadores e Investigadoras" at Civican Pamplona"

The "Noche Europea de los investigadores e investigadoras" is an event held every year on the last Friday of September in more than 300 cities in 30 countries across Europe. Its objective is to bring research, innovation and its protagonists, men and women scientists, closer to citizens in a simple and fun way. Thus, all types of public can learn about and participate in the science that is done at the Public University of Navarra.

7.3 Maker Faire Estella

Figure 7.3: Stand dedicated to Acoustic Levitation at the Estella Maker Faire.

The "Encuentro Maker Estella" is an annual event held in Estella, that focuses on the maker movement, innovation, and entrepreneurship. The event is typically held over a weekend and includes activities such as workshops, talks, and exhibitions related to digital fabrication, electronics, robotics, and other maker-related topics. The event provides a space for makers, entrepreneurs, and innovators to come together, share their projects and knowledge, and collaborate on new ideas. It also serves as a platform for networking and connecting with potential investors, customers, and collaborators. The "Encuentro Maker Estella" is organized by a group of local makers and is open to anyone interested in the maker movement and entrepreneurship. The event emphasizes accessibility and inclusivity and aims to inspire and empower individuals to become makers and entrepreneurs themselves.

We dedicated a stand to demonstrate acoustic levitation, showcasing its applications to kids, adults and other makers.

7.4 Workshops at Navarra LAN Party and Semana de la Electrónica

Figure 7.4: Left) Navarra Lan Party event. Right) Acoustic Levitation Workshop at Semana de la Electronica.

The "Navarra LAN Party" is an annual event held in Pamplona that focuses on technology, video games, and digital culture. The event is typically held over several days and includes activities such as LAN gaming tournaments, workshops on topics like programming and robotics, and talks by industry professionals, researchers and experts. With more than 400 attendees, Navarra Lan Party is one of the largest LAN parties in Spain, and attracts participants from across the country and beyond. The event provides a space for technology enthusiasts to come together and share their knowledge and skills, as well as to socialize and enjoy their shared interests. A workshop on the construction of a DIY levitator has been conducted on the NLP 2022. The attendees could build their own standing wave levitator using an Arduino and several transducers.

A similar workshop has been conducted also for a workshop promoted by the "Semana de la Electronica" event, organized by the student's association i^2tec.

7.5 SonicSurface Instructables

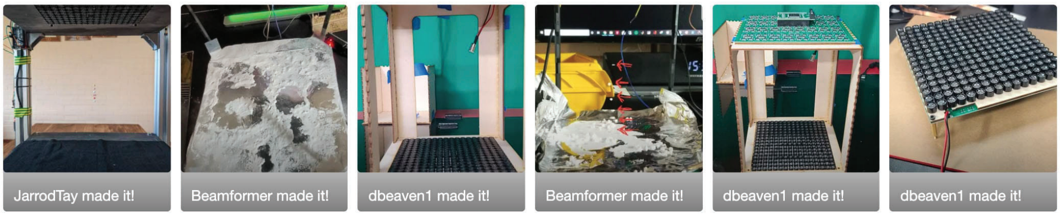

Figure 7.5: Examples of devices built by users following the instructables' tutorial.

As *UpnaLab*, we have published a tutorial on instructbales.com titled "SonicSurface: Phased-array for Levitation, Mid-air Tactile Feedback and Target Directional Speakers". This tutorial instructs on how to build a SonicSurface device (See section 2.1).

- **Link for the Instructables:** `https://bit.ly/3KcXwfD`
- **Link for the video tutorial:** `https://www.youtube.com/watch?v=vAEZvYlUnEM`

This project has more than 30.000 visits and several people have uploaded photos of their devices built. It's been a featured project and has won the 1st prize in the "Make it fly" contest.

7.6 Projects appearances in media

I find it important to communicate findings and engage with the broader community to ensure that research has a meaningful impact. In this section, I showcase some examples of the research projects that I have been involved in that have had an impact beyond academia, and have been featured in various media outlets, how my research has translated into real-world impact, and how it has been communicated to a broad audience through different channels:
LeviPrint: Contactless Fabrication Using Full Acoustic Trapping of Elongated Parts. See section 2.2.

- **Video visualizations:** More than 400000 visualizations combined in CNET YT, CNET FB UPNALAB, Ingegneria Italia, Canal USP, Olhar Digital, and others.
- **Articles:** vice.com, levtech.jp, hackster.io, 20minutos.es, CNET.com, xataka.com, gadgetany.com, theiet.org, gizmodo.com, focus.ua, usp.br and others.
- **Social media:** Tweet by @shiropen2 with more than 8000 retweets, 516000 video visualizations and 18000 likes.

Complex selective manipulations of thermomagnetic programmable matter. See section 6.2.4.

- **Altmetrics:** "In the top 5% of all research outputs scored by Altmetric" and "High Attention Score compared to outputs of the same age (98th percentile)"
- **Articles:** labmanager.com, naked-science.ru, todayuknews.com, scienmag.com, miragenews.com, phys.org, azom.com, bioengineer.org and others.

7.7 Participation in divulgation webinars and courses

The author has attended the following courses, workshops and seminars to improve his divulgation skills:

- *"Curso práctico de comunicación y divulgación científica"*, organized by the "Escuela de Doctorado de la Universidad Pública de Navarra", "CSIE" and "Unidad de Cultura y Deportes de la Universidad Pública de Navarra".
- *"G9 LIVE: Effective Public Speaking"*, organized by G9 and Charlesworth Knowledge.
- *"Hablar en público y técnicas de oratoria"*, organized by "Centro Superior de Innovación Educativa de la Universidad Pública de Navarra".

8 Teaching

8.1 Experience as Associate Lecturer

The author has been giving lessons as an Associate Lecturer since September 2018 for the "Grado en Ingeniería Informática" and "Master en Ingeniería Informática" at the Public University of Navarra. Approximately 1,400 teaching hours have been given in the following subjects:

- Ingeniería Web
- Programación
- Sistemas Operativos
- Informática
- Sistemas Multimedia y Diseño Centrado en el Usuario
- Sistemas Distribuidos Empotrados y Ubicuos

Additionally, the author has collaborated giving several lessons on the following "Títulos Propios".

- Diploma de Especialización en Desarrollo de Videojuegos y Aplicaciones de Realidad Virtual
- Diploma de Especialización en Internet de las Cosas (IoT) e Industria 4.0

In general, the student body has shown a high level of satisfaction with the lessons received. This is demonstrated by the results of teacher satisfaction surveys, in which the author obtains an average grade of 3.75 out of 4.

Additionally, the author has also participated in the project "Realidad Virtual: Su impacto en los procesos de aprendizaje" presented for the "proyectos de innovación educativa PINNE-2022". This project is led by Amalia Ortiz and has been already accepted for the courses 2022/2023 and 2023/2024. This project has two objectives. First, it will study the way to adapt teaching methodologies to integrate VR as an educational resource. Secondly, the impact of its use in the learning processes will be evaluated.

8.2 Mentoring of Students' Final Degree Projects

As a mentor, one of the most rewarding aspects of working with students is helping them develop their final degree projects. In this section, I am pleased to present the final degree and master projects that I have had the privilege of mentoring:

- *Design and development of a geolocation-based VR app for tech events* by Joel Marín.
- *Design of a website template that primes usability and accessibility* by Ainhoa Izkue.
- *Design and implementation of a Wordpress' plugin to create product catalogues compatible with WooComerce* by Julen Sanzol.
- *Web platform for assistance in the design and implementation of dynamic HTML forms based on rules* by Haizea Martín.
- *ARDepth: Depth perception techniques for Augmented Reality* by Xabier Jimenez.
- *HapticHitter: Enabling directed inertial haptic stimuli on Virtual Reality environments* by Yago Sayans.
- *A Multi-Object Grasp Technique for Placement of Objects in Virtual Reality* by Unai Fernandez.
- *Arcade Physical and Virtual Interface for Acoustic Levitators* by Ines del Tránsito

During this course I am also mentoring the following projects:

- *Low-Cost 16x16 InForm with depth and computer vision tracking* by Ohiana Elizagoyen.
- *DIY helicoidal volumetric display* by Endika Aguirre. (See section 5.2.1.3).

