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Jared Nakahara

Contact-less Object Handling: Manipulation and Sensing Methods for Acoustic Levitation Systems

Jared Nakahara

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Reading Committee:

Joshua R. Smith, Chair

Nadya Peek

Christopher Thachuk

Akshay Gadre

Program Authorized to Offer Degree:
Electrical and Computer Engineering

University of Washington

Abstract

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Jared Nakahara

Chair of the Supervisory Committee:
Professor Joshua R. Smith
Electrical and Computer Engineering

This dissertation will discuss the design, control, and sensing capabilities of acoustic levitation systems for laboratory automation providing a flexible and programmable method for contact-less sample manipulation. Conventional tools like pipettes and well plates rely on surface contact to handle small volumes of liquids and reagents. This introduces risks of contamination, sample loss, and measurement uncertainty. Assays and laboratory experiments can require hundreds or even thousands of steps which can be labor intense if done by hand. Automated liquid handling systems can help streamline labor intense workflows, alleviate shortages in labor, and free up scientist to focus on task that benefit from individual training and expertise. These traditional tools also generate significant plastic waste and often require separate, siloed systems for manipulation and sensing, increasing operational complexity and benchtop footprint.

Acoustic levitation offers an alternative by using high-intensity ultrasonic waves to trap, lift, move, mix, and measure solids, liquids, and even living organisms in mid-air without any physical contact. This eliminates contamination risk and enables continuous, real-time monitoring of samples from the moment of mixing through analysis.

Advances in computing power, acoustic field modeling, and holographic beamforming have dramatically expanded the capabilities of acoustic levitation systems. This work draws

from fields such as ultrasonic holography, robotics, and sensor fusion to create programmable systems capable of vessel-free containment, automated liquid handling, and embedded sensing. The system architecture discussed in this dissertation integrates control algorithms, custom hardware, and on-board sensing to enable a contact-less liquid handling instrument: one that merges manipulation and measurement in a unified platform.

This dissertation will discuss contributions in acoustic levitator sensing, control and manipulation, including the ability to pick up objects from acoustically reflective surfaces, weigh droplets and particles in air using trap dynamics, translate levitated objects via frequency modulation, dispense droplets of liquid into the levitator with an acoustic launching system and control the shape of levitated liquid droplets.

When applied to disciplines like chemistry, pharmaceuticals, and molecular biology, this approach could provide a contact-less robotic liquid handling solution that is programmable while minimizing contamination, eliminating consumables, reducing human error, and enabling new opportunities for automation. Acoustic levitation systems thus represent not just a new tool, but a possible shift in how laboratories can conduct precise, clean, and scalable research.

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DEDICATION

To my family Jae Ahn, Mike, Kevin and Raelynn.

Chapter 1

INTRODUCTION

1.1 Acoustic Levitation Scientific Research Tools

What if the next scientific discovery was lost inside a pipette tip? Scientific research tools in modern day life science are taking advantage of automation [44], miniaturization [204], and high precision sample manipulation [124] and sensing capabilities [89]. In fields like synthetic biology, microfluidics tools and methods have enabled complex handling of small-volume samples [49, 120]. Traditional liquid handling methods use tools like pipettes [83], robotic dispensers [17], and microfluidic chips [171] which rely on mechanical contact with surfaces or channels. Over time, without routine maintenance and laboratory protocols, these tools can causing contamination [206], limiting manipulation and sensing flexibility, and creating barriers for certain types of experiments and assays. Additionally, fields like genomics, synthetic biology, and high throughput screening and diagnosis tools are trending toward ultra-small volume assays to increase reagent efficiency and sensitivity while decreasing costs [56]. This has resulted in an increased demand for scientific instruments capable of handling nanoliter to picoliter liquid droplets while tightly integrating the manipulation system with sensors[139].

