HOLOGRAPHIC ACOUSTIC ELEMENTS FOR MANIPULATION OF LEVITATED PARTICLES: APPLICATIONS TO HUMAN-COMPUTER INTERACTION.

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This Thesis is a Compendium of Research Papers

This dissertation is presented as 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 on them. In Section 2, there is a summary of each paper, the methodology and access to the papers.

The request of presenting this thesis by compendium has been approved by the thesis director ***[authDirector.pdf]*** and the doctoral school ***[authComittee.pdf]*** following the rules of the university for presenting a thesis in this modality ***[rulesCompendium.pdf]***.

The following articles are included in this thesis:

- **Holographic Acoustic Elements for Manipulation of Levitated Objects. Nature Communications.** 2015. Impact Factor 10.5, Applied Physics. Asier Marzo, Sue Ann Seah, Bruce W. Drinkwater, Deepak Ranjan Sahoo, Benjamin Long, Sriram Subramanian. *A.M. and B.W.D. designed, developed and implemented the algorithms and simulations; A.M. and S.A.S. measured the acoustic slices; A.M and D.R.S. measured the spring constants; A.M. conducted the rest of the experiments and wrote the paper; all the authors contributed to the discussion and edited the manuscript.*
- GauntLev: A Wearable to Manipulate Free-floating Objects. ACM CHI. 2016 (to appear). Core A*, Human-Computer Interaction. Asier Marzo. ***[acceptance_GauntLev.pdf]***
- **LeviPath: Modular Acoustic Levitation for 3D Path Visualisations. ACM CHI**. 2015. Core A*, Human-Computer Interaction. Themis Omirou, Asier Marzo, Sue Ann Seah, Sriram Subramanian. *A.M. developed the technical implementation based on the S.A. Moreover, A.M. wrote around half of the paper and made major editions to the rest of it.*
- **Ghost Touch: Turning Surfaces into Interactive Tangible Canvases with Focused Ultrasound. ACM ITS** 2015, Core A. Asier Marzo, Richard McGeehan, Jess McIntosh, Sue Ann Seah, Sriram Subramanian. *A.M. developed the technical part and wrote the paper.*

Summary / Resumen

Summary (English)

Acoustic waves can levitate particles of a wide range of materials and sizes through air, water or biological tissues. This is of paramount importance for crystallography, cell manipulation, lab-on-a-chip scenarios, pharmacology, containerless transportation and even levitation of living things. To date, the levitated particles had to be enclosed by acoustic elements as single-sided levitators only exerted lateral trapping forces or pulling forces. Furthermore, translation and rotation of the trap was limited. Here, for the first time we show full acoustic trapping, translation and rotation of levitated particles using a single-sided phased array. Our approach creates optimum traps at the target positions for any spatial arrangement and significantly enhances previous manipulators. We report three optimum acoustic traps: Twin traps, a novel acoustic phenomenon with the ability to rotate objects; Vortex traps, previously only shown theoretically; and Bottle traps, never proven to levitate objects before. We also introduce the concept of Holographic Acoustic Elements (HAEs) based on interpreting the phase modulations of the transducers as a holographic plate that combines the encoding of identifiable acoustic elements. HAEs allow us to analyse and efficiently generate acoustic traps as well as to compare them with optical traps.

This work brings the advantages of optical levitation (single-beam, rotation, holographic control and multiple particles) to the efficiency and versatility of acoustic levitation. As a result, we expect the development of powerful tractor beams, 3D physical displays or acoustically-controlled internal nanomachines that do not interfere with MRI visualization.

New applications for Human-Computer Interaction (HCI) can be derived from the possibility of remotely moving objects in mid-air to specific locations and even through obstacles. In the most basic configuration, we move particles over a surface to paint on sand or liquids a distance and without contact. A more advance system positions a couple of objects in 3D allowing us to represent functions and positions of objects such as planes or asteroids. The ultimate goal for a display is to levitate hundreds of particles independently to form different shapes.

Resumen (Español)

Las ondas acústicas ejercen fuerzas de radiación que forman trampas acústicas en los puntos donde estas fuerzas convergen. Estas trampas acústicas permiten la levitación de partículas de una amplia gama de materiales y tamaños a través de aire, agua o tejidos biológicos. Esto es de suma importancia para cristalografía, manipulación celular, sistemas lab-on-a-chip, biomateriales, transporte sin contacto e incluso la levitación de seres vivos.

Con los levitadores acústicos anteriores, las partículas atrapadas tenían que ser rodeadas por elementos acústicos. Los levitadores de una sola cara (o de un solo haz), sólo ejercían fuerzas laterales, empuje o requerían del uso de una lente acústica. Además, la translación y rotación de las partículas eran limitadas.

Los levitadores de un solo eje son la forma más común de generar trampas acústicas. Se componen de un transductor acústico y un reflector u otro transductor encima. Esto genera una onda estacionaria entre los dos elementos y sus nodos actúan como trampas. Al cambiar la diferencia de fase entre los transductores, las trampas se mueven en una sola dimensión sin necesidad de accionamiento mecánico. Varias configuraciones para la manipulación en dos dimensiones se han explorado, por ejemplo, una matriz plana de transductores y un reflector paralelo proporcionan movimiento dentro del plano de la matriz. Alternativamente, una formación circular de transductores orientada hacia el interior puede trasladar y rotar una partícula dentro del círculo. La translación en 3D es posible con cuatro matrices colocadas formando un cuadrado. Recientemente, elementos piezoeléctricos fabricados a medida se han utilizado para crear trampas con dispositivos de una sola cara (pinzas acústicas). Sin embargo, estas trampas ejercen solamente fuerzas laterales y por lo tanto las partículas tienen que estar apoyadas sobre una superficie. Fuerzas de tracción que actúan en contra de la dirección de propagación (rayos tractores) se han observado en agua usando partículas de forma triangular y en aire usando botellas acústicas. Trampas en tres dimensiones con dispositivos de una sola cara se han demostrado teóricamente y recientemente una trampa 3D estática bajo el agua ha sido reportada. No obstante, se requería una lente acústica física, lo que introduce una considerable pérdida de energía y limita la posición de la trampa al foco.

Atrapamiento controlado en 3D, traslación y rotación con un dispositivo de una sola cara permitiría a las pinzas acústicas convertirse en los homólogos de mayor escala de las pinzas ópticas, abriendo aplicaciones en el procesamiento de materiales, fabricación de micro-escala y biomedicina.