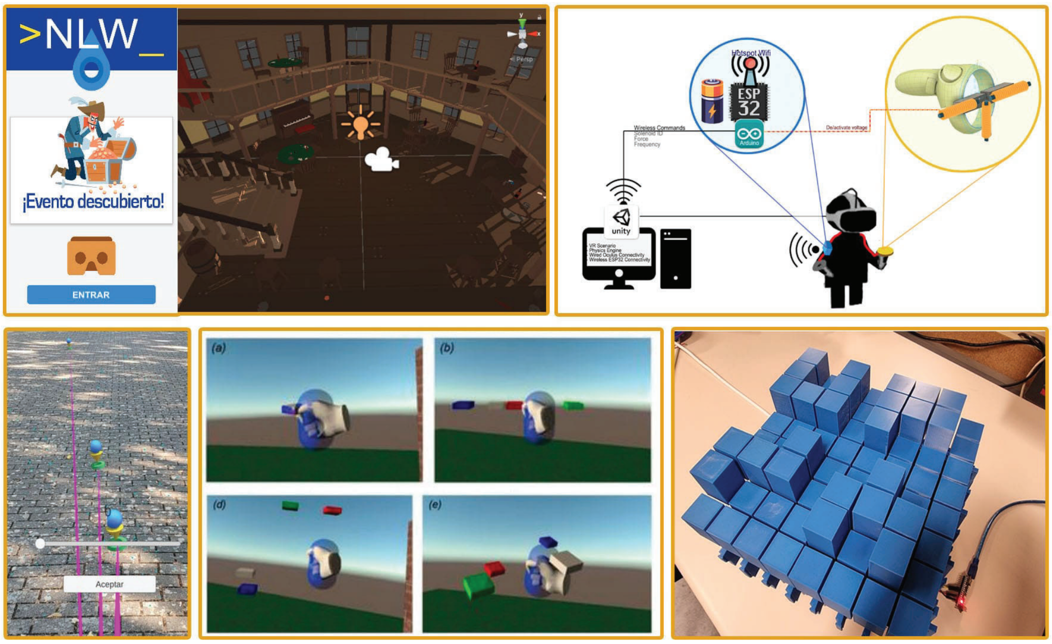

Figure 8.1: Images of some of the final degree and master projects mentored.

8.3 Participation in teaching webinars and courses

The author has attended the following courses, workshops and seminars to improve his teaching skills:

- *"Técnicas de Oratoria: Cómo sacar el máximo partido a nuestras clases"*,organized by "Centro Superior de Innovación Educativa de la Universidad Pública de Navarra".
- *"Avanzado en el manejo de situaciones complejas en el entorno universitario"*, organized by "Centro Superior de Innovación Educativa de la Universidad Pública de Navarra".
- *"Gamificación de la docencia universitaria"*, organized by "Centro Superior de Innovación Educativa de la Universidad Pública de Navarra".
- *"Unity: Programación de videojuegos 2D y 3D"*, organized by "Centro Superior de Innovación Educativa de la Universidad Pública de Navarra".
- *"Inglés P.D.I. C1 "*, a training course that enables teaching in English, organized by "Centro Superior de Idiomas de la Universidad Pública de Navarra".

Acronyms

2FM	Two-frequency modulation
3D	Three Dimensional
AI	Artificial Inteligence
AR	Augmented Reality
ARF	Acoustic Radiation Force
ATM	Automated Teller Machine
CD	Compact Disk
DIY	Do It Yourself
DMF	Digital MicroFluidic
DoF	Degrees of Freedom
EPS	Expanded Polystyrene
ERM	Eccentric Rotating Mass Vibration Motor
EWOD	ElectroWetting On Dielectric
FOV	Field of View
FPGA	Field-Programmable Gate Array
GPIO	General Purpose Inputs/Outputs
GPS	Global Positioning System
HCI	Human-Computer Interaction
HIFU	High-Intensity Focused Ultrasound
HMD	Head-Mounted Display
I/O	Input and Output
IBP	Iterative BackPropagation
IoT	Internet of Things
LED	Light Emitting Diode
LORA	LoRange (radio-communication technique)
LRA	Linear Resonant Acutator
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MR	Mixed Reality
MSE	Mean Square Error

MT	Mounted
NLP	Navarra LAN Party
OT	Oportunistic Trap
PAL	Phased Array Levitator
PAT	Phased Array of Transducers
PCB	Printed Circuit Board
PI	Principal Investigator
PIN	Personal Identification Number
PLA	PolyLactic acid
PLL	Phase-Locked Loop
POV	Point of View
PPW	Pairs Per Wavelength
PSP	Peak Sound Pressure
PWM	Pulse Width Modulation
RGB-D	Red, Green, Blue and Depth
RVD	Reach-through Volumetric Display
SCD	Surface Charge Density
SMD	Surface Mounted Device
SoA	State of the Art
TCT	Task Completion Time
TH	Through-Hole
U	Gor'kov potential
UART	Universal Asynchronous Receiver-Transmiter
UV	Ultra Violet
UX	User Experience
V	Voltage
Vp-p	Peak to Peak Voltage
VR	Virtual Reality
XR	Extended Reality

Bibliography

1. URL: http://dgward.com/physo101/sm06_pages/labs/Peripheral%20Vision%20and%20Visual%20Pathways.htm.
2. URL: https://immersiveweb.dev/.
3. Y. Abdrabou, M. Khamis, R. M. Eisa, S. Ismail, and A. Elmougy. "Just gaze and wave: Exploring the use of gaze and gestures for shoulder-surfing resilient authentication". In: *Proceedings of the 11th acm symposium on eye tracking research & applications*. 2019, pp. 1–10.
4. K. Agarwal, R. Jegadeesan, Y.-X. Guo, and N. V. Thakor. "Wireless power transfer strategies for implantable bioelectronics". *IEEE reviews in biomedical engineering* 10, 2017, pp. 136–161.
5. J. I. Agbinya. *Wireless power transfer*. CRC Press, 2022.
6. T. Amemiya, H. Ando, and T. Maeda. "Lead-me interface for a pulling sensation from hand-held devices". *ACM Transactions on Applied Perception (TAP)* 5:3, 2008, pp. 1–17.
7. M. A. B. Andrade, T. S. A. Camargo, and A. Marzo. "Automatic contactless injection, transportation, merging, and ejection of droplets with a multifocal point acoustic levitator". *Review of Scientific Instruments* 89:12, 2018, p. 125105. ISSN: 0034-6748. DOI: 10.1063/1.5063715. URL: http://aip.scitation.org/doi/10.1063/1.5063715.
8. M. A. B. Andrade, S. Polychronopoulos, G. Memoli, and A. Marzo. "Experimental investigation of the particle oscillation instability in a single-axis acoustic levitator". *AIP Advances* 9:3, 2019, p. 035020. DOI: 10.1063/1.5078948. eprint: https://doi.org/10.1063/1.5078948. URL: https://doi.org/10.1063/1.5078948.
9. M. A. Andrade, A. L. Bernassau, and J. C. Adamowski. "Acoustic levitation of a large solid sphere". *Applied Physics Letters* 109:4, 2016, p. 044101.
10. M. A. Andrade and A. Marzo. "Numerical and experimental investigation of the stability of a drop in a single-axis acoustic levitator". *Physics of Fluids* 31:11, 2019, p. 117101.
11. M. A. Andrade, A. Marzo, and J. C. Adamowski. "Acoustic levitation in mid-air: Recent advances, challenges, and future perspectives". *Applied Physics Letters* 116:25, 2020, p. 250501.

12. M. A. Andrade, F. T. Okina, A. L. Bernassau, and J. C. Adamowski. “Acoustic levitation of an object larger than the acoustic wavelength”. *The Journal of the Acoustical Society of America* 141:6, 2017, pp. 4148–4154.

13. M. A. Andrade, N. Pérez, and J. C. Adamowski. “Particle manipulation by a non-resonant acoustic levitator”. *Applied physics letters* 106:1, 2015, p. 014101.

14. M. A. Andrade, N. Pérez, and J. C. Adamowski. “Review of progress in acoustic levitation”. *Brazilian Journal of Physics* 48:2, 2018, pp. 190–213.

15. M. A. Andrade, T. S. Ramos, J. C. Adamowski, and A. Marzo. “Contactless pick-and-place of millimetric objects using inverted near-field acoustic levitation”. *Applied Physics Letters* 116:5, 2020, p. 054104.

16. B. Araujo, R. Jota, V. Perumal, J. X. Yao, K. Singh, and D. Wigdor. “Snake charmer: Physically enabling virtual objects”. In: *Proceedings of the TEI’16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction*. 2016, pp. 218–226.

17. S. Asif, P. Chansoria, and R. Shirwaiker. “Ultrasound-assisted vat photopolymerization 3D printing of preferentially organized carbon fiber reinforced polymer composites”. *Journal of Manufacturing Processes* 56, 2020, pp. 1340–1343.

18. A. G. Athanassiadis, L. Schlieder, K. Melde, V. Volchkov, and P. Fischer. “Animating sound using neurally multiplexed holograms”. *The Journal of the Acoustical Society of America* 148:4, 2020, pp. 2807–2807.

19. A. Baby, C. Augustine, C. Thampi, M. George, A. Abhilash, and P. C. Jose. “Pick and place robotic arm implementation using Arduino”. *IOSR Journal of Electrical and Electronics Engineering* 12:2, 2017, pp. 38–41.

20. P. Bach-y-Rita, M. E. Tyler, and K. A. Kaczmarek. “Seeing with the brain”. *International journal of human-computer interaction* 15:2, 2003, pp. 285–295.

21. O. Bau, I. Poupyrev, A. Israr, and C. Harrison. “TeslaTouch: electrovibration for touch surfaces”. In: *Proceedings of the 23nd annual ACM symposium on User interface software and technology*. 2010, pp. 283–292.

22. D. Beattie, W. Frier, O. Georgiou, B. Long, and D. Ablart. “Incorporating the perception of visual roughness into the design of mid-air haptic textures”. In: *ACM Symposium on Applied Perception 2020*. 2020, pp. 1–10.

23. C. Benmore and J. Weber. “Amorphization of molecular liquids of pharmaceutical drugs by acoustic levitation”. *Physical Review X* 1:1, 2011, p. 011004.

