A Survey on Acoustic Control Systems

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Abstract. Acoustic manipulation techniques have recently become a current research hotspot, especially their application aspects are receiving increasing attention in important fields such as medicine, engineering, environment, and military, yet the precise control mechanisms and the associated techniques are still a challenge nowadays. Needing to take into account the current trends, this review focuses on the traditional methods used in physical field (acoustic field) driven manipulation techniques and the current mainstream optimization algorithms.

Keywords: Acoustic manipulation · Acoustic Tweezers · Algorithm optimization · Machine Learning

1 Introduction

Holography is a powerful technique used for generating complex acoustic fields, forming the basis for a range of applications such as acoustic imaging, particle manipulation, and energy deposition. Acoustic holography utilizes interference principles to acquire information about the amplitude and phase distribution of the observed object's acoustic field. Currently, the generation of dynamic holographic sound fields for acoustic manipulation purposes is a major research focus in the field of acoustic holography. As biomedical, inkjet printing, micro and nano manufacturing, materials engineering, new energy, and environmental protection have developed, the demand for manipulation of micro and nano scale objects has increased. Traditional manipulation techniques are often limited in terms of selectivity and device structure, making it difficult to accomplish many of the manipulation functions required. Researchers from different fields have proposed and studied different methods for micro and nano manipulation, including optical, magnetic, electrical, microfluidic, mechanical, and acoustic approaches. Non-contact manipulation techniques like "optical tweezers", "magnetic tweezers [11]", and "acoustic tweezers" [10] have gained a lot of attention in recent years. These methods rely on light waves, magnetic fields, and acoustic waves to act on micro and nano objects without causing damage. Although contact manipulation techniques have reached a practical level in China, direct manipulation with mechanical tools can harm delicate cells and tissue structures, and handling multiple targets is often challenging. Non-contact micromanipulation is a rapidly developing technology that holds enormous potential for a range of fields. These techniques offer high precision, non-contact capabilities that do not cause damage and have the potential to revolutionize the way we manipulate micro and nano scale objects.

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2 Acoustic Manipulation

2.1 Acoustic Particle Manipulation Function

Acoustic trapping (acoustic trapping) technology is a technique that uses acoustic waves to manipulate objects without contact. In optics, focusing on a particle is sufficient for trapping, while in acoustics, only negative contrast particles (i.e., the acoustic impedance of the particle is less than the acoustic impedance of the medium) are trapped. To date, many acoustic capture techniques have been implemented for use in one-dimensional space [26], two-dimensional space [27], three-dimensional space [28–30], and a proliferation of functions based on acoustic particle manipulation (e.g., focusing, separating, sorting, mixing, and patterning) [31–34] at the beginning of the twenty-first century. However, none of these methods achieved the dexterity of optical tweezers, and none of them could precisely manipulate individual particles or cells along arbitrary paths in two dimensions. 2012, Ding et al. proposed an acoustic tweezer that could capture and manipulate individual particles, cells, and whole. The technique can capture and manipulate individual particles, cells and whole organisms in a single layer microfluidic chip. The latest advancement is the ability of holographic acoustic tweezers (HAT) proposed by Asier Marzo et al. to dynamically manipulate multiple individual particles simultaneously in mid-air [22] (Table 1).

2.2 Methods of Acoustic Manipulation

Table 2 There are roughly 3 ways to acoustically manipulate particles: one is the previous use of acoustic levitators, where the captured particles must be surrounded by acoustic elements [22, 26, 36]. The unilateral (or single-beam) levitator applies only a lateral capture force. Another one requires the use of an acoustic lens that can focus the acoustic waves to improve the resolution. The third one drives the phase of the ultrasonic phased array to translate, rotate, and manipulate the particles.

(1) Acoustic focusing.Wang and Lin et al. verified the focusing effect of Fresnel lenses in the field of acoustics [9], The principle of Fresnel acoustic lenses is to design equidistant tooth shapes on one side of the lens, through which static focusing of a specified range of acoustic waves is achieved [17]. By combining a 5 MHz center frequency ultrasonic transducer with a lens that can eliminate standing waves, the acoustic pressure pattern associated with a specific excitation signal is generated. The experiment takes advantage of the fact that the phase is periodic (mode 2π) and the thickness of the lens at each point is set to introduce a specific phase delay, thus creating a focal point at the target. The very thin Fresnel lens obtained by design leads to lower attenuation and achieves closer focus, and it can be concluded that the Fresnel lens focusing transducer is tightly focused and its focusing characteristics vary with the excitation signal, and likewise the Fresnel lens improves the resolution of the focused ultrasound. There are many other current focusing methods, such as mechanical indentation [13, 14] in which a single-piece focusing transducer is used in applications where a ball pressure is applied to the piezoelectric material [15]. One disadvantage of this method of mechanical indentation is the possibility of element fracture during the molding process. The other involves acoustic lenses,