As the scale of assays and material testing experiments become smaller, even trace contaminants from pipette tips, tubes and containment vessel walls become more significant [139]. High-throughput applications like drug screening need to scale down volumes to remain cost effective [56]. In fields like single cell analysis or personalized medicine, even minute contamination can cause misleading or unusable results [224]. Another disadvantage of traditional tools is the loss or inefficient use of expensive, precious, or irreplaceable samples and chemicals [14]. Carry over occurs when trace amounts of chemical or sample

material are left behind in test tubes, pipette tips and well plates, due to physical contact with the containment vessels or manipulation tool surfaces. This results in increased experimental uncertainty, or worse misleading or unusable data [16, 38]. For techniques like polymerase chain reaction (PCR) amplification, contamination can lead to false positives [95]. A contact-less method for containing and manipulating samples would reduce waste and carry over instances.

Today, laboratories are looking to implement automation as a solution to workforce shortages and as a method of freeing operators to focus on specialized testing that could benefit from a humans' unique training [77]. Additionally, automation could be a solution to decreasing costs and improve laboratory services for diagnostic manufacturers [134]. Total laboratory automation can improve workflow efficiency by connecting the processing and testing steps of a laboratory enabling more efficient use of scientists' time [227]. Contact-less tools like acoustic levitation systems for manipulation and sensing are one of many solutions for automation but offer an alternative to contact-based automation solutions. Automated liquid handling and data collection systems are programmable, and software defined, enabling autonomous discovery like self-driving labs [192].

Acoustic levitation tools are an alternative to traditional tools for preparing nano-liter to pico-liter sample volumes without contamination due to container walls [168]. These systems can manipulate [211], mix [210], and analyze a wide range of materials like liquids [212], powders [148], and even living organisms [217]. This flexibility makes it a useful tool in fields and applications that benefit from aspects of acoustic levitation like wall-less containment vessels. With samples suspended in midair, sensors have an unobstructed direct path. This allows sensing methods like integrated Raman, infrared, fluorescence, or spectroscopy-based sensing to have direct access to the levitated sample and could enable real-time or even adaptive experiments and data-driven smart workflows.

Among these contact-less options, acoustic levitation stands out for its ability to trap, contain, and move objects and liquid droplets midair, using sound waves. Acoustic levitation takes advantage of the acoustic radiation force [33] which applies force to levitate liquids

and solids that are more dense than the gas that the acoustics propagate through. As a method for translating objects through three-dimensional space [138] and controlling the object rotational motion [136], acoustic levitation systems can be paired with touch-less sensing methods for real-time or closed-loop operation that combine the acoustic control framework with a sensing and levitation state perception system. Acoustic levitation systems also enable interesting possibilities for integration with laboratory automation and reprogrammable workflows since the acoustic levitation force can be software controlled [146]. This dissertation presents work and solutions for laboratory automation and contact-less liquid handling. It will cover methods for acoustic levitation control, contact-less sensing methods synergistic with acoustic levitation systems, and discuss the application of acoustic levitation systems in robotics, automation, and scientific instrumentation.

1.2 *Contact-less Manipulation Technologies*

Contact-less manipulation refers to the suspension and movement of objects against gravity without direct physical contact between a manipulator and the suspended object, typically achieved through the application of opposing force fields. These approaches enable the handling of materials without contact interactions like contamination or mechanical interference. In a contact-based manipulator or tool, unintended forces like friction, thermal exchange and surface adhesion can occur between the manipulator and target object. Several technologies can accomplish levitation and contact-less manipulation, each with its own advantages, limitations, and areas of application. The some examples of types of contact-less manipulation techniques include magnetic [88], electrostatic [170], optical [80], and acoustic levitation [214]. Each method relies on different interactions between fields and material properties to achieve stable suspension and movement.

Magnetic levitation uses magnetic fields to repel and stabilize an object with the help of diamagnetic, superconducting [130], or actively controlled electromagnetic systems [101]. These systems are commonly known for its applications in high-speed trains and contact-less bearings [219]. It can levitate relatively heavy and bulky objects. However, magnetic

levitation generally requires the levitated object to exhibit specific magnetic properties, but has been used in chemistry, material science and biochemistry [76], including cells [57].

Electrostatic levitation suspends charged particles and object using electric fields [170] and can be used in physics experiments involving objects or materials in vacuum environments where objects or particles can be studied without chemical or mechanical interactions with air [78].