24. M. V. Berry and A. K. Geim. "Of flying frogs and levitrons". *European Journal of Physics* 18:4, 1997, p. 307.
25. A. Bianchi, I. Oakley, and D. S. Kwon. "The secure haptic keypad: a tactile password system". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 2010, pp. 1089–1092.
26. G. Blaj, M. Liang, A. L. Aquila, P. R. Willmott, J. E. Koglin, R. G. Sierra, J. S. Robinson, S. Boutet, and C. A. Stan. "Generation of high-intensity ultrasound through shock propagation in liquid jets". *Physical Review Fluids* 4:4, 2019, p. 043401.
27. A.-C. Bourland, P. Gorman, J. McIntosh, and A. Marzo. "Project telepathy". *Interactions* 25:5, 2018, pp. 16–17.
28. M. D. Brown, B. T. Cox, and B. E. Treeby. "Design of multi-frequency acoustic kinoforms". *Applied Physics Letters* 111:24, 2017, p. 244101.
29. K. Bücks and H. Müller. "Über einige Beobachtungen an schwingenden Piezoquarzen und ihrem Schallfeld". *Zeitschrift für Physik* 84:1, 1933, pp. 75–86.
30. P. Budhiraja, R. Sodhi, B. Jones, K. Karsch, B. Bailey, and D. Forsyth. "Where's my drink? Enabling peripheral real world interactions while using HMDs". *arXiv preprint arXiv:1502.04744*, 2015.
31. M. Caleap and B. W. Drinkwater. "Acoustically trapped colloidal crystals that are reconfigurable in real time". *Proceedings of the National Academy of Sciences* 111:17, 2014, pp. 6226–6230.
32. M. Campoverde-Molina, S. Lujan-Mora, and L. V. Garcia. "Empirical studies on web accessibility of educational websites: A systematic literature review". *IEEE Access* 8, 2020, pp. 91676–91700.
33. Y. Cao, W. Xie, J. Sun, B. Wei, and S. Lin. "Preparation of epoxy blends with nanoparticles by acoustic levitation technique". *Journal of applied polymer science* 86:1, 2002, pp. 84–89.
34. T. Carter, S. A. Seah, B. Long, B. Drinkwater, and S. Subramanian. "UltraHaptics: multi-point mid-air haptic feedback for touch surfaces". In: *Proceedings of the 26th annual ACM symposium on User interface software and technology*. 2013, pp. 505–514.
35. C. H. Cartwright. "Infra-red transmission of the flesh". *JOSA* 20:2, 1930, pp. 81–84.
36. B. K. Chen, Y. Zhang, and Y. Sun. "Active release of microobjects using a MEMS microgripper to overcome adhesion forces". *Journal of microelectromechanical systems* 18:3, 2009, pp. 652–659.

37. D. Chen, A. Song, and L. Tian. "A novel miniature multi-mode haptic pen for image interaction on mobile terminal". In: *2015 IEEE International Symposium on Haptic, Audio and Visual Environments and Games (HAVE)*. IEEE. 2015, pp. 1–6.

38. L.-P. Cheng, E. Ofek, C. Holz, and A. D. Wilson. "Vroamer: generating on-the-fly VR experiences while walking inside large, unknown real-world building environments". In: *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE. 2019, pp. 359–366.

39. Y. Cheng, Y. Yan, X. Yi, Y. Shi, and D. Lindlbauer. "Semanticadapt: Optimization-based adaptation of mixed reality layouts leveraging virtual-physical semantic connections". In: *The 34th Annual ACM Symposium on User Interface Software and Technology*. 2021, pp. 282–297.

40. J.-P. Choiniere and C. Gosselin. "Development and experimental validation of a haptic compass based on asymmetric torque stimuli". *IEEE transactions on haptics* 10:1, 2016, pp. 29–39.

41. L. Cox, A. Croxford, B. Drinkwater, and A. Marzo. "Acoustic lock: Position and orientation trapping of non-spherical sub-wavelength particles in mid-air using a single-axis acoustic levitator". *Applied Physics Letters* 113:5, 2018, p. 054101.

42. L. Cox, K. Melde, A. Croxford, P. Fischer, and B. W. Drinkwater. "Acoustic Hologram Enhanced Phased Arrays for Ultrasonic Particle Manipulation". *Phys. Rev. Applied* 12:6, 2019, p. 64055. DOI: 10.1103/PhysRevApplied.12.064055. URL: https://link.aps.org/doi/10.1103/PhysRevApplied.12.064055.

43. J. Cui, A. Kuijper, D. W. Fellner, and A. Sourin. "Understanding people's mental models of mid-air interaction for virtual assembly and shape modeling". In: *Proceedings of the 29th International Conference on Computer Animation and Social Agents*. 2016, pp. 139–146.

44. H. Culbertson, S. B. Schorr, and A. M. Okamura. "Haptics: The present and future of artificial touch sensation". *Annual Review of Control, Robotics, and Autonomous Systems* 1:1, 2018, pp. 385–409.

45. H. Culbertson, J. M. Walker, and A. M. Okamura. "Modeling and design of asymmetric vibrations to induce ungrounded pulling sensation through asymmetric skin displacement". In: *2016 IEEE Haptics Symposium (HAPTICS)*. IEEE. 2016, pp. 27–33.

46. H. Culbertson, J. M. Walker, M. Raitor, and A. M. Okamura. "WAVES: a wearable asymmetric vibration excitation system for presenting three-dimensional translation and rotation cues". In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. 2017, pp. 4972–4982.

47. T.-S. Dalsgaard, J. Bergström, M. Obrist, and K. Hornbæk. "A user-derived mapping for mid-air haptic experiences". *International Journal of Human-Computer Studies* 168, 2022, p. 102920.

48. C. Dodd, R. Athauda, and M. Adam. "Designing user interfaces for the elderly: a systematic literature review", 2017.

49. R. H. Doremus and P. Nordine. *Materials processing in the reduced gravity environment of space; Proceedings of the Symposium, Boston, MA, Dec. 1-3, 1986*. Technical report. Materials Research Society, Pittsburgh, PA, 1987.

50. W. Dou and J. E. Subotnik. "Perspective: How to understand electronic friction". *The Journal of Chemical Physics* 148:23, 2018, p. 230901.

51. J. R. Ehrlich, L. V. Ojeda, D. Wicker, S. Day, A. Howson, V. Lakshminarayanan, and S. E. Moroi. "Head-mounted display technology for low-vision rehabilitation and vision enhancement". *American journal of ophthalmology* 176, 2017, pp. 26–32.

52. I. Ezcurdia, R. Morales, M. A. Andrade, and A. Marzo. "LeviPrint: Contactless Fabrication using Full Acoustic Trapping of Elongated Parts." In: *ACM SIGGRAPH 2022 Conference Proceedings*. 2022, pp. 1–9.

53. M. Faridan, M. Friedel, and R. Suzuki. "UltraBots: Large-area mid-air haptics for VR with robotically actuated ultrasound transducers". In: *Adjunct Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology*. 2022, pp. 1–3.

54. A. R. Fender, D. Martinez Plasencia, and S. Subramanian. "ArticuLev: An Integrated Self-Assembly Pipeline for Articulated Multi-Bead Levitation Primitives". In: *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. 2021, pp. 1–12.

55. D. Foresti, M. Nabavi, M. Klingauf, A. Ferrari, and D. Poulikakos. "Acoustophoretic contactless transport and handling of matter in air". *Proceedings of the National Academy of Sciences* 110:31, 2013, pp. 12549–12554. ISSN: 0027-8424. DOI: 10.1073/pnas.1301860110. arXiv: arXiv:1507.02142v2. URL: http://www.pnas.org/cgi/doi/10.1073/pnas.1301860110.

56. D. Foresti, K. T. Kroll, R. Amissah, F. Sillani, K. A. Homan, D. Poulikakos, and J. A. Lewis. "Acoustophoretic printing". *Science advances* 4:8, 2018, eaat1659.

57. D. Foresti, M. Nabavi, M. Klingauf, A. Ferrari, and D. Poulikakos. "Acoustophoretic contactless transport and handling of matter in air". *Proceedings of the National Academy of Sciences* 110:31, 2013, pp. 12549–12554.

58. D. Foresti, G. Sambatakakis, S. Bottan, and D. Poulikakos. "Morphing surfaces enable acoustophoretic contactless transport of ultrahigh-density matter in air". *Scientific reports* 3:1, 2013, pp. 1–6.

59. E. Freeman, R. Anderson, J. Williamson, G. Wilson, and S. A. Brewster. "Textured surfaces for ultrasound haptic displays". In: *Proceedings of the 19th ACM International Conference on Multimodal Interaction*. 2017, pp. 491–492.

60. E. Freeman, A. Marzo, P. B. Kourtelos, J. R. Williamson, and S. Brewster. "Enhancing physical objects with actuated levitating particles". In: *Proceedings of the 8th ACM International Symposium on Pervasive Displays*. 2019, pp. 1–7.

61. E. Freeman, A. Marzo, P. B. Kourtelos, J. R. Williamson, and S. Brewster. "Enhancing Physical Objects with Actuated Levitating Particles". In: *Proceedings of the 8th ACM International Symposium on Pervasive Displays - PerDis '19*. ACM, 2019, Article 2. DOI: 10.1145/3321335.3324939. URL: http://euanfreeman.co.uk/levitate/enhancing-physical-objects-with-actuated-levitating-particles/.