En mi trabajo, demostramos simultáneamente atrapamiento 3D, traslación y rotación de las partículas utilizando dispositivos de una sola cara. Esto se logra mediante el ajuste de manera óptima los retardos de fase usados para alimentar los transductores; de esta manera se generan estructuras acústicas sin precedentes y sin recurrir a lentes físicas, transductores hechos a medida o accionamiento mecánico. Nuestro método genera trampas óptimas en las posiciones deseadas con cualquier disposición espacial de los transductores; además, mejora significativamente los manipuladores anteriores. Presentamos tres trampas acústicas óptimas: trampas pinza, un nuevo fenómeno acústico que también puede rotar objetos; trampas tornado, cuyas capacidades de levitación se mostraron teóricamente y recientemente se observaron experimentalmente usando una lente acústica fija; y trampas en botella, que nunca han sido ni probadas ni sugeridas para levitar objetos. También introducimos el concepto de elementos holográficos acústicos basado en la interpretación de los retardos de fase como una placa holográfica que combina la codificación de elementos acústicos. Esta teoría permite el análisis y la generación eficiente de trampas acústicas, así como comparaciones con trampas ópticas. Este trabajo lleva las ventajas de la levitación óptica (es decir, un solo haz, rotación, control holográfico y múltiples partículas) a la eficiencia y versatilidad de la levitación acústica. Como resultado, esperamos el desarrollo de potentes rayos tractores, pantallas físicas 3D o control de micro-máquinas que están dentro de nuestro cuerpo.

Nuevas aplicaciones en interacción hombre-máquina (IHM) se pueden derivar de la posibilidad de posicionar en medio del aire objetos a distancia e incluso a través de obstáculos. En la configuración más básica, movemos partículas sobre una superficie para pintar sobre la arena o líquidos a distancia y sin contacto. Un sistema más avanzado puede posicionar un par de objetos en 3D, esto nos permite representar funciones y posiciones de objetos tales como aviones o asteroides. El objetivo final sería crear un display compuesto de cientos de partículas que levitan de forma independiente para formar diferentes formas.

Acknowledgements

It may seem obvious but the first people to whom I should be thankful are my family. I am here because my parents had me; and I got a degree because they had money to pay for it. Furthermore, they have always allowed me to pursue whatever goal I wanted, being it as stupid as creating a band or following a research career. Similarly, since I was very little, I remember my brothers playing with computers. Therefore, programming is something natural for me.

The second most important people are my friends, since school we have spent lot of time together. We all had different hobbies, degrees or ways of facing problems. I really appreciate this variety and have the naive idea that it would be fantastic working with them in a company.

Tax payers give to research a significant amount of what they earn with tremendous effort, even when sometimes it seems like wasted money in our hands, the researchers. I will always have them present in future research. My papers may not have been useful but I will work to create useful technology for humankind and to answer questions with deep implications or that greatly satisfy our curiosity.

To my teachers, they put lot of effort into teaching me the most important concepts required for being a successful computer engineer or a scientist. But more than technical knowledge, their curious and humble attitude is what really inspire their pupils. Similarly, I should be thankful to my colleagues, most of the ideas that I have or I will have are just a conglomeration of things that I have heard from them or that we have discussed while drinking tea and playing videogames.

To rejections: all the research papers presented in this thesis are accepted ones; however, rejections have been more common, especially in the early days. I have learnt most of the things trough rejections and now I do not mind them. After this thesis, I truly enjoy learning and do not get stressed by all the things that I do not know or I get wrong.

Introduction: our new hands

Curiosity is one of the most beautiful and interesting features of humankind. It is the inherent desire to discover and understand all the things that surround us: from the tide of the oceans to the fundamental particles that compose matter. This desire to understand and explore could be an evolutionary trait or an indirect necessity of answering the ultimate questions of who are we, where do we come from and where are we going. In any case, curiosity has been a strong determinant in our success.

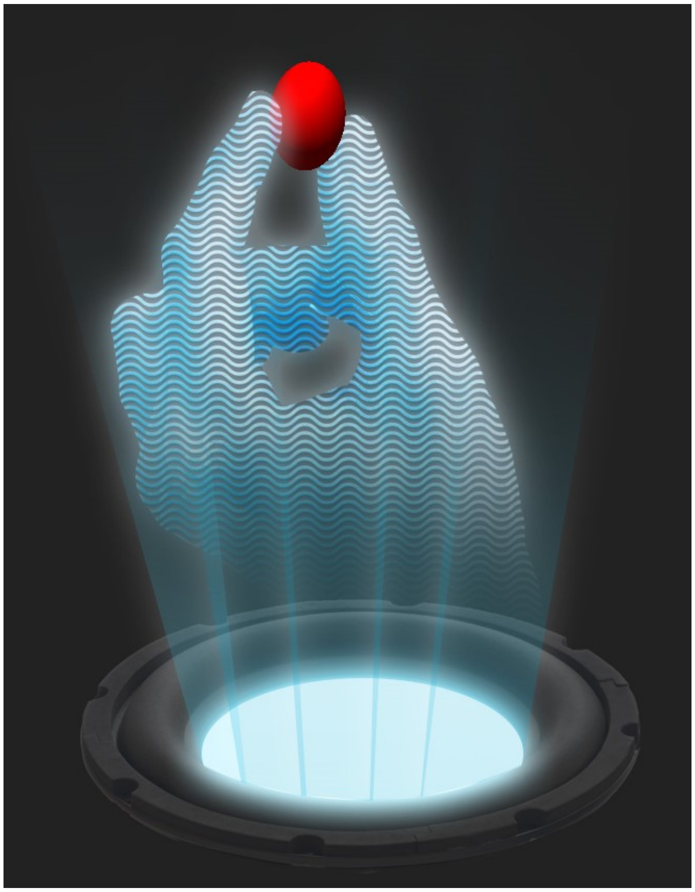
Curiosity requires the ability to see and manipulate the entities around us. We need to see for acquiring information about the environment, the main method for this is our senses and among them, our eyes are the most developed one. On the other hand, we need to manipulate the entities that we are observing, either for building new ones or just to understand their inner mechanisms. In this regards, our hands are capable of incredible feats of millimetric accuracy guided by motor-eye coordination, proprioception and touch.

Nonetheless, our hands present several limitations, for instance they require contact with the manipulated objects and partially occlude them, they are vulnerable to heat or certain substances and picking or releasing small objects is difficult. To overcome these constraints, we create and employ tools. Holding a hammer, wearing gloves or tweezing out a splinter are examples of how tools have hastened our success as a species.