Table 1. Acoustic particle manipulation functions

Acoustic particle manipulation functions (focus, separation, classification, mixing, patterning and positioning, etc.)			
First author	Content	Year	Quote
M Wiklund	Combining short-range dielectric electrophoresis (DEP) operations with long-range ultrasonic standing wave (USW) operations for high-throughput processing of individual bioparticles in microfluidic chips	2006	[32]
T Frommelt	Mixing efficiency of a flat cylinder driven by two surface acoustic waves	2008	[34]
J Shi	Separation of acoustically continuous particles induced by standing surface acoustic waves (SSAW) in microfluidic channels based on volume, density, compressibility	2009	[33]
J Shi	Three-dimensional (3D) continuous particle focusing in monolayer polydimethylsiloxane (PDMS) microfluidic channels using standing surface acoustic waves (SSAW)	2011	[31]
Xiaoyun Ding	SAW-based acoustic tweezers for manipulating individual particles/cells/organisms in microfluidic chips	2012	[35]
Whymark R R	Experimental melting and curing of aluminum, glass and plastic materials in a vessel-free state using an acoustic levator for contactless positioning	1975	[26]
Ding xiao yun	Techniques for capturing and manipulating individual particles, cells and whole organisms in a single layer microfluidic chip to generate a two-dimensional picture	2012	[27]
Takayuki Hoshi	Three-dimensional acoustic manipulation - generates local standing waves at arbitrary locations by phased-array focusing technology, and manipulates particles suspended at the standing wave nodes according to the location of the standing waves.	2014	[28]
Asier Marzo	Optimized the phase used to drive the ultrasonic phased array and showed that acoustic levitation can be used to translate, rotate and manipulate particles even with a single-sided emitter	2015	[29]
M Prisbrey	The ultrasonic non-contact particle manipulation (NPM) method allows dynamic control of user-specified particle patterns in three dimensions	2018	[30]
Asier Marzo	HAT's ability to dynamically manipulate multiple particles in mid-air at the same time	2019	[22]

which are composed of a refractive material that resembles the curved interface of an optical lens, and acoustic radiation force devices with 3D printed holographic acoustic lenses are used to generate complex particle patterns [16], although acoustic lenses can be applied for similar high-resolution phase modulation, but it is static.

(2) Ultrasonic phased-array. Ultrasonic phased-array transducer design is based on the Huygens principle. The transducer is composed of multiple independent piezoelectric wafers in an array, each wafer is called a unit, according to certain rules and timing control with electronic systems to excite each unit. The ultrasonic waves emitted by each unit in the array are superimposed to form a new wavefront. Similarly, in the process of receiving reflected waves, according to certain rules and timing control the reception of the receiving unit and signal synthesis, and then the synthesis results in the appropriate form of display. From its principle, it is clear that the most significant feature of phased-array transducer is that it can control the sound beam shape and sound pressure distribution flexibly, conveniently and effectively.

There are many scholars who use ultrasonic phased arrays for controlling the acoustic field, such as ultrasonic phased arrays to manipulate the levitation of near-field/far-field objects. Seki Inoue et al. proposed a 40 kHz (8.5 mm wavelength) ultrasonic phased array to levitate a polystyrene sphere and an ortho-octahedron with dimensions of about 50 mm at a distance of 200 mm from the acoustic element in the air. by 40 kHz Photo of the sphere and the ortho-octahedron suspended in air by ultrasonic waves. The ortho-octahedron with a diagonal length of 50 mm is suspended at the center of a two-sided phased array at a distance of 200 mm; the array consists of a total of 1992 transducers (i.e., two 996 arrays). The three laser lines show an orthogonal base crossing at the levitation point [36].

The developed levitation technique is suitable for 3D manipulation of multiple objects so that they follow complex 3D paths in air or liquid, which is not possible using a robotic arm, but indeed cannot be demonstrated dynamically. Asier Marzo et al. described and evaluated an algorithm for acoustic tweezers (HAT) by controlling an ultrasonic phased-array emission field [25]. A 40 kHz airborne HAT system was experimentally demonstrated, which was implemented using two 256-emitter phased arrays and simultaneously manipulated up to 25 mm of particles individually.