62. T. Fushimi, K. Yamamoto, and Y. Ochiai. *Acoustic Hologram Optimisation Using Automatic Differentiation*. 2020. arXiv: 2012.02431 [cs.SD].

63. T. Fushimi, K. Yamamoto, and Y. Ochiai. "Target acoustic field and transducer state optimization using Diff-PAT". *AIP Advances* 11:12, 2021, p. 125007.

64. L. Gao, J. Hardwick, D. M. Plasencia, S. Subramanian, and R. Hirayama. "DATALEV: Acoustophoretic Data Physicalisation". In: *Adjunct Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology*. 2022, pp. 1–3.

65. L. Gavrilov, G. Gersuni, O. Ilyinsky, M. Sirotyuk, E. Tsirulnikov, and E. Shchekanov. "The effect of focused ultrasound on the skin and deep nerve structures of man and animal". *Progress in brain research* 43, 1976, pp. 279–292.

66. D. Geng, N. Yan, W. Xie, Y. Lü, and B. Wei. "Extraordinary Solidification Mechanism of Liquid Alloys Under Acoustic Levitation State". *Advanced Materials*, 2022, p. 2206464.

67. Z. J. Geng. *Method and apparatus for an interactive volumetric three dimensional display*. US Patent 7,098,872. 2006.

68. O. Georgiou, W. Frier, E. Freeman, C. Pacchierotti, and T. Hoshi. "Mid-Air Haptics: Future Challenges and Opportunities". *Ultrasound Mid-Air Haptics for Touchless Interfaces*, 2022, pp. 385–397.

69. O. Georgiou, W. Frier, and O. Schneider. "User Experience and Mid-Air Haptics: Applications, Methods, and Challenges". *Ultrasound Mid-Air Haptics for Touchless Interfaces*, 2022, pp. 21–69.

70. M. Gharat, R. Patanwala, and A. Ganaparthi. "Audio guidance system for blind". In: *2017 International conference of Electronics, Communication and Aerospace Technology (ICECA)*. Vol. 1. IEEE. 2017, pp. 381–384.

71. L. P. Gor'kov. "On the forces acting on a small particle in an acoustical field in an ideal fluid". In: *Sov. Phys. Dokl.* Vol. 6. 1962, pp. 773–775.

72. T. Grossman and R. Balakrishnan. "Collaborative interaction with volumetric displays". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 2008, pp. 383–392.

73. T. Grossman and R. Balakrishnan. "The design and evaluation of selection techniques for 3D volumetric displays". In: *Proceedings of the 19th annual ACM symposium on User interface software and technology*. 2006, pp. 3–12.

74. T. Grossman, D. Wigdor, and R. Balakrishnan. "Multi-finger gestural interaction with 3d volumetric displays". In: *Proceedings of the 17th annual ACM symposium on User interface software and technology*. 2004, pp. 61–70.

75. A. Hamada, H. G. Jung, K. Orozco, and G. Mattson. "Anticipated Stigma and Self-Racialization: From Alcohol Flush Reaction to Panethnic Asian Glow". *Deviant Behavior* 43:8, 2022, pp. 976–990.

76. J. D. Hardy, C. Muschenheim, et al. "The radiation of heat from the human body. IV. The emission, reflection, and transmission of infra-red radiation by the human skin". *The Journal of clinical investigation* 13:5, 1934, pp. 817–831.

77. W. A. Harkness and J. H. Goldschmid. *Free-form spatial 3-D printing using part levitation*. US Patent 9,908,288. 2018.

78. D. Harley, A. P. Tarun, D. Germinario, and A. Mazalek. "Tangible vr: Diegetic tangible objects for virtual reality narratives". In: *Proceedings of the 2017 conference on designing interactive systems*. 2017, pp. 1253–1263.

79. J. Hartmann, C. Holz, E. Ofek, and A. D. Wilson. "Realitycheck: Blending virtual environments with situated physical reality". In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 2019, pp. 1–12.

80. J. J. Hawkes and W. T. Coakley. "Force field particle filter, combining ultrasound standing waves and laminar flow". *Sensors and Actuators B: Chemical* 75:3, 2001, pp. 213–222.

81. Z. He, F. Zhu, and K. Perlin. "Physhare: Sharing physical interaction in virtual reality". In: *Adjunct Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology*. 2017, pp. 17–19.

82. P. Henry, M. Krainin, E. Herbst, X. Ren, and D. Fox. "RGB-D mapping: Using Kinect-style depth cameras for dense 3D modeling of indoor environments". *The international journal of Robotics Research* 31:5, 2012, pp. 647–663.

83. D. Herlach, R. Cochrane, I. Egry, H. Fecht, and A. Greer. "Containerless processing in the study of metallic melts and their solidification". *International Materials Reviews* 38:6, 1993, pp. 273–347.

84. R. Hirayama, G. Christopoulos, D. Martinez Plasencia, and S. Subramanian. "High-speed acoustic holography with arbitrary scattering objects". *Science advances* 8:24, 2022, eabn7614.

85. R. Hirayama, D. Martinez Plasencia, N. Masuda, and S. Subramanian. "A volumetric display for visual, tactile and audio presentation using acoustic trapping". *Nature* 575:7782, 2019, pp. 320–323. ISSN: 14764687. DOI: 10.1038/s41586-019-1739-5. URL: http://dx.doi.org/10.1038/s41586-019-1739-5.

86. R. Hirayama, D. Martinez Plasencia, N. Masuda, and S. Subramanian. "A volumetric display for visual, tactile and audio presentation using acoustic trapping". *Nature* 575:7782, 2019, pp. 320–323.

87. K. Hirota and M. Hirose. "Simulation and presentation of curved surface in virtual reality environment through surface display". In: *Proceedings Virtual Reality Annual International Symposium'95*. IEEE. 1995, pp. 211–216.

88. M. Hoppe, P. Knierim, T. Kosch, M. Funk, L. Futami, S. Schneegass, N. Henze, A. Schmidt, and T. Machulla. "VRHapticDrones: Providing haptics in virtual reality through quadcopters". In: *Proceedings of the 17th International Conference on Mobile and Ubiquitous Multimedia*. 2018, pp. 7–18.

89. T. Hoshi, M. Takahashi, T. Iwamoto, and H. Shinoda. "Noncontact tactile display based on radiation pressure of airborne ultrasound". *IEEE Transactions on Haptics* 3:3, 2010, pp. 155–165.

90. V. A. Hosseinzadeh, C. Brugnara, and R. G. Holt. "Shape oscillations of single blood drops: applications to human blood and sickle cell disease". *Scientific reports* 8:1, 2018, pp. 1–8.

91. S. Hou, B. H. Thomas, and X. Lu. "VRMenuDesigner: A toolkit for automatically generating and modifying VR menus". In: *2021 IEEE International Conference on Artificial Intelligence and Virtual Reality (AIVR)*. IEEE. 2021, pp. 154–159.

92. T. M. Huh, K. Sanders, M. Danielczuk, M. Li, Y. Chen, K. Goldberg, and H. S. Stuart. "A multi-chamber smart suction cup for adaptive gripping and haptic exploration". In: *2021 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE. 2021, pp. 1786–1793.

93. R. W. Hyers and J. R. Rogers. “A review of electrostatic levitation for materials research”. *High Temperature Materials and Processes* 27:6, 2008, pp. 461–474.

94. S. Inoue, S. Mogami, T. Ichiyama, A. Noda, Y. Makino, and H. Shinoda. “Acoustical boundary hologram for macroscopic rigid-body levitation”. *The Journal of the Acoustical Society of America* 145:1, 2019, pp. 328–337.

95. E. Jankauskis, S. Elizondo, R. Montano Murillo, A. Marzo, and D. Martinez Plasencia. “TipTrap: A Co-located Direct Manipulation Technique for Acoustically Levitated Content.” In: *Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology*. 2022, pp. 1–11.

96. V. M. Jooss, J. S. Bolten, J. Huwyler, and D. Ahmed. “In vivo acoustic manipulation of microparticles in zebrafish embryos”. *Science advances* 8:12, 2022, eabm2785.

97. K. Kabassi. “Evaluating websites of museums: State of the art”. *Journal of cultural heritage* 24, 2017, pp. 184–196.

98. K. Kataoka, T. Yamamoto, M. Otsuki, F. Shibata, and A. Kimura. “A new interactive haptic device for getting physical contact feeling of virtual objects”. In: *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE. 2019, pp. 1323–1324.

99. J. Kaye. “Sawtooth planar waves for haptic feedback”. In: *Adjunct proceedings of the 25th annual ACM symposium on User interface software and technology*. 2012, pp. 5–6.

100. M. Keller and F. Exposito. “Game room map integration in virtual environments for free walking”. In: *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE. 2018, pp. 763–764.

101. M. Keller and T. Tchilinguirian. “Obstacles awareness methods from occupancy map for free walking in VR”. In: *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE. 2019, pp. 1012–1013.