Similarly, our eyes can only capture a minuscule fraction of the electromagnetic spectrum and in a scale that seems far away from atoms or stars. Luckily, we have developed microscopes and telescopes that expanded our range and scale. We have even surpassed the inherent limit of light to image things smaller than its wavelength with technologies such as electron microscopy, x-ray crystallography or super resolution microscopy. We can even observe the trail of fundamental particles in bubble-chambers.

We have also created new manipulation tools or in other words, new hands. Microscopic tweezers or cranes are a couple of examples but we have much more advanced "hands". Even since the 60s it was known that a focalized laser could trap small particles (aka optical tweezers), with this technology we can stretch DNA strains or hold atoms to cool them down to the lowest temperatures. We have also used electricity to manipulate particles (electrophoretics) being the manipulated entities things as varied as proteins in a petri dish or plasma inside a Tokamak. CRISPR or TALEN are just some of the techniques that imply that we can edit gene sequences with unprecedented control. Nowadays, 3D printers are mainstream and counterparts for the nanoworld are becoming more and more used (e.g. 2 photon lithography).

However, our ability to see has always predated our capacity to manipulate; new technologies for manipulation are highly coveted. In this thesis, we advance beyond the state of the art in acoustophoretics; namely, the manipulation of particles using the acoustic radiation force. Being sound a mechanical wave, acoustic manipulation has the best efficiency in input power to output force. Sound can travel through air, water, tissue or solids and its range of frequency permits to manipulate things from the microscopic scale (like cells or microorganisms) to the macroscale (steel bearings or blobs of liquid). We apply the new results to Human-Computer Interaction (HCI) but Holographic Acoustic Levitation will also find impactful applications on other fields.



Levitation for Human-Computer Interaction

Levitation is the process of suspending objects in mid-air without any mechanical support. Additionally, the possibility of moving these objects is usually associated with levitation. As it can be expected, the applications of moving objects in mid-air are numerous and attractive. For instance, an object levitating in mid-air can represent the position of a plane or asteroid; linked objects could represent atoms forming a molecule; and floating particles can be used as voxels to represent 3D volumes, or simply as a projector screen to project in that can be moved and moulded.

Several ways of creating levitation have been explored and utilized for the manipulation of objects. Optical levitation is based on the transfer of photons momentum [1]. Although it is extraordinarily accurate for manipulating cells and atoms, the forces and sizes of the particles that can be controlled make it unsuitable for HCI applications. Similarly, the quantum Casimir effect allows levitation but only of nanoscale objects [2].

Magnetic levitation has been used in HCI and was exemplified by the system called ZeroN [3], where a magnetic sphere of 3cm diameter was levitated in a 20cm interaction space. However, the magnetic control is for one of the dimensions, only one levitated object can be controlled and the material properties of the tangible object are limited as it needs to be magnetic. More traditional approaches like air jets have been used to control the position of an object [4]. However, the nozzles were positioned around the object and the levitation was interrupted as soon as any of the jets was occluded by the user’s hand.

Acoustic Levitation

An interesting option to move objects is the use of ultrasound waves as they exert radiation forces [5]. Moreover, with the use of phased arrays [6] the sound beams can be steered and focalized at different positions with pinpoint accuracy and without the need of for mechanical actuation. For instance, bursts of ultrasound can be used to move light objects over a flat surface [7] enabling the actuation of tangible objects.

Using adequate acoustic structures, particles can be completely suspended in air using sound [8]. The most basic arrangement to produce this effect is a transducer (sound emitter) and a reflector on top [9], creating a standing wave and allowing particles to levitate in the nodes.

By changing the phase delay or the amplitude of the transducers, movement of the particle can be achieved. A grid of transducers and a reflector on top enable to move a particle in 2D, parallel to the reflector, by changing the transducers amplitude [10,12]. Also, a ring formation of transducers can translate a particle inside the formed 2D circle [11]. Finally, 3D translation was achieved with 4 orthogonal arrays [13].

Principles of Acoustic Levitation

A monofrequential acoustic field is generated when all the sound sources are emitting with the same frequency. The sources are usually transducers that can transform electrical pulses into mechanical waves. Monofrequential acoustic fields can be defined with a complex value for each position of the space, i.e. $acoutiscField(x, y, z) = p$ being p the complex pressure at a determinate point. The amplitude is the modulus of the pressure and the phase is the argument: $amplitude = |p|$, $phase = \arg p$.

The Gor'kov potential (U) is a simplification of the Navier-stokes equations that can be used to determine the forces acting on a small sphere when it is inside an acoustic field.

$$U = 2\pi R^3 \left[\frac{\langle p^2 \rangle}{3\rho_m c_m^2} - \frac{\rho_m \langle u^2 \rangle}{2} \right]$$

where R is the radius of the sphere, ρ_m is the medium density and c_m is the speed of sound in the medium. $\langle p^2 \rangle$ and $\langle u^2 \rangle$ are the mean square amplitudes of the pressure and velocity at the centre of the sphere. The gradient of the potential represents the forces acting on a small sphere. Therefore, a levitation point is a position to which all the forces converge; that is, a minimum of the potential.

Standing waves can trap particles in their nodes [9] because these areas represent a minimum of the Gor'kov potential. Standing waves contain a sequence of nodes and antinodes being nodes points with minimum amplitude and antinodes points with maximum amplitude. Standing waves are created when two waves of the same frequency coming opposite directions encounter. The capability of controlling standing waves enables the translation of the levitating objects that are contained within.

Single-axis levitators consist of two opposite acoustic elements that generate a standing wave between them. A transducer and a reflector on top is a simple configuration for a static single-axis levitator [9]. If the reflector is replaced with another transducer, then changing the phase difference between the transducers will displace the standing wave up and down generating 1D movement in the trapped particles.

Planar array levitators comprise a 2D grid of transducers and a reflector on top [10,12]. By changing the amplitude of subsequent transducers, the standing wave can be moved in a 2D plane parallel to the reflector and the array of transducers.

Both single-axis and planar manipulators lack 3D manoeuvrability. Recent research has recurred to opposed phased arrays for having full control on the standing wave. A phased array is a grid of transducers all emitting with the same frequency and amplitude. Phased arrays can steer and focalize the beam without mechanically moving the array. Ochiai et al. [13] used four orthogonally placed phased arrays to generate two perpendicular focal lines, in which the intersections generate a levitation point.