Optical levitation, also referred to as optical tweezers [80], is a highly focused laser beam to trap and manipulate microscopic particles, including biological cells and molecules. The provides high spatial precision and is widely used in applications which require precision handling [52].

Acoustic levitation employs high-frequency sound waves to generate structured sound fields that exert pressure on objects and hold them midair [138]. Unlike the other methods of levitation, acoustic levitation does not require the object to have specific electrical, magnetic, or optical properties. Instead, the target object must have a density greater than the surrounding gas [33] and the acoustic radiation force must be greater than the weight of the object for levitation to occur. This makes it especially attractive for manipulating different objects like liquids, biological samples, or heterogeneous materials, in standard air temperature and pressure.

Each levitation method brings unique strengths. Among these, acoustic levitation has gained increased attention due to its ability to manipulate both solid and liquid samples, opening up possibilities in chemistry, biology, and material science. This versatility makes acoustic levitation systems a promising method for contact-less material processing and liquid handling.

1.3 Acoustic Levitation Background

Acoustic levitation systems have benefited from advances in high-performance computing and signal processing. Modern systems are capable of solving for hundreds or even thousands of acoustic phase delays in real time [146], enabling precise control of one or many ultrasonic

transducers within a phased array. This level of control allows researchers to dynamically shape acoustic fields and create stable traps or transport paths for levitated objects [159]. In following chapters, this dissertation will review contributions and work on acoustic levitation systems.

When ultrasonic standing waves or dynamically focused beams are created in air [137], they generate pressure nodes and antinodes that exert sufficient upward force to counteract gravity, allowing objects to be suspended in midair [99]. This effect can be used not only to hold objects in place but also to translate and rotate them. Acoustophoresis [123], or the migration of particles in a fluid medium due to these forces, is the movement of particles in a fluid due to acoustic radiation forces.

Acoustic levitators commonly operate in the ultrasonic frequency range (above 20 kHz), which is inaudible to the human ear and generally considered safe for use around people [55]. Most levitators use piezoelectric transducers to convert electrical signals into acoustic pressure waves. These transducers can be arranged in a variety of configurations — from single-axis standing wave systems with reflectors [202], to advanced phased arrays that enable dynamic manipulation in 3 dimensions [138], beam steering [137], and simultaneous control of multiple particles or droplets [132].

Recent advances have extended the capabilities of acoustic levitation beyond static trapping. Time-modulated arrays [21], phase holograms [138], and machine learned [109] field shaping algorithms now allow for programmable manipulation of droplets and particles in 3-D space. These capabilities are also compatible with closed-loop control, where computer vision or sensing methods are used to detect object positions [208] and adjust acoustic fields trajectories [165]. These dynamic control strategies make acoustic levitation especially promising for integration into robotic platforms and autonomous laboratory workflows.

Despite these advantages, acoustic levitation is not without limitations. Acoustic forces are relatively weak compared to mechanical actuators, and levitation in air is generally limited to objects roughly half the wavelength of the ultrasound, typically under a few millimeters in diameter, with some specific exceptions [7]. Additionally, acoustic streaming

and droplet evaporation can influence manipulation fidelity over time [225]. Nevertheless, as transducer technologies improve and control algorithms mature, these challenges are being addressed, paving the way for broader adoption in research and industry.

1.4 Acoustic Levitation as a Platform for Laboratory Automation

While acoustic levitation has historically been studied in academia in a variety of applications and fields including contact-less robotics and volumetric display technology, this dissertation will discuss application of acoustic levitation as a practical instrument for scientific experimentation and laboratory automation. As research tools continue to improve and evolve toward higher levels of precision, adaptability, and programmability, acoustic levitation offers a unique combination of properties that align well with the needs of today’s automated scientific workflows. These acoustic levitation systems are not only reconfigurable and provide unique contact-less containment and handling features, but are also compatible with a wide range of materials; platform characteristics that can be combined into a single manipulation technology.