102. H. Kim, H. Yi, H. Lee, and W. Lee. “Hapcube: A wearable tactile device to provide tangential and normal pseudo-force feedback on a fingertip”. In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 2018, pp. 1–13.

103. J. Kim and H. Gil. “Top-Levi: Multi-User Interactive System Using Acoustic Levitation”. In: *Adjunct Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology*. 2022, pp. 1–3.

104. M. Kim, J. Lee, H. Lee, S. Kim, H. Jung, and K.-H. Han. "The color and blink frequency of LED notification lights and smartphone users' urgency perception". In: *HCI International 2014-Posters' Extended Abstracts: International Conference, HCI International 2014, Heraklion, Crete, Greece, June 22-27, 2014. Proceedings, Part II 16*. Springer. 2014, pp. 621–625.

105. D. P. Kingma and J. Ba. "Adam: A method for stochastic optimization". *arXiv preprint arXiv:1412.6980*, 2014.

106. G. R. Kirkham, E. Britchford, T. Upton, J. Ware, G. M. Gibson, Y. Devaud, M. Ehrbar, M. Padgett, S. Allen, L. D. Buttery, et al. "Precision assembly of complex cellular microenvironments using holographic optical tweezers". *Scientific reports* 5:1, 2015, pp. 1–7.

107. M. Kiyokawa and N. Hashimoto. "Dynamic Projection Mapping with 3D Images Using Volumetric Display". In: *2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*. IEEE. 2021, pp. 597–598.

108. S. Kondo and K. Okubo. "Mid-air acoustic tweezers for non-contact pick up using multichannel controlled ultrasonic transducer arrays". *Japanese Journal of Applied Physics* 60:SD, 2021, SDDD16.

109. R. Körner, L.-E. Petersen, and A. Schütz. "Do expansive or contractive body postures affect feelings of self-worth? High power poses impact state self-esteem". *Current Psychology* 40, 2021, pp. 4112–4124.

110. V. Kostov, J. Ozawa, and S. Matsuura. "Analysis of wearable interface factors for appropriate information notification". In: *Eighth International Symposium on Wearable Computers*. Vol. 1. IEEE. 2004, pp. 102–109.

111. T. Kozuka, K. Yasui, T. Tuziuti, A. Towata, and Y. Iida. "Noncontact acoustic manipulation in air". *Japanese Journal of Applied Physics* 46:7S, 2007, p. 4948.

112. K. Kumagai and Y. Hayasaki. "Colored voxels of laser-excited aerial volumetric display". In: *Digital Holography and Three-Dimensional Imaging*. Optica Publishing Group. 2022, W3A–1.

113. K. Kumagai, S. Miura, and Y. Hayasaki. "Colour volumetric display based on holographic-laser-excited graphics using drawing space separation". *Scientific reports* 11:1, 2021, p. 22728.

114. K. Kumagai, S. Miura, and Y. Hayasaki. "Laser-excited volumetric display using aerial re-imaging by parabolic mirrors". In: *Digital Optical Technologies 2021*. Vol. 11788. SPIE. 2021, pp. 99–103.

115. A. Kundt. "Ueber eine neue Art akustischer Staubfiguren und über die Anwendung derselben zur Bestimmung der Schallgeschwindigkeit in festen Körpern und Gasen". *Annalen der Physik* 203:4, 1866, pp. 497–523.

116. *Kundtsches Staubrohr*. 2017. URL: http://www.uranmaschine.de/44450.Kundtsches_Rohr/.

117. B. Laha and D. A. Bowman. "Volume cracker: a bimanual 3D interaction technique for analysis of raw volumetric data". In: *Proceedings of the 1st symposium on Spatial user interaction*. 2013, pp. 61–68.

118. N. A. Lal, S. Prasad, and M. Farik. "A review of authentication methods". *vol* 5, 2016, pp. 246–249.

119. K. Langhans, D. Bahr, D. Bezecny, D. Homann, K. Oltmann, K. Oltmann, C. Guill, E. Rieper, and G. Ardey. "FELIX 3D display: an interactive tool for volumetric imaging". In: *Stereoscopic Displays and Virtual Reality Systems IX*. Vol. 4660. SPIE. 2002, pp. 176–190.

120. K. Langhans, K. Oltmann, S. Reil, L. Goldberg, and H. Hatecke. "FELIX 3D display: Human-machine interface for interactive real three-dimensional imaging". In: *Virtual Storytelling. Using Virtual Reality Technologies for Storytelling: Third International Conference, ICVS 2005, Strasbourg, France, November 30-December 2, 2005. Proceedings 3*. Springer. 2005, pp. 22–31.

121. T. Laurell, F. Petersson, and A. Nilsson. "Chip integrated strategies for acoustic separation and manipulation of cells and particles". *Chemical Society Reviews* 36:3, 2007, pp. 492–506.

122. R. Law, S. Qi, and D. Buhalis. "Progress in tourism management: A review of website evaluation in tourism research". *Tourism management* 31:3, 2010, pp. 297–313.

123. D. Lawrence and S. Tavakol. "Website Usability". *Balanced Website Design: Optimising Aesthetics, Usability and Purpose*, 2007, pp. 37–58.

124. I. Lediaeva and J. LaViola. "Evaluation of body-referenced graphical menus in virtual environments". In: *Graphics Interface 2020*. 2020.

125. J. Lee and H. Ishii. "Beyond: collapsible tools and gestures for computational design". In: *CHI'10 Extended Abstracts on Human Factors in Computing Systems*. 2010, pp. 3931–3936.

126. J. Li, W. D. Jamieson, P. Dimitriou, W. Xu, P. Rohde, B. Martinac, M. Baker, B. W. Drinkwater, O. K. Castell, and D. A. Barrow. "Building programmable multicompartment artificial cells incorporating remotely activated protein channels using microfluidics and acoustic levitation". *Nature Communications* 13:1, 2022, pp. 1–12.

127. Y. Li, K. Kim, A. Erickson, N. Norouzi, J. Jules, G. Bruder, and G. F. Welch. "A Scoping Review of Assistance and Therapy with Head-Mounted Displays for People Who Are Visually Impaired". *ACM Transactions on Accessible Computing (TACCESS)* 15:3, 2022, pp. 1–28.

128. H. W. Lim, I. Kohli, C. Granger, C. Trullàs, J. Piquero-Casals, M. Narda, P. Masson, J. Krutmann, and T. Passeron. "Photoprotection of the skin from visible light–induced pigmentation: current testing methods and proposed harmonization". *Journal of Investigative Dermatology* 141:11, 2021, pp. 2569–2576.

129. Y. Liu and J. Hu. "Trapping of particles by the leakage of a standing wave ultrasonic field". *Journal of Applied Physics* 106:3, 2009, p. 034903.

130. T. M. Llewellyn-Jones, B. W. Drinkwater, and R. S. Trask. "3D printed components with ultrasonically arranged microscale structure". *Smart Materials and Structures* 25:2, 2016, 02LT01.

131. R. Lyu, H. Hao, W. Chen, Y. Liu, F. Wang, and A. C. Wu. "Elastylus: flexible haptic painting stylus". In: *SIGGRAPH Asia 2015 Emerging Technologies*. 2015, pp. 1–3.

132. M. Manabe, K. Ushiyama, A. Takahashi, and H. Kajimoto. "Vibrotactile Presentation using a Motor within a Housing and Rotor Fixed to the Skin". In: *2021 IEEE World Haptics Conference (WHC)*. IEEE. 2021, pp. 906–911.

133. M. Marshall, T. Carter, J. Alexander, and S. Subramanian. "Ultra-tangibles: creating movable tangible objects on interactive tables". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 2012, pp. 2185–2188.

134. A. Marzo. "Prototyping Airborne Ultrasonic Arrays". In: *Ultrasound Mid-Air Haptics for Touchless Interfaces*. Springer, 2022, pp. 335–346.

135. A. Marzo, A. Barnes, and B. W. Drinkwater. "TinyLev: A multi-emitter single-axis acoustic levitator". *Review of Scientific Instruments* 88:8, 2017, p. 085105.

136. A. Marzo, A. Barnes, and B. W. Drinkwater. "TinyLev: A multi-emitter single-axis acoustic levitator". *Review of Scientific Instruments* 88:8, 2017. ISSN: 10897623. DOI: 10.1063/1.4989995.

137. A. Marzo, M. Caleap, and B. W. Drinkwater. "Acoustic virtual vortices with tunable orbital angular momentum for trapping of mie particles". *Physical review letters* 120:4, 2018, p. 044301.

138. A. Marzo, T. Corkett, and B. W. Drinkwater. "Ultraino: An open phased-array system for narrowband airborne ultrasound transmission". *IEEE transactions on ultrasonics, ferroelectrics, and frequency control* 65:1, 2017, pp. 102–111.

139. A. Marzo and B. W. Drinkwater. "Holographic acoustic tweezers". *Proceedings of the National Academy of Sciences* 116:1, 2019, pp. 84–89. ISSN: 0027-8424. DOI: 10.1073/pnas.1813047115.

140. A. Marzo, R. McGeehan, J. McIntosh, S. A. Seah, and S. Subramanian. "Ghost touch: Turning surfaces into interactive tangible canvases with focused ultrasound". In: *Proceedings of the 2015 International Conference on Interactive Tabletops & Surfaces*. 2015, pp. 137–140.