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Compiled Research Papers

As stated previously, this thesis is a compendium of research papers. That is, the contribution of the thesis should be judged attending to the works presented in this section.

All the presented papers have a coherent research line which in general is acoustic radiation forces and more specifically, acoustic manipulation for applications on human-computer interaction.

For each paper, we include the abstract, the employed methodology and how it is encompassed by the overarching theme of the thesis. The full papers are attached; they have been published in high-impact journals or conferences. Furthermore, in all of them the doctorate has made a significant contribution.

Ghost Touch: Turning Surfaces into Interactive Tangible Canvases with Focused Ultrasound.

Full paper ***[paper_GhostTouch.pdf]***, online link.

Digital art technologies take advantage of the input, output and processing capabilities of modern computers. However, full digital systems lack the tangibility and expressiveness of their traditional counterparts. We present Ghost Touch, a system that remotely actuate the artistic medium with an ultrasound phased array. Ghost Touch transforms a normal surface into an interactive tangible canvas in which the users and the system collaborate in real-time to produce an artistic piece. Ghost Touch is able to detect traces and reproduce them, therefore enabling common digital operations such as copy, paste, save or load whilst maintaining the tangibility of the traditional medium. Ghost Touch has enhanced expressivity since it uses a novel algorithm to generate multiple ultrasound focal points with specific intensity levels. Different artistic effects can be performed on sand, milk&ink or liquid soap.

The methodology for the algorithm is basically an optimization approach. More specifically, the pressure at that target points is defined with an analytical formula that has only the phase of the transducers as the parameters. This formula is obtained by using the Piston model to predict the pressure that one transducer exerts at one point depending on its different parameters (i.e. aperture, power, position and orientation). The acoustic field is linear and thus field exerted by all the transducers is the complex addition of the complex pressure generated by each transducer. Then, a non-linear optimizer is used to minimize the difference between the desired and current pressure at the target points. For developing the system, we used a phased-array composed of 256 speakers, a camera and a small projector. A normal PC received the data from all the devices and ran a software developed in Java with the following functionalities: detect the trace of the user, project at the desired position with a mapping between the virtual space and the real canvas; and finally, calculating the phases to send to the phased-array for creating the focal points at the desired targets and with the required pressure.

This work is the simplest of all in terms of acoustic levitation but it illustrates how to control the pressure very finely and thus the acoustic radiation force. Although levitation is not directly achieved, the artistic media (sand or liquids) are displaced along the canvas. This could be considered as 2D levitation.

LeviPath: Modular Acoustic Levitation for 3D Path Visualisations

Full paper ***[paper_Levipath.pdf]***, online link.

LeviPath is a modular system to levitate objects across 3D paths. It consists of two opposed arrays of transducers that create a standing wave capable of suspending objects in mid-air. To control the standing wave, the system employs a novel algorithm based on combining basic patterns of movement. Our approach allows the control of multiple beads simultaneously along different 3D paths. Due to the patterns and the use of only two opposed arrays, the system is modular and can scale its interaction space by joining several LeviPaths. In this paper, we describe the hardware architecture, the basic patterns of movement and how to combine them to produce 3D path visualisations.

This is the first algorithm to position a levitating particle in 3D using only 2 opposed arrays of transducers. The algorithm is very simple and based on linearly interpolating basic patterns that levitate objects in known positions. When the patterns get interpolated, the levitation points also get interpolated.

Despite using a basic algorithm, this work was a great improvement on acoustic manipulation, for the first time it was possible to control a particle in 3D with only two opposed arrays. This simplifies the systems and makes them more modular. Additionally, some application in HCI such as the representation of 3D paths are highlighted.

Holographic Acoustic Elements for Manipulation of Levitated Objects

Full paper ***[paper_holographicLevitation.pdf]***, ***[paper_holographicLevitation_Appendix.pdf]***, online link.

Sound can levitate objects of different sizes and materials through air, water and tissue. This allows us to manipulate cells, liquids, compounds or living things without touching or contaminating them. However, acoustic levitation has required the targets to be enclosed with acoustic elements or had limited manoeuvrability. Here we optimize the phases used to drive an ultrasonic phased array and show that acoustic levitation can be employed to translate, rotate and manipulate particles using even a single-sided emitter. Furthermore, we introduce the holographic acoustic elements framework that permits the rapid generation of traps and provides a bridge between optical and acoustical trapping. Acoustic structures shaped as tweezers, twisters or bottles emerge as the optimum mechanisms for tractor beams or containerless transportation. Single-beam levitation could manipulate particles inside our body for applications in targeted drug delivery or acoustically controlled micro-machines that do not interfere with magnetic resonance imaging.

The methodology for this paper is based on expressing the trapping strength at one point as the Laplacian of the Gorkov potential. The Gorkov Laplacian measures the convergence of the forces to which a spherical object is subjected when placed on specific position of an acoustic field. This function can be expressed with only the phase of the transducers as the parameters. Then, with a non-linear optimizer, the optimal phases can be obtained. That is, the phases that generate the strongest trapping forces at the desired points. More important, we observed that the optimum phases could always be decomposed into a focus element and a phase signature that was the same regardless of the levitation point. In other words, the optimum solutions represent holographic plates equivalents to the ones used in Holographic Optical Elements. For building the devices we used 3D printers, laser cutters and custom-made driver boards.

This is the main paper of the thesis. This paper allows for the first time to levitate particles with any device, even single-sided ones. Also, this paper presents a new understanding of the optimum traps since they can be analysed as acoustic holograms. We hope that this paper becomes a referent in acoustic manipulation and motivate more work on it.

GauntLev: A Wearable to Manipulate Free-floating Objects

Full paper ***[paper_GauntLev.pdf]***

A tool able to generate remote forces would allow us to handle dangerous materials and adrift objects in Zero-g environments without contact or occlusions. Acoustic levitation is a suitable technology since it can trap particles trough air or water. However, no approach has tried to endow humans with an intertwined way of controlling it. Previously, the acoustic elements were static, had to enclosure the particles and only translation was possible. Here, we present the basic manoeuvres that can be performed when levitators are attached to our moving hands. A Gauntlet of Levitation and a Sonic Screwdriver are presented with their manoeuvres for capturing, moving, transferring and combining particles. Manoeuvres can be performed manually or assisted by a computer for repeating patterns, stabilization and enhanced accuracy or speed. The presented prototypes have limited forces but symbolize a milestone in our expectations of future technology.