Acoustic levitation provides a workspace where droplets, particles, material samples, or small living organisms can be contained, dynamically positioned, and rotated without mechanical interference. This changes the manipulation capabilities and design constraints of a physical containment vessel and enables the development of non-contact experimental protocols, such as midair mixing, controlled evaporation studies, exposure to control atmospheres, and direct access to optical or capacitive sensors. In this way, acoustic levitation systems serve not only as a containment vessel or manipulation technology, but also as a touch-less experimental chamber that can facilitate the development of contact-less sensing methods and instrumentation development.

Recent advances in transducer arrays, closed-loop feedback, and software-defined field shaping can allow acoustic system operation to be scripted, making them well-suited for integration into robotic and automated laboratory workflows. By treating the acoustic field as a dynamic reprogrammable workspace, researchers can develop workflows where the same

physical hardware performs multiple experimental functions in parallel, like holding, moving, mixing, and sensing samples. These building block functions will enable contact-less, operator-free workflow possibilities in laboratory automation by reducing manual operator intervention, increasing throughput, and providing reproducible, data-rich experimentation.

In this thesis, acoustic levitation is explored as a foundational platform for next-generation scientific instrumentation. The following chapters will present contributions in three primary areas: (1) in situ sensing methods; (2) acoustic control methods; (3) levitator toolkit functions. Together, these contributions as a whole aim to establish a basic feature set for acoustic levitation handling and techniques for the development of a clean adaptable, and autonomous laboratory systems.

Chapter 2

REVIEW OF RELEVANT LITERATURE

2.1 Introduction to Advances in Acoustic Levitation

Acoustic levitation systems most commonly use high frequency sound to apply acoustic radiation force to an object [6, 8]. Objects of lower weight than the acoustic radiation force can be lifted, overcoming gravity and suspended in midair [33]. Acoustic levitation systems are a mode of contact-less manipulation which can enable new methods of scientific exploration in fields such as material science [194, 72], chemistry [31], biology [13], robotics [5], and medicine [163]. With advances in phased array holographic field shaping [138] and machine learning [109], new control systems are being developed to increase the capabilities and robustness of these machines [4].

Acoustophoresis was first demonstrated in 1866 by Kundt’s tube experiments [114]. These experiments were designed to calculate the speed of sound in gas but also showed that the acoustic radiation force of standing waves within a tube could gather dust particles in the nodes. In 1933, Bücks and Müller demonstrated the first acoustic levitation device by levitating droplets of alcohol between a vibrating quartz crystal and a reflector [36]. Today modern computing has enabled the development of more complex levitation systems which shape the time averaged volumetric acoustic pressure field to lift and move objects in real time [132, 135].

2.2 Acoustic Field Shaping and Control

Acoustic levitation systems use the acoustic radiation force to lift, move and contain small particles and objects [33]. Unlike other methods of levitation, acoustic levitation does not need special material properties and can be applied to a variety of experiments [67]. Over the

years, control methods for acoustic levitation systems have matured [5], improving in reliability and manipulability. These acoustic levitation systems consist of holographic acoustic elements that use phased arrays to shape the acoustic field, moving levitated objects through space [138, 156]. Through structured acoustic fields and precise formulation of the acoustic radiation force hitting the levitated object, acoustic levitation systems can levitate objects larger than the wavelength of the emitted sound wave [98]. Using acoustic vortices [136] or vertex beams [21], acoustic levitation systems could tune and control the angular momentum of levitated objects [230], enabling six-degree of freedom control [173]. These systems can precisely move and rotate objects through space [137], enabling software driven systems for advanced manipulation [10].

Due to the flexibility and accessible nature of acoustic levitation systems [105], these levitation systems have been applied to a variety of applications with modifications to the software and hardware to fit the use case [229, 24]. Many of the foundational acoustic levitation systems used a Langevin transducer horn and an acoustic reflector to create high intensity standing pressure waves to trap particles [111]. As a software control algorithms matured, acoustic levitation systems have become a versatile tool for manipulating bio-particles [61]. Systems like acoustic tweezers [137] can precisely move and rotate cells and other living organisms in three dimensions [164]. Since levitated objects can be moved quickly [40] and with stability [66, 20, 73], acoustic levitation systems have been used as volumetric displays [70]. These systems use levitated polystyrene balls moving rapidly through a three dimensional trajectory to create volumetric displays [155].