141. A. Marzo, S. A. Seah, B. W. Drinkwater, D. R. Sahoo, B. Long, and S. Subramanian. "Holographic acoustic elements for manipulation of levitated objects". *Nature communications* 6:1, 2015, pp. 1–7.

142. A. Marzo, S. A. Seah, B. W. Drinkwater, D. R. Sahoo, B. Long, and S. Subramanian. "Holographic acoustic elements for manipulation of levitated objects". *Nature Communications* 6:May, 2015, p. 8661. ISSN: 2041-1723. DOI: 10.1038/ncomms9661. URL: http://www.nature.com/doifinder/10.1038/ncomms9661.

143. M. Maunsbach, K. Hornbæk, and H. Seifi. "Whole-Hand Haptics for Mid-air Buttons". In: *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications*. Springer. 2022, pp. 292–300.

144. N. Mauro and K. Kelton. "A highly modular beamline electrostatic levitation facility, optimized for in situ high-energy x-ray scattering studies of equilibrium and supercooled liquids". *Review of Scientific Instruments* 82:3, 2011, p. 035114.

145. J. G. McDaniel and R. G. Holt. "Measurement of aqueous foam rheology by acoustic levitation". *Physical Review E* 61:3, 2000, R2204.

146. A. Mehrabian. "Significance of posture and position in the communication of attitude and status relationships." *Psychological bulletin* 71:5, 1969, p. 359.

147. K. Melde, E. Choi, Z. Wu, S. Palagi, T. Qiu, and P. Fischer. "Acoustic fabrication via the assembly and fusion of particles". *Advanced Materials* 30:3, 2018, p. 1704507.

148. K. Melde, A. G. Mark, T. Qiu, and P. Fischer. "Holograms for acoustics". *Nature* 537:7621, 2016, pp. 518–522.

149. G. Memoli, M. Caleap, M. Asakawa, D. R. Sahoo, B. W. Drinkwater, and S. Subramanian. "Metamaterial bricks and quantization of meta-surfaces". *Nature Communications* 8, 2017, p. 14608. ISSN: 2041-1723. DOI: 10.1038/ncomms14608. URL: http://www.nature.com/doifinder/10.1038/ncomms14608.

150. L. Meng, F. Cai, F. Li, W. Zhou, L. Niu, and H. Zheng. "Acoustic tweezers". *Journal of Physics D: Applied Physics* 52:27, 2019, p. 273001.

151. D. Michael. *https://thecriticaltechnologist.wordpress.com/audiovisual/*.

152. P. Monteiro, H. Coelho, G. Gonçalves, M. Melo, and M. Bessa. "Comparison of radial and panel menus in virtual reality". *IEEE Access* 7, 2019, pp. 116370–116379.

153. R. Morales, I. Ezcurdia, J. Irisarri, M. A. Andrade, and A. Marzo. "Generating airborne ultrasonic amplitude patterns using an open hardware phased array". *Applied Sciences* 11:7, 2021, p. 2981.

154. R. Morales, O. Georgiou, A. Marzo, and W. Frier. "Comparison of Experiment and Simulation of Ultrasonic Mid-air Haptic Forces". In: *2022 International Conference on Interactive Media, Smart Systems and Emerging Technologies (IMET)*. IEEE. 2022, pp. 1–4.

155. R. Morales, A. Marzo, S. Subramanian, and D. Martınez. "LeviProps: Animating levitated optimized fabric structures using holographic acoustic tweezers". In: *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*. 2019, pp. 651–661.

156. R. Morales, D. Pittera, O. Georgiou, B. Kappus, and W. Frier. "UltraButton: A Minimalist Touchless Multimodal Haptic Button". *IEEE Transactions on Haptics*, 2022.

157. R. Morales González, E. Freeman, and O. Georgiou. "Levi-loop: a mid-air gesture controlled levitating particle game". In: *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems*. 2020, pp. 1–4.

158. R. Morales González, A. Marzo, E. Freeman, W. Frier, and O. Georgiou. "UltraPower: Powering Tangible & Wearable Devices with Focused Ultrasound". In: *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction*. 2021, pp. 1–13.

159. B. A. Morgan, Z. Xing, E. D. Cranston, and M. R. Thompson. "Acoustic levitation as a screening method for excipient selection in the development of dry powder vaccines". *International Journal of Pharmaceutics* 563, 2019, pp. 71–78.

160. S. Nagasaka, Y. Uranishi, S. Yoshimoto, M. Imura, and O. Oshiro. "Haptylus: haptic stylus for interaction with virtual objects behind a touch screen". In: *SIGGRAPH Asia 2014 Emerging Technologies*. 2014, pp. 1–3.

161. J. R. Napier. "The prehensile movements of the human hand". *The Journal of bone and joint surgery. British volume* 38:4, 1956, pp. 902–913.

162. A. Naumann and P. Methfessel. "Improving 3D-Editing Workflows via Acoustic Levitation". In: *Adjunct Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology*. 2022, pp. 1–4.

163. K. C. Neuman and S. M. Block. "Optical trapping". *Review of scientific instruments* 75:9, 2004, pp. 2787–2809.

164. M. K. Nichols, R. K. Kumar, P. G. Bassindale, L. Tian, A. C. Barnes, B. W. Drinkwater, A. J. Patil, and S. Mann. "Fabrication of Micropatterned Dipeptide Hydrogels by Acoustic Trapping of Stimulus-Responsive Coacervate Droplets". *Small* 14:26, 2018, p. 1800739.

165. Y. Nishii, G. T. Sameshima, J. K. Mah, R. Enciso, T. Takaki, and K. Sueishi. "Hard palate thickness for temporary anchorage devices placement: differences in sex and ethnicity". *orthodontic waves* 73:4, 2014, pp. 121–129.

166. M. A. Norasikin, D. Martinez-Plasencia, G. Memoli, and S. Subramanian. "SonicSpray: a technique to reconfigure permeable mid-air displays". In: *Proceedings of the 2019 ACM International Conference on Interactive Surfaces and Spaces*. 2019, pp. 113–122.

167. I. I. I. Al-Nuaimi, M. N. Mahyuddin, and N. K. Bachache. "A Non-Contact Manipulation for Robotic Applications: A Review on Acoustic Levitation". *IEEE Access*, 2022.

168. J. O'keefe and L. Nadel. "Précis of O'Keefe & Nadel's The hippocampus as a cognitive map". *Behavioral and Brain Sciences* 2:4, 1979, pp. 487–494.

169. H. O'Neil. "Theory of focusing radiators". *The Journal of the Acoustical Society of America* 21:5, 1949, pp. 516–526.

170. Y. Ochiai, T. Hoshi, and J. Rekimoto. "Three-dimensional mid-air acoustic manipulation by ultrasonic phased arrays". *PloS one* 9:5, 2014, e97590.

171. Y. Ochiai, K. Kumagai, T. Hoshi, J. Rekimoto, S. Hasegawa, and Y. Hayasaki. "Fairy lights in femtoseconds: aerial and volumetric graphics rendered by focused femtosecond laser combined with computational holographic fields". *ACM Transactions on Graphics (TOG)* 35:2, 2016, pp. 1–14.

172. A. Olwal and B. Kress. "1D eyewear: peripheral, hidden LEDs and near-eye holographic displays for unobtrusive augmentation". In: *Proceedings of the 2018 ACM International Symposium on Wearable Computers*. 2018, pp. 184–187.

173. T. Omirou, A. M. Perez, S. Subramanian, and A. Roudaut. "Floating charts: Data plotting using free-floating acoustically levitated representations". In: *2016 IEEE Symposium on 3D User Interfaces (3DUI)*. IEEE. 2016, pp. 187–190.

174. M. Ott, F. Schaeffel, and W. Kirmse. "Binocular vision and accommodation in prey-catching chameleons". *Journal of Comparative Physiology A* 182, 1998, pp. 319–330.

175. A. Ozcelik, J. Rufo, F. Guo, Y. Gu, P. Li, J. Lata, and T. J. Huang. "Acoustic tweezers for the life sciences". *Nature methods* 15:12, 2018, pp. 1021–1028.

176. S. Pan, A. K. Kota, J. M. Mabry, and A. Tuteja. “Superomniphobic surfaces for effective chemical shielding”. *Journal of the American Chemical Society* 135:2, 2013, pp. 578–581.

177. V. Paneva, A. Fleig, D. M. Plasencia, T. Faulwasser, and J. Müller. “OptiTrap: Optimal Trap Trajectories for Acoustic Levitation Displays”. *ACM Transactions on Graphics (TOG)*, 2022.

178. J. F. Parker Jr and V. R. West. “Bioastronautics Data Book: NASA SP-3006.” *NASA Special Publication* 3006, 1973.

179. S. Pei, A. Chen, J. Lee, and Y. Zhang. “Hand Interfaces: Using Hands to Imitate Objects in AR/VR for Expressive Interactions”. In: *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*. 2022, pp. 1–16.

180. K. Pfeuffer, L. Mecke, S. Delgado Rodriguez, M. Hassib, H. Maier, and F. Alt. “Empirical evaluation of gaze-enhanced menus in virtual reality”. In: *Proceedings of the 26th ACM Symposium on Virtual Reality Software and Technology*. 2020, pp. 1–11.