The methods to generate the traps between two fingers or with the palm were the same as from the previous paper. For identifying the manoeuvres that are possible to perform with wearable levitators, firstly we used a virtual environment to simulate and test them interactively and then when the best candidates were selected, we tried them with the real levitators.

This paper is a demonstration of how the new traps discovered in the previous paper could be used for a practical application. Moreover, the application is quite futuristic and aims at proving that we are not that far from some of the concepts that have been restrained to sci-fi.

Frequently Asked Questions about the Research

What are the main findings and why is this important?

That it is possible to create acoustic fields that levitate, move and rotate particles without contact, even when the sound is emitted from a flat surface (single-beam). Also, we demonstrate that this flat surface represents a holographic plate and therefore that this problem can be analysed with a holographic framework.

Importance of levitating with sound: sound waves have the best ratio of input power to exerted force; sound can travel through air, water and human tissue.

Importance of single-beam: No need to surround the particle with acoustic elements. This gives more manoeuvrability and better visibility of the manipulated particle.

Importance of the holographic framework: It is the fastest way to generate acoustic traps at the desired position. Moreover, it is a bridge between optical and acoustical trapping that permits to transfer the techniques that were already known from one field to another.

What are the practical applications of this tractor beam technology?

With more powerful tractor beams capable of levitating bigger objects and from farther distances, I imagine applications in controlling adrift floating objects in Zero-gravity environments (i.e. the International Space Station).

In-vivo manipulation: Sound cannot travel through the void of space but it can do it through water or human tissue. This potentially enables the manipulation of clots, kidney stones, drug capsules, microsurgical instruments or cells inside our body without any incision.

We are also exploring how to manipulate thousands of particles individually. This would enable the development of 3D displays composed of millions of levitating particles that act as tangible pixels. This type of display will redefine how we interact with interactive graphics and open the door new research in HCI.

Why tractor beams? How did you decide to do this research? (Was it Star Trek or the sonic screwdriver?)

The possibility of holding and manipulating objects from a distance and without physical contact is intrinsically exciting.

It can be something mundane like levitating the remote control from the table to your hand; or something incredible sophisticated like tangible displays composed of millions of levitating particles acting as pixels. And why not, I like the ultimate vision of rearranging asteroids or building things atom by atom.

This essentially is a sonic "tractor beam," correct? How is it that sound waves can be harnessed to work as a tractor beam, what type of sounds are used, can they be heard by human ears (basically, how does this work)?

Exactly. We use sound waves to exert the forces. As a mechanical wave, sound can exert significant forces on objects, just remember the last time you were in a concert and your chest was vibrating with the music, or that time in the sea when you were pushed by a wave.

A simple wave will just push the particle in the direction of propagation. However, multiple waves will interfere with each other and create complex acoustic 3D shapes that exert forces from all directions and keep the particle in place.

An ultrasonic phased-array is composed of several loudspeakers denominated transducers. Each transducer plays a sinusoidal wave of the same frequency and amplitude but with slightly different offsets (phase-delays). The waves are emitted from a two-dimensional surface yet their interference patterns create a tri-dimensional shape above.

A canon is a musical composition in which the same melody is played by several instruments but starting at different times. The composition is carefully engineered to create beautiful harmonies at every instant that result from the combination of the same melody played at different points. Similarly, our computer algorithm calculates the phase-delays for each transducer so that the listener, the particle in our case, gets surrounded by the desired acoustic levels.

We use ultrasound of 40Khz frequency, humans can only hear below 20Khz.

Other researchers last year had a paper published in Nature describing a tractor beam using laser technology. Does your paper and that paper indicate that there are various possible approaches to tractor beam technology?

Different fields can exert forces on remote objects, each field has its advantages and disadvantages. Magnetic levitation is powerful but restricted in reach, not very controllable and limited on the materials that can be levitated. Optical levitation exerts very weak forces and Quantum levitation even weaker ones.

I think it is important to explore all the different technologies for contactless manipulation. In the past, our hands were our main tool to manipulate objects but we need new tools for solving today's challenges (space exploration, nanoparticles or nuclear fusion just to mention a few.

What made sound the right method of manipulation?

Magnetic levitation is restricted in reach, not very controllable and limited on the materials that can be levitated. Optical levitation exerts very weak forces and Quantum levitation even weaker ones. That only leaves sound, which as a mechanical wave can exert significant forces on objects. Also, our team has a lot of experience controlling ultrasound. Unfortunately, our tractor beam will not work on the vacuum of space since mechanical waves do no travel through it.

In very simple terms, could you explain what an acoustic hologram is?

In Star Wars, you can see a hologram of the princess Leia (a 3D light-field) project from a disk of the robot R2D2 (a 2D surface). An acoustic hologram is exactly the same but instead of using light-waves we use sound-waves. You cannot see an acoustic hologram but it will exert forces on the objects that are contained within.

Is this correct: this technology uses high-amplitude sound waves to move objects less than 1 mm in size: levitating them, moving them up and down, side-to-side, and rotating them?

With our current systems we can manipulate particles ranging from 0.6mm to 4mm in diameter. And we can control the position and orientation of the levitated particles, so it is possible to make the particle follow any 3D path.

Is this correct: To move the objects, the researchers use the sound waves to create an "acoustic hologram" that can take the form of a pair of fingers or tweezers to lift an object, an acoustic "vortex" that holds a levitating object in place and a "cage" that surrounds an object and holds it in place by exerting sound from all directions?

Yes. It is possible to create other shapes but the aforementioned shapes are optimum for levitation in terms of the trapping forces that they exert on particles.

And 64 miniature loudspeakers were used to emit the sounds that created the sonic force fields?

Yes, these miniature loudspeakers (1cm diameter) are called transducers and basically they are optimized for a single frequency (40Khz in our case).

Could you describe the actual objects that you managed to manipulate with the tractor beam?

In the tractor beam scene we used a spherical bead (1.98mm of diameter) made of expanded polystyrene (29.36 Kg per square meter, that is around 10micrograms). The bead was dragged in from 4cm away.

What kind of sound did you use? How loud was it? How big is the array? How do you change the shape of the force fields so they manipulate the objects?

We were using around 60 ultrasonic transducers driven at 40Khz with 15Vpp. The current drawn by the whole system was 0.56A, that is 9 Watts of power (a traditional lightbulb consumes 60W). Each transducer created pressure levels of 120±3 dB (measured on the axis at a z = 30cm). Each transducer is 1cm in diameter so an 8x8 array (64 transducers) is 8x8cm.