3 Acoustic Manipulation Optimization Algorithm

Of course, the phased array technology mentioned above has to face many challenges in implementation, such as the requirement of good electro-acoustic performance of the piezoelectric wafer; good acoustic performance of adjacent cell spacing; avoidance of side flaps, and more attention should be paid to this problem when the angle of the acoustic beam is large; precise control of the time delay and simulation of the acoustic beam direction, shape and acoustic pressure distribution, etc. In order to achieve a better ability to manipulate the field and particles, there are many algorithms to solve, such as the iterative angular spectrum method (IASA) borrowed from the optical field, and improved algorithms based on IASA, and some GS-based algorithms, as well as optimization algorithms based on deep learning and other aspects.

The Gerchberg-Saxton (GS) algorithm is a phase retrieval algorithm, which was first proposed by Gerchberg and Saxton in 1972 for solving phase recovery problems in electron microscope imaging studies, and is widely used for beam shaping and optical information processing to improve diffraction efficiency. However, the GS algorithm is difficult to obtain an exact solution after iteration and often yields an approximate

Table 2. Acoustic manipulation of particles

Traditional method - using acoustic components			
First author	Content	Year	Quote
Whymark R R	Non-contact positioning of the material in the space treatment chamber using acoustic levitators, the control of the position is obtained by the movement of the acoustic reflector	1975	[26]
Sue Ann Seah	The first-order Bessel function-shaped sound field generated using an 8-element circular array operating at 40 kHz can capture millimeter-sized objects against gravity, and the device can manipulate objects with an accuracy of ± 0.09 mm in a vertical plane of a few millimeters	2014	[36]
Peter Glynne-Jones	Using piezoelectric arrays for ultrasonic manipulation of particles and cells along microfluidic channels, a 12-element one-dimensional array coupled to a rectangular capillary was used for the experiments.	2012	[22]
Acoustic Lenses - Acoustic Focus			
D Wang	Transducers with 3D printed Fresnel lenses produce evolvable sound fields that can be used to solve particle manipulation	2021	[9]
Melde K	Acoustic radiation force device with 3D printed holographic acoustic lens for generating complex particle patterns	2016	[16]
Phased Array			
S Inoue	Boundary holography: generates a static stable suspension field for a macroscopic non-spherical rigid body larger than the acoustic wave length k.	2017	[36]
Asier Marzo	HAT - the ability to dynamically manipulate multiple particles in mid-air at the same time	2019	[22]

solution. The improved GS algorithms based on the Fresnel transform domain include the single-phase retrieval (SPR) algorithm, the dual-phase retrieval (DPR) algorithm and the multiphase retrieval (MPR) algorithm. The analysis results show that the SPR algorithm has better convergence than the GS algorithm, but does not obtain an exact solution. The DPR and MPR algorithms converge well and obtain an exact solution; i.e., the information is recovered losslessly.

The acoustic hologram is the cornerstone of modern acoustics, which encodes the 3D acoustic field in two dimensions and its quality determines the performance of the acoustic system. Long et al. proposed an algorithm based on Eigenproblem and Tikhonov in 2014. The optimization method controlling only the acoustic phase iterative angular spectral method (IASA), which itself is based on the GS algorithm. Plasencia et al. proposed GS-PAT in 2020, Tatsuki Fushimi et al. 2021, an optimization algorithm for

Table 3. Acoustic manipulation of particles

Algorithm	Optimization method	Optimization methods	Quote
SPR	The convergence of SPR algorithm is better than GS algorithm, but no exact solution is obtained	Improved GS algorithm	[39]
DPR/MPR	DPR and MPR algorithms have good convergence and can obtain exact solutions	Improved GS algorithm	[39]
Eignproble and Tikhonov regularization	Algorithms for controlling the volume distribution of acoustic radiation force fields in three-dimensional shapes, demonstrating how to create such acoustic radiation force fields and how to interact with them	Optimizing the amplitude and phase of acoustic holograms	[42]
IASA	IASA is a technique for modeling acoustic wave propagation, which extends complex waves to an infinite number of sums of plane waves, essentially modeling spatial frequencies. Applicable to plane wave propagation, i.e., generation of acoustic holograms	Based on GS algorithm	[16]
GS-PAT	Phase recovery algorithms that allow the computation of multipoint sound fields at normally high interaction rates. Enables a paradigm shift in PAT devices. General versatility in the power management provided by PAT by using a single point of high speed sound field to using multiple high speed (tactile or hover) points	Improved GS algorithm	[41]