181. C. Poirier, A. De Volder, D. Tranduy, and C. Scheiber. “Pattern recognition using a device substituting audition for vision in blindfolded sighted subjects”. *Neuropsychologia* 45:5, 2007, pp. 1108–1121.

182. S. Polychronopoulos and G. Memoli. “Acoustic levitation with optimized reflective metamaterials”. *Scientific reports* 10:1, 2020, pp. 1–10.

183. F. Priego-Capote and L. de Castro. “Ultrasound-assisted levitation: Lab-on-a-drop”. *TrAC Trends in Analytical Chemistry* 25:9, 2006, pp. 856–867.

184. M. Prisbrey and B. Raeymaekers. “Aligning high-aspect-ratio particles in user-specified orientations with ultrasound-directed self-assembly”. *Physical Review Applied* 12:1, 2019, p. 014014.

185. D. R. Pur, N. Lee-Wing, and M. D. Bona. “The use of augmented reality and virtual reality for visual field expansion and visual acuity improvement in low vision rehabilitation: a systematic review”. *Graefe’s Archive for Clinical and Experimental Ophthalmology*, 2023, pp. 1–13.

186. L. Puskar, R. Tuckermann, T. Frosch, J. Popp, V. Ly, D. McNaughton, and B. R. Wood. “Raman acoustic levitation spectroscopy of red blood cells and Plasmodium falciparum trophozoites”. *Lab on a Chip* 7:9, 2007, pp. 1125–1131.

187. O. Putkis. *Contactless manipulation apparatus, assembly method and 3d printing*. US Patent App. 15/765,126. 2018.

188. M. Rauter, C. Abseher, and M. Safar. “Augmenting virtual reality with near real world objects”. In: *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE. 2019, pp. 1134–1135.

189. C. A. Rey. *Acoustic levitation and methods for manipulating levitated objects*. US Patent 4,284,403. 1981.

190. M. Reynal, E. Freeman, and S. Brewster. “Towards Adding Pseudo-Haptic Effects to Acoustic Levitation Displays”. In: *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems*. 2021, pp. 1–6.

191. M. Röthlisberger, M. Schuck, L. Kulmer, and J. W. Kolar. “Contactless picking of objects using an acoustic gripper”. In: *Actuators*. Vol. 10. 4. MDPI. 2021, p. 70.

192. D. J. Ryan, A. Kamel, and G. J. Bruck. *Acoustic manipulation and laser processing of particles for repair and manufacture of metallic components*. US Patent App. 14/997,554. 2016.

193. N. Sae-Bae, J. Wu, N. Memon, J. Konrad, and P. Ishwar. “Emerging NUI-based methods for user authentication: A new taxonomy and survey”. *IEEE Transactions on Biometrics, Behavior, and Identity Science* 1:1, 2019, pp. 5–31.

194. D. R. Sahoo, T. Nakamura, A. Marzo, T. Omirou, M. Asakawa, and S. Subramanian. “JOLED: A Mid-air Display based on Electrostatic Rotation of Levitated Janus Objects”. *Proceedings of the 29th Annual Symposium on User Interface Software and Technology - UIST ’16*, 2016, pp. 437–448. DOI: 10.1145/2984511.2984549. URL: http://dl.acm.org/citation.cfm?doid=2984511.2984549.

195. D. R. Sahoo, T. Nakamura, A. Marzo, T. Omirou, M. Asakawa, and S. Subramanian. “Joled: A mid-air display based on electrostatic rotation of levitated janus objects”. In: *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. 2016, pp. 437–448.

196. S. Santesson and S. Nilsson. “Airborne chemistry: acoustic levitation in chemical analysis”. *Analytical and bioanalytical chemistry* 378:7, 2004, pp. 1704–1709.

197. M. Seckler, S. Heinz, S. Forde, A. N. Tuch, and K. Opwis. “Trust and distrust on the web: User experiences and website characteristics”. *Computers in human behavior* 45, 2015, pp. 39–50.

198. S. Sepehrirahnama, H. McManus, and S. Oberst. “ACOUSTIC LEVITATOR-TWEEZER USING PRE-PRO-GRAMMED ACOUSTIC HOLOGRAMS”. In: *28th International Congress on Sound and Vibration 2022*. 2022.

199. C. D. Shultz. “Understanding and Exploiting Electroadhesion of Human Fingertips for High Performance Surface Haptic Applications”. PhD thesis. Northwestern University, 2017.

200. G. T. Silva, J. H. Lopes, J. P. Leão-Neto, M. K. Nichols, and B. W. Drinkwater. “Particle patterning by ultrasonic standing waves in a rectangular cavity”. *Physical Review Applied* 11:5, 2019, p. 054044.

201. G. Simon, Y. Pailhas, M. A. Andrade, J. Reboud, J. Marques-Hueso, M. P. Desmulliez, J. M. Cooper, M. O. Riehle, and A. L. Bernassau. “Particle separation in surface acoustic wave microfluidic devices using reprogrammable, pseudo-standing waves”. *Applied Physics Letters* 113:4, 2018, p. 044101.

202. M. Simon and A. Geim. “Diamagnetic levitation: Flying frogs and floating magnets”. *Journal of applied physics* 87:9, 2000, pp. 6200–6204.

203. G. Sinclair, P. Jordan, J. Courtial, M. Padgett, J. Cooper, and Z. J. Laczik. “Assembly of 3-dimensional structures using programmable holographic optical tweezers”. *Optics Express* 12:22, 2004, pp. 5475–5480.

204. A. F. Siu, E. J. Gonzalez, S. Yuan, J. B. Ginsberg, and S. Follmer. “Shapeshift: 2D spatial manipulation and self-actuation of tabletop shape displays for tangible and haptic interaction”. In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 2018, pp. 1–13.

205. D. Spelmezan, R. M. González, and S. Subramanian. “SkinHaptics: Ultrasound focused in the hand creates tactile sensations”. In: *2016 IEEE Haptics Symposium (HAPTICS)*. IEEE. 2016, pp. 98–105.

206. M. Sra, S. Garrido-Jurado, C. Schmandt, and P. Maes. “Procedurally generated virtual reality from 3D reconstructed physical space”. In: *Proceedings of the 22nd ACM Conference on Virtual Reality Software and Technology*. 2016, pp. 191–200.

207. S. Stepper and F. Strack. “Proprioceptive determinants of emotional and nonemotional feelings.” *Journal of personality and social psychology* 64:2, 1993, p. 211.

208. L. Strobino. *Acoustic levitation on SoC FPGA (DE0-Nano-SoC)*. 2019. URL: https://gitlab.com/leastrobino/acoustic-levitation.

209. Y. Sugiura, K. Toda, T. Hoshi, Y. Kamiyama, T. Igarashi, and M. Inami. “Graffiti fur: turning your carpet into a computer display”. In: *Proceedings of the 27th annual ACM symposium on User interface software and technology*. 2014, pp. 149–156.

210. D. Sukhanov, S. Roslyakov, and F. Emelyanov. “Layer-by-layer application of particles using acoustic levitation”. In: *Journal of Physics: Conference Series*. Vol. 1499. 1. IOP Publishing. 2020, p. 012024.

211. M. Sundvik, H. J. Nieminen, A. Salmi, P. Panula, and E. Hæggström. “Effects of acoustic levitation on the development of zebrafish, Danio rerio, embryos”. *Scientific reports* 5:1, 2015, pp. 1–11.

212. R. Suzuki, E. Ofek, M. Sinclair, D. Leithinger, and M. Gonzalez-Franco. “Hapticbots: Distributed encountered-type haptics for vr with multiple shape-changing mobile robots”. In: *The 34th Annual ACM Symposium on User Interface Software and Technology*. 2021, pp. 1269–1281.

213. T. Tanabe, H. Endo, and S. Ino. “Effects of asymmetric vibration frequency on pulling illusions”. *Sensors* 20:24, 2020, p. 7086.

214. T. Tanabe, K. Nunokawa, K. Doi, and S. Ino. “Training System for White Cane Technique using Illusory Pulling Cues Induced by Asymmetric Vibrations”. *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 30, 2022, pp. 305–313.

215. T. Tanabe, H. Yano, H. Endo, S. Ino, and H. Iwata. “Motion guidance using translational force and torque feedback by induced pulling illusion”. In: *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications*. Springer. 2020, pp. 471–479.

216. T. Tanabe, H. Yano, H. Endo, S. Ino, and H. Iwata. “Pulling illusion based on the phase difference of the frequency components of asymmetric vibrations”. *IEEE/ASME Transactions on Mechatronics* 26:1, 2020, pp. 203–213.

217. T. Tanabe, H. Yano, and H. Iwata. “Evaluation of the perceptual characteristics of a force induced by asymmetric vibrations”. *IEEE Transactions on Haptics* 11:2, 2017, pp. 220–231.

218. L. Tian, N. Martin, P. G. Bassindale, A. J. Patil, M. Li, A. Barnes, B. W. Drinkwater, and S. Mann. “Spontaneous assembly of chemically encoded two-dimensional coacervate droplet arrays by acoustic wave patterning”. *Nature communications* 7:1, 2016, pp. 1–10.