To change the shape of the force field we update in real time the phase-delay of the waves emitted by each transducer. This changes the interference patterns that is what ultimately creates the tridimensional force field. It is like an updatable hologram, waves emitted from a 2D surface interfere with each other to create 3D shapes; we do not use light but sound (sound and light both can behave as waves).

What is the largest object that this type of technique in theory could be used to move?

We are designing some experiments that aim at levitating a beach ball from 10m away.

As it is currently employed, what's the largest object that has been moved?

A 4mm polystyrene bead, the densest object was a cube (1mm side) of acrylic (1400 Kg per square meter). However, our systems were designed for testing the acoustic structures as easily as possible, that is not being dangerous or cumbersome to use. With special high-power transducers it would be possible to levitate even steel balls.

You have mentioned applications in Human-Computer Interaction in the form of a tangible display composed of thousands of levitated particles. How much time we will have to wait until this and who will be the early adopter?

Currently we have funding for a project called “Levitating Atoms”, I reckon that in two years prototypes capable of manipulating a few thousands of particles should be working. In the beginning, displays made with this technology will be used only with advertisement purposes given the impact and memorability that they create into the public. As the resolution of the systems progresses, the advantage of supporting multiple observers of dynamic 3D information will be more evident. These displays could be used in medicine (e.g. scattering of a drug inside the body or MRI scans) or air traffic control.

Tractor beams have been a staple of science fiction for decades, could you give your thoughts on contributing to making a reality out of such a great sci-fi concept?

It appears that lots of the emblematic sci-fi concepts are becoming a reality: invisibility cloaks, levitating skateboards or tractor beams. As you said, it is little by little but at some point they may even surpass fiction. However, we would like to highlight that our research is more than a whimsical endeavour for materializing a sci-fi concept. There are useful application for a sonic tractor-beam.

What are your favourite tractor-beam moments or uses in science fiction?

The StarTrek tractor-beam that is made with two beams emerging from the sides of the ship and coinciding at the target, it is surprisingly close to the approach that I am trying now for increasing reach and power. Also, it is not exactly a tractor-beam but I really like when Doctor Manhattan (from Watchmen) displays his ability to manipulate and assemble several pieces without contact, especially because he is trying to create a fusion reactor to solve the imminent energy crisis.

Conclusion / Conclusiones

Conclusion (English)

The ground-breaking contributions of this thesis are:

- An optimization method that produces optimal traps in any system.
- A classification of three optimal single-beam acoustic traps that for the first time enable full levitation, translation and rotation with single-sided arrays. Twin traps are completely new, Vortex traps have demonstrated levitation capabilities only theoretically and Bottle traps have never been suggested to enable levitation. Also, the traps can be generated at different positions and were not explicitly crafted, they emerged from an optimizer.
- The introduction of the Holographic Acoustic Element framework that permits to generate traps directly (without an iterative optimization) and analyse them. Also, it represents a bridge with optical manipulation.

Other systems can be created for different wavelengths, media (air, water or tissue), size, power, number of transducers or spatial configurations. In all cases, they will be able to benefit from our methods and acoustic traps.

This thesis presents a method to create three optimal traps with any arrangement and at different positions. Furthermore, the Holographic Acoustic Element framework is another important contribution of our paper that could influence thinking in the field. The contribution of this thesis is not only a system; it is a method that works optimally in any system, and for the first time, even in single-sided arrays.

The levitated particles could be as varied as the applications of acoustic levitation. For instance, the levitation of a micro-capsule in blood would require a small wavelength but not very powerful acoustic fields. The key is that once that the system has been designed for a specific application (by choosing the number of transducers, power, frequency or spatial arrangement), then our method can be used to generate optimal traps with it.

Our work is settled in the middle ground between the microscopic and the macroscopic world. The possibility of adaptation to systems of different sizes and power is one of the main advantages of acoustic levitation. Our method can be used in all these systems, at different scales of size and power. Until now, only standing waves and Bessel beams have enabled full levitation. This thesis specifies how to generate three acoustic structures for levitation that have been never used before; furthermore, the structures can be generated with single-sided arrays and rotate objects.

Some applications using acoustic levitation have been explored in the field of Human-Computer Interaction. In the paper GhostTouch, the radiation force is used to displace particles that are resting on a flat surface. By doing that, it is possible to remotely paint in sand or in liquids. In the paper LeviPath, a modular levitation system is used to move particles in a 3D space for representing functions or the trajectories of flying objects. Finally, GauntLev is the most innovative paper in the use of levitation for HCI. The paper propose the first use of wearable levitators and the manoeuvres that can be realized with them in order to manipulate particles without contact. Levitators in the shape of gloves, tweezers and a screwdriver are presented.

Conclusiones (Español)

Las contribuciones pioneras de esta tesis son:

- Un método de optimización que produce trampas óptimas en cualquier sistema.
- Una clasificación de tres trampas acústicas óptimas de un solo haz que por primera vez permiten levitación, traslación y rotación con dispositivos de una sola cara. Las trampas Twin son completamente nuevas, las trampas Vortex sólo habían probado capacidad de levitar teóricamente y las trampas Bottle nunca se habían sugerido como candidatas para levitación. Además, estas trampas se pueden generar en diferentes posiciones y surgieron de un optimizador, es decir, no se estaba explícitamente buscando este tipo de formaciones.
- La introducción del framework Elementos Acústicos Holográficos permite generar directamente trampas (sin una optimización iterativa) y analizar mejor las trampas. Además, representa un nexo de entendimiento entre la manipulación acústica y la manipulación óptica.

Otros sistemas pueden ser creados para diferentes longitudes de onda, medios (aire, agua o tejidos), tamaño, potencia, número de transductores o configuraciones espaciales; todos estos sistemas podrán beneficiarse de nuestros métodos y trampas acústicas.

En esta tesis se presenta un método para crear tres trampas óptimas en diferentes posiciones y con cualquier tipo de dispositivo. El framework de Elementos Acústicos Holográficos es otra contribución importante de la tesis que podrían influir la forma de pensar tanto en el campo de óptica como de acústica. La contribución de esta tesis no es sólo un sistema; es un método que funciona de manera óptima en cualquier sistema, y por primera vez, incluso en dispositivos de una sola cara.