(*continued*)

Table 3. (*continued*)

Algorithm	Optimization method	Optimization methods	Quote
Diff PAT	A phase-only gradient descent algorithm with automatic differentiation. Applies a chain rule to each basic operation of a given function to calculate the derivative of the function with high accuracy. It is commonly used in machine learning	Based on IASA algorithm	[40]
LMA	LMA is an iterative algorithm for solving nonlinear least squares problems. The constraint for using the algorithm LMA is that the amplitudes of the transducers must be equal	Optimal transducer amplitude only	[43]
IB	The IB algorithm uses propagators derived from specific sensor models suitable for 3-D holographic sound field generation, and IB can create focal points as well as enforce phase dependencies between these points, allowing efficient generation of different traps (i.e. focal points, twin traps and vortices) at arbitrary locations	Improved IASA algorithm,	[22]

(*continued*)

Table 3. (*continued*)

Algorithm	Optimization method	Optimization methods	Quote
CNN	A machine learning (CNN) optimization method to obtain the phase gradient of the sound field hypersurface for regional control of the local sound field, including enhancement/attenuation. By 2 CNNs, CNN1 is utilizing the Google model that	Phase optimization of multi-point local sound field	[38]
AcousNet	AcousNet is a CNN-based regression network that calculates the mapping from the holographic sound field distribution to the transducer phase array for phase optimization	Predictive optimization of transducer phase	[37]
PhysNet-AH	An unsupervised network model that provides individual sound fields recorded from holograms to PhysNet AH, where network parameters can be automatically optimized without labeled training data	Reconstruction of sound field optimization	[44]

acoustic holography with automatic differentiation (Diff PAT) They can optimize the amplitude and phase of the acoustic hologram, but their proof that Diff PAT outperforms both the conventional feature solver and GS-PAT in terms of amplitude and phase control, and this method is an optimization based on IASA and does not change the basic IASA algorithm. Recently, the optimization of acoustic holograms using the Levenberg-Marquardt algorithm (LMA) was demonstrated by Sakiyama et al. They examined the accuracy of ultrasonic stimuli in both real and simulated environments. The Iterative Back Propagation (IB) algorithm, which is used to calculate the emission phase of array elements for functional HAT, is a modified version of the Iterative Angular Spectroscopy (IASA) method. Unlike IASA and GS, IB can create focal points as well as enforce phase dependencies between these points, allowing efficient generation of different traps (i.e., focal points, twin traps, and vortices) at arbitrary locations. But once the desired holographic sound field becomes complex, the computational results of the IB algorithm are not even close to the real values. While LMA optimizes the amplitude of the transducer, IB optimizes only the phase of the transducer array, GS-PAT and Eigenproblem can optimize the amplitude and phase of the acoustic hologram.

Many methods using machine learning deep learning have emerged in recent years to solve the sound field optimization problem, Tianyu Zhao et al. in 2021 proposed a machine learning optimization method to obtain the phase gradient of the super-surface of the sound field, and using this method, regional control of the local sound field, including enhancement/diminution, can be achieved. In the same year 2021, Chengxi Zhong et al. proposed a deep learning-based phased array dynamic 3D holographic sound field generation method [37] to optimize the transducer phase by predicting the phase of the generated holographic sound field.Boyi Li et al. in 2022 proposed a new DL-based unsupervised reconstruction method, called PhysNet-AH, which was developed by combining convolutional neural networks with a physical model representing the acoustic hologram formation process to achieve this. The results show that only a single acoustic field recorded from the hologram needs to be provided to PhysNet AH and the network parameters can be automatically optimized without labeled training data. The input to the network as shown in Fig. is a hologram of the sound field intensity Φ(x,y,z = d) and the output is a target object, which is then propagated numerically through the physical model H to synthesize the sound field intensity.

4 Conclusions

In summary, this paper provides a comprehensive review of the research progress in acoustic manipulation techniques, covering acoustically suspended particles to acoustically manipulated individual particles. It outlines various methods of acoustic manipulation, including the use of acoustic lenses, conventional acoustic elements, and ultrasonic transducer arrays to change the acoustic aggregation. Moreover, this paper primarily focuses on the optimization algorithm of the acoustic field, summarizing the use of ultrasonic transducers to manipulate the acoustic field by controlling its phase or amplitude to achieve acoustic manipulation goals.

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