219. X. de Tinguy, T. Howard, C. Pacchierotti, M. Marchal, and A. Lécuyer. “Weatavix: wearable actuated tangibles for virtual reality experiences”. In: *Haptics: Science, Technology, Applications: 12th International Conference, EuroHaptics 2020, Leiden, The Netherlands, September 6–9, 2020, Proceedings 12*. Springer. 2020, pp. 262–270.

220. E. Trinh and C. Hsu. “Acoustic levitation methods for density measurements”. *The Journal of the Acoustical Society of America* 80:6, 1986, pp. 1757–1761.

221. S. Tsujino and T. Tomizaki. "Ultrasonic acoustic levitation for fast frame rate X-ray protein crystallography at room temperature". *Scientific reports* 6:1, 2016, pp. 1–9.

222. u/Evlmnkey. *R/arduino - this is my take at a 'hologram' for my bachelors. far from perfect but I hope it being true 3D and live-captured sets it apart. Ama if you want :)* URL: https://www.reddit.com/r/arduino/comments/lmtdf9/this_is_my_take_at_a_hologram_for_my_bachelors/?sort=qa.

223. Ultraleap. *The end of public touchscreens? [study]*. URL: https://www.ultraleap.com/company/news/resources/public-touchscreens-whitepaper/.

224. V. Vandaele, P. Lambert, and A. Delchambre. "Non-contact handling in microassembly: Acoustical levitation". *Precision engineering* 29:4, 2005, pp. 491–505.

225. T. Vasileiou, D. Foresti, A. Bayram, D. Poulikakos, and A. Ferrari. "Toward contactless biology: Acoustophoretic DNA transfection". *Scientific reports* 6:1, 2016, pp. 1–10.

226. Vasturiano. *Vasturiano/3D-force-graph: 3D force-directed graph component using threejs/webgl*. URL: https://github.com/vasturiano/3d-force-graph.

227. C. T. Vi, A. Marzo, D. Ablart, G. Memoli, S. Subramanian, B. Drinkwater, and M. Obrist. "Tastyfloats: A contactless food delivery system". In: *Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces*. 2017, pp. 161–170.

228. C. T. Vi, A. Marzo, G. Memoli, E. Maggioni, D. Ablart, M. Yeomans, and M. Obrist. "LeviSense: A platform for the multisensory integration in levitating food and insights into its effect on flavour perception". *International Journal of Human-Computer Studies* 139, 2020, p. 102428.

229. VoxonNew and L. Manuel. *The voxon VX1 - now available for purchase*. 2020. URL: https://voxon.co/voxon-vx1-available-for-purchase/.

230. V. Vuibert, W. Stuerzlinger, and J. R. Cooperstock. "Evaluation of docking task performance using mid-air interaction techniques". In: *Proceedings of the 3rd ACM Symposium on Spatial User Interaction*. 2015, pp. 44–52.

231. K. Wakatsuki, C. Fujikawa, and M. Omodani. "Evaluation of visible region in volumetric 3D display using a rotating helical screen". *Japanese Journal of Applied Physics* 61:6, 2022, p. 062005.

232. W.-H. Wang, H.-E. Chen, and M. Y. Chen. "UltraBat: An Interactive 3D Side-Scrolling Game using Ultrasound Levitation". In: *Adjunct Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology*. 2022, pp. 1–2.

233. A. Watanabe, K. Hasegawa, and Y. Abe. "Contactless fluid manipulation in air: Droplet coalescence and active mixing by acoustic levitation". *Scientific reports* 8:1, 2018, pp. 1–8.

234. B. Weber, S. Schätzle, T. Hulin, C. Preusche, and B. Deml. "Evaluation of a vibrotactile feedback device for spatial guidance". In: *2011 IEEE World Haptics Conference*. IEEE. 2011, pp. 349–354.

235. R. J. Weber, C. J. Benmore, S. K. Tumber, A. N. Tailor, C. A. Rey, L. S. Taylor, and S. R. Byrn. "Acoustic levitation: recent developments and emerging opportunities in biomaterials research". *European Biophysics Journal* 41:4, 2012, pp. 397–403.

236. F. Weineck, D. Schultchen, G. Hauke, M. Messner, and O. Pollatos. "Using bodily postures to reduce anxiety and improve interoception: A comparison between powerful and neutral poses". *PLoS One* 15:12, 2020, e0242578.

237. D. Wenham and P. Zaphiris. "User interface evaluation methods for internet banking web sites: a review, evaluation and case study". In: 2003.

238. M. S. Westphall, K. Jorabchi, and L. M. Smith. "Mass spectrometry of acoustically levitated droplets". *Analytical chemistry* 80:15, 2008, pp. 5847–5853.

239. E. J. Whitesell. *Volumetric display*. US Patent 6,177,913. 2001.

240. R. R. Whymark. "Acoustic field positioning for containerless processing". *Ultrasonics* 13:6, 1975, pp. 251–261. ISSN: 0041624X. DOI: 10.1016/0041-624X(75)90072-4. URL: http://linkinghub.elsevier.com/retrieve/pii/0041624X75900724.

241. R. Whymark. "Acoustic field positioning for containerless processing". *Ultrasonics* 13:6, 1975, pp. 251–261.

242. E. Williams. *3D printed helix displays graphics in 3D*. 2015. URL: https://hackaday.com/2015/10/29/3d-printed-helix-displays-graphics-in-3d/.

243. A. Withana, M. Kondo, Y. Makino, G. Kakehi, M. Sugimoto, and M. Inami. "ImpAct: Immersive haptic stylus to enable direct touch and manipulation for surface computing". *Computers in Entertainment (CIE)* 8:2, 2010, pp. 1–16.

244. S. Xiao, E. Angjeli, H. C. Wu, E. D. Gaier, S. Gomez, D. A. Travers, G. Binenbaum, R. Langer, D. G. Hunter, M. X. Repka, et al. "Randomized controlled trial of a dichoptic digital therapeutic for amblyopia". *Ophthalmology* 129:1, 2022, pp. 77–85.

245. W. Xie, C. Cao, Y. Lü, Z. Hong, and B. Wei. "Acoustic method for levitation of small living animals". *Applied Physics Letters* 89:21, 2006, p. 214102.

246. W. Xie and B. Wei. "Parametric study of single-axis acoustic levitation". *Applied Physics Letters* 79:6, 2001, pp. 881–883.

247. P. Xiong, Q. Wei, and J. Zhang. "Rendering of Visual Roughness Using Ultrasound Phased Array". In: *2022 6th International Conference on Automation, Control and Robots (ICACR)*. IEEE. 2022, pp. 242–246.

248. W. Yamada, H. Manabe, D. Ikeda, and J. Rekimoto. "RayGraphy: Aerial Volumetric Graphics Rendered Using Lasers in Fog". In: *Proceedings of the 2020 ACM Symposium on Spatial User Interaction*. 2020, pp. 1–9.

249. A. Yarin, G. Brenn, J. Keller, M. Pfaffenlehner, E. Ryssel, and C. Tropea. "Flowfield characteristics of an aerodynamic acoustic levitator". *Physics of fluids* 9:11, 1997, pp. 3300–3314.

250. K. Yasuda, S.-i. Umemura, K. Takeda, M. Tamura, and N. Shimizu. *Particle handling method by acoustic radiation force and apparatus therefore*. US Patent 5,902,489. 1999.

251. T. Yoshida, J. Ogawa, K. Y. Choi, S. Bushnaq, K. Nakagaki, and H. Ishii. "InDepth: Force-based interaction with objects beyond a physical barrier". In: *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction*. 2021, pp. 1–6.

252. O. Youssefi and E. Diller. "Contactless robotic micromanipulation in air using a magneto-acoustic system". *IEEE Robotics and Automation Letters* 4:2, 2019, pp. 1580–1586.

253. D. Zang. *Special topic on Drops and Flows in Acoustic Levitation*. 2021.

254. D. Zang, J. Li, Z. Chen, Z. Zhai, X. Geng, and B. P. Binks. "Switchable opening and closing of a liquid marble via ultrasonic levitation". *Langmuir* 31:42, 2015, pp. 11502–11507.

255. S. Zehnter and C. Ament. "A Modular FPGA-based Phased Array System for Ultrasonic Levitation with MATLAB". In: *2019 IEEE International Ultrasonics Symposium (IUS)*. IEEE. 2019, pp. 654–658.

256. J. S. Zelek, S. Bromley, D. Asmar, and D. Thompson. "A haptic glove as a tactile-vision sensory substitution for wayfinding". *Journal of Visual Impairment & Blindness* 97:10, 2003, pp. 621–632.

257. P. Zhang, H. Bachman, A. Ozcelik, and T. J. Huang. "Acoustic microfluidics". *Annual review of analytical chemistry (Palo Alto, Calif.)* 13:1, 2020, p. 17.

258. S. Zhao and J. Wallaschek. "A standing wave acoustic levitation system for large planar objects". *Archive of Applied Mechanics* 81:2, 2011, pp. 123–139.

259. F. Zhong, G. A. Koulieris, G. Drettakis, M. S. Banks, M. Chambe, F. Durand, and R. Mantiuk. "DiCE: dichoptic contrast enhancement for binocular displays". In: *ACM SIGGRAPH 2019 Posters*. 2019, pp. 1–2.