Las partículas que levitan pueden ser tan variadas como las aplicaciones de la levitación acústica. Por ejemplo, la levitación de un micro-cápsula en la sangre requeriría una longitud de onda pequeña pero los campos acústicos no necesitan ser muy potentes. La clave es que una vez que el sistema ha sido diseñado para una aplicación específica (eligiendo el número de transductores, potencia, frecuencia o disposición espacial), nuestro método se puede utilizar para generar trampas óptimas para ésta.

El trabajo se estableció en el punto medio entre lo microscópico y el mundo macroscópico. La posibilidad de adaptación a sistemas de diferentes tamaños y potencia es una de las principales ventajas de la levitación acústica. Hasta ahora, sólo las ondas estacionarias y los rayos Bessel permitían levitación completa. En esta tesis se especifica cómo generar tres estructuras acústicas que nunca se habían usado para la levitación. Además, se puede generar con dispositivos de una sola cara y pueden rotar objetos.

Varias aplicaciones que usan levitación acústica han sido exploradas en el campo de la Interacción Persona-Ordenador . En el paper GhostTouch , la fuerza de la radiación se utiliza para desplazar las partículas que están sobre una superficie plana. De este modo es posible pintar de forma remota en arena o en líquidos. En el trabajo LeviPath, un sistema de levitación modular se utiliza para mover partículas en un espacio 3D para la representación de funciones o las trayectorias de objetos voladores. Por último, GauntLev es el trabajo más innovador en el uso de levitación para HCI . En el paper se propone el primer uso de levitadores llevables y las maniobras que se pueden realizar con ellos para manipular partículas sin contacto. Levitadores en forma de guantes, pinzas y destornilladores son presentados.

Future Work

In this section I have gathered some research related to the topic of the thesis that I plan to conduct. The degree of development is varied: some points are just ideas that I have been discussing with some colleagues; others are papers in which I have collaborated and are about to be published. And some, are mere ideas that I am still ruminating; only a few make sense and even less will be materialized. But I believe that the capacity or at least the interest in generating new research ideas is the most important skill that a doctorate should prove.

Kindly, if you have any interest on any of them, let me know. You can count with me for future collaborations, just do not rip them off. If we work together, we will do things better and faster.

Non-linear Optimization in Ultrasonic Phased Arrays

Phased arrays permit to accurately focalise sound at different locations without mechanically translating the device. Furthermore, various focal points can be created simultaneous. This is of paramount importance for applications in medicine and haptic displays. However, until now the algorithms to control the arrays were based on linear optimization. Here, we show that non-linear optimizers such as BFGS can perform better in the generation of several focal points and provide more versatility for constructing the target function. Firstly, maximum, minimum or specific intensities can be defined independently at each point without the necessity of stipulating the phases. Secondly, the power consumption of the array can be controlled in the target function. And thirdly, the intensity can be specified not only at points but also in volumes, enabling for instance to minimize the radiation on sensitive organs. By introducing non-linear optimization for phased arrays control, we pave the way for more complex optimization problems such as spatial distributions, materials or sizes of transducers.

Thunderstorm: combining acoustic levitation and electro-rotation

Acoustic levitation permits to suspend objects in mid-air and translate them around free 3D paths. This represents a new opportunity for creating dynamic physical visualizations without the restrains of gravity or mechanical actuation. Also, floating grids of particles can be used as projection surfaces that change their position and shape.

However, the angle of the levitated objects has never been controlled, acoustic manipulators have significant limitations and only cross-shaped moving screens have been generated.

Here, we show a method for endowing any object with dielectric properties by coating it with transparent nanopowder. Thereby, an electric field generated with engineered voltages applied into transparent electrodes can control the orientation of the levitating objects. Moreover, we present a new optimization approach for creating acoustic levitation points at any position and moving 2D grids of particles.

The benefits of combining the electric field for rotation and the acoustic field for translation are exemplified with two scenarios. Firstly, levitating objects can now adopt any 3D position as well as angle for conveying different states or rotation information. Secondly, grids of floating particles do not need to receive projected light, they can be orientated to show the desired facet; therefore, reducing eye fatigue as well as improving readability, viewing angle and dynamic range.

Holographic Acoustic Lenses

It is now a common practice to create acoustic lenses that can focalised sound; they are analogous in functioning to the optical lenses. That is, due to the difference in speed across the medium the phases get shifted. So far, lots of acoustic lenses have been made of PMMA or materials that have similar acoustic impedance to water. Here, we prove that apart from focusing, other phase-modulations can be achieved to enable acoustic levitation with one transducers or even the creations of pressure holograms for haptic or stamping processes.

Wormhole metamaterials

Acoustic metamaterials have important applications in sonar, medical ultrasound or cloaking devices since they permit to steer, focalize and deflect acoustic waves. Most of the existing metamaterials can be classified as labyrinthine structures. That is, a piece of material that contains micro-channels of different lengths shaped as zigzag tubes, curves or hollow spheres. The different lengths introduce phase-shifts that shape the waves that pass through the material.

Despite their popularity, labyrinthine structures present several limitations. Firstly, due to the curved nature of the conduits, the waves suffer significant attenuation. Secondly, the focus is achieved by phase-shift and thus the acoustic energy still gets spread. And finally, all the conduits are local, meaning that they are contained in the same lateral position, thus the available space in the material is misused.

Here, we propose a new type of metamaterials, Wormholes. In them, the conduits are not locally constrained but they can start and end at any position. This generates a complex structures of entangled tubes similar to the ones observed in long-chain polymers or proteins.

The layout of the tubes should minimize their curvature and maximize the occupied space. Therefore, the design of wormhole metamaterial can be seen as an optimization problem or as physical simulation of bendy tubes. Later, this structure can be 3D printed with FDM for the macroscale and with two-photon lithography for the microscale applications.

We expect that Wormhole metamaterials will lead to powerful tractor beams for the manipulation of either macroscopic or microscopic elements, acoustic holograms for haptic sensations or stamping and to the first low-attenuation air lenses that would improve sonars and other forms of ultrasound imaging.

Phantom Acoustic Force Fields: sub-wavelength multiplexing

Phased Arrays can focalize and steer acoustic waves electronically with incredible speed and accuracy. Here, we present a novel method for multiplexing focal points at sub-periodic speeds to make the resultant radiation force a superposition of the multiplexed points. This permits to create force field with unprecedented strength and shapes. These force fields can be used either for constraining or shielding areas.

For instance, constraining a particle from all sides will levitate it, enabling the levitation of particles bigger than the wavelength. Other future applications could be constraining oil spills, drug delivered inside the human body or hot plasma. On the other hand, it could be possible to shield an area from toxic gases or water drops.

Taming the Acoustic Vortices

Bessel beams (aka Vortices) have been theorized to be the perfect candidates for tractor beams. That is, a beam emitted from a single-sided device that is capable of exert pulling forces towards the source. Vortex traps emerged from our optimizer as one of the solutions. However, that is only the case when the levitated particle is considered as a point without volume. Both experimentally and with enhanced models we observed that a Vortex is only adequate for trapping small particles. Particles that are bigger than 1/3 of the wavelength start to orbit until being ejected, rendering the trap impractical.

We characterize the orbiting and stability of a particle inside a Vortex and present methods to made the vortex stable. Also, the transfer of orbital angular momentum (OAM) can be controlled to rotate at the desired speed even symmetric particles. The basic principle to control the transfer of OAM and make the vortex stable is to switch its direction with microseconds accuracy.

Full Lock

We have introduced the Twin trap, a single-beam that can fully hold a particle in the desired position, move it around and also rotate asymmetric particles. However, the particles can be rotated with only one degree of freedom and they still rotate uncontrollably in one axis. That is, the Twin trap locks the particle with 3Dof in translation but only with 2Dof in rotation.

We present the Quad trap, a modification of the Twin trap that looks like four cylinders of high-intensity. A particle with the shape of a cross can be trapped inside the cylinder and become completely locked.

Now, with a full lock in position and rotation it is possible to expand our manipulation capabilities. For instance, the trapped particles can be used for sewing or twisting the attached elements being them DNA, polymer chains or suture threads. This method also works in optical trapping and has never been reported.

Standing Twins and Standing Vortices

Until this thesis, only standing waves were able to create full trapping (i.e. lock in three dimensions). We introduced the Twin, Vortex and Bottle traps; these traps are single-beam, Twin traps can rotate particles controllably and Vortex traps can centrifuge particles at very high speeds.

However, they still have limited transversal trapping force compared to the standing waves. A Bottle traps is 7 times weaker in the direction of propagation than a Standing wave and Twin or Vortex traps are 30 times weaker than the Standing wave.

We introduced the Standing Twins and Standing Vortices which still require two opposed arrays to be generated but provide transversal forces comparable to Standing waves while retaining the ability to controllably rotate or centrifuge the levitated particles. Additionally, these novel acoustic structures can trap several particles between the two opposed arrays; namely, one particle every half of the wavelength.

That is, these acoustic structures have strong transversal forces capable of levitating heavy objects and can also orientate them. We show applications in 3D printing with a levitated printing head or in sewing across different materials.

Hollow focal points

Acoustic Bottles emerged from our optimizer as one of the optimum levitation mechanisms. From all the single-beam traps, Bottle traps exert the strongest transversal forces. Other papers had described Bottle beams as Airy-beams with axial symmetry.

Here, we prove that Bottle beam have a simpler interpretation. They are hollow focal points; that is, a small-aperture array focalised in the same point as a large-aperture array with a pi-phase difference. The small-aperture array creates a wide focal point and the large-aperture one a sharper focal point. Due to the phase difference, the sharper focal point makes the wide focal point a hollow Bottle.

Following this interpretation, it is possible to generate Bottle beams of different sizes that permit to levitate heavier and bigger objects.

Abduction Ray

A tractor beam is capable of seizing a particle that is floating adrift and pulling it towards the source. However, most of the particles are not floating in mid-air but resting on a surface. In this thesis, we have shown particles being trapped when they are floating in mid-air or resting on acoustically absorbent or transparent materials; but capturing particles that are resting on a reflective surface (e.g. a petri dish, a table or sea rock) remain as an open problem.

No approach exists for picking up a particle from a reflective surface without contact. A reflective surface alters the acoustic field and render the traps inoperative. A standing wave is formed between one emitter and the reflective surface but the node is always in the same position independent to the emitter position. That is, it is easy to lift the particle from the surface to the first node but there is no way of elevating it further.

We call "abduction ray" to a mechanisms able to pull particles that are resting on a reflective surface. Here, we present the first realization of an abduction ray. The main mechanism is based on creating a standing wave using the surface as a reflector and changing the frequency of the emitter to elevate the particle until the next node. Then, switching back to the original frequency and repeating the process. For focalising the acoustic energy, an acoustic lens will be used in water and an acoustic mirror in air.

Acoustic waveguides induced in mid-air with lasers

One of the futuristic weapons that has been realized realized is the Electrolaser. In this weapon, a high-intensity laser is fired to create an ionic channel of along its path. Then, microseconds afterwards, a high-voltage current is fired and travels through the ionic channel. Thereby, it is possible to transfer high voltage in mid-air without the necessity of any wire or cable.

We propose to use the same principle to create an acoustic waveguide in mid-air. Firstly, a laser is fired and heats the air. Then or meanwhile, acoustic waves are transmitted through this channel of hot air that due to the difference of speed between hot and cold air acts as a waveguide. This may be a way of transferring mechanical energy between long distances.

Levitating Atoms

So far we have levitated a couple of objects, but it has never been studied in depth how to control multiple objects independently. We propose to employ acoustic levitation to create dynamic 3D physical shapes made of numerous lightweight levitating objects. Hundreds of levitating voxels will be able to form different 3D objects that can be touched and viewed from any angle.

As we shift towards touchless interactions (e.g. Kinect, Leap Motion or over the surface tabletops), the lack of physicality becomes an emerging problem that hinders the user experience. The user has no tangible controller and the interaction is indirect, meaning that the visual feedback and the interaction space are not in the same location. This creates a big cognitive disconnection. In this future project, users could touch and interact with the objects that are composed of hundreds of levitating atoms as they would do with objects in real life but with the versatility of controlling computationally the shape and appearance of the mid-air objects.

In-vivo Levitation

Sound cannot propagate through the void of space; however, it can travel through water and more important, through human tissue. In fact, sound travelling through human flesh suffers less attenuation than across air.

Controllably holding and manipulating particles inside the human body would enable new medical procedures with lots of potential applications. For instance, an external levitator could be used to move particles inside the kidneys, eyes, lungs or veins. The particles could be harmful entities like kidney stones and clots; or deliberately inserted particles such as micro-surgical instruments controlled from the outside without any incision or capsules of drugs that are hold around the area of interest in targeted drug delivery scenarios.