Floating midair, levitated objects are trapped in a state of equilibrium between gravity and the acoustic radiation force [30]. Since acoustic levitation systems have a range of applications and relies on the acoustic ponderomotive force [99], researchers have tested a range of objects including levitating a tungsten ball [29], supercooled liquids [211], and large planar objects [233]. Acoustic levitation systems are able to levitated a large range of objects including dense tungsten [218], supercooled solids and liquids and asymmetrical and non-spherical objects.

2.3 *Displays and Data Representation*

Acoustic levitation systems have been developed as a method of data representation in volumetric displays [70] and three-dimensional animated structures [147]. Hirayama et al. have shown displays capable of visual, tactile and audio presentation possible through acoustic levitation systems [94, 205, 222]. Systems, like Articulev [64], demonstrate how acoustic levitation can be used as physicality midair representation for content via shape primitives, or another system, DataLev [74], which uses acoustic levitation to encode data spatially in multi-modal data physicalisation. By representing content in this way, interactive systems like Top-Levi [108], use acoustic levitation as tool to enable multi-user interactions with three dimensional content. Content visualization can include data information visualization [160], and interactions for human computer interfaces [18] (HCI) which are entirely contactless. Work in this field aimed at display methods [93], evaluates levitation stability at high speeds. It also considers system design questions such as scalability and acoustic array synchronization between devices [189].

2.4 *Medical and Biotech Applications*

In biological research, acoustic levitation offers a unique advantage [45] for handling delicate or contamination sensitive samples such as DNA [144] and proteins [51]. Acoustic levitation has been used as manipulation platform for acoustophoretic DNA transfection [201] and as a containment mechanisms for x-ray protein crystallography [198]. Acoustic levitation systems provide a contactless containment vessel [86] that does not introduce contamination [179] and does not need to be subtracted from sensor readings [141]. Acoustic levitation systems are contactless microfluidic circuits in air [42]. While acoustic levitation serves as a contactless containment and manipulation method for laboratory automation for industries such as biology [126], chemistry [199], and pharmaceuticals [106], it can also be used for field specific functions like amorphization of molecular liquids [25] and structural characterization of levitated drugs [26]. Acoustic levitation has emerged as a tool for biomedical and

biotechnological research [3]. It's ability to precisely control the position and motion of small droplets [228] and living organisms [217] in air makes it a compelling alternative to liquid handling robots and contact-based laboratory automation systems [87].

2.5 *Robotic Manipulation*

Far-field acoustic levitation can be applied to robotics as a non-contact manipulator [223]. These systems combine concepts from acoustics and mechatronics [63] to augment robot manipulator capabilities. Acoustic levitation systems can expand the manipulation capabilities of robots as a contact-less tool for picking up objects from acoustically reflective surfaces [152] and acoustically transparent surfaces [174] and as grippers to enable contact-less robotic manipulation [173]. Acoustic levitation systems can also be used in an assembly or manufacturing setting, combine with magnetic levitation systems for micro-assembly of micro-robots [226]. Chen [39] showed that acoustic levitation systems could be used for multi-material, omnidirectional 3-D printing. Near-field acoustic levitation systems can also be used a contact-less robotic manipulator [40] or a contact-less pick-and-place manipulator [9].

2.6 *Weighing of Levitated Objects*

Phase controlled acoustic field shaping and precision contact-less manipulator systems, are capable of manipulating small fragile objects without making direct contact [217]. However, in addition to manipulation, sensing attributes and collecting information about levitated objects are also useful [86]. The principle of determining the mass of objects from shifts in the resonant frequency of a mechanical structure is well establish, [53]. There are multiple examples of mechanical resonators such as micro-electromechanical structures [35] and piezoelectric transducers in microfluidic systems [34] which use the shift in resonant frequency to determine the mass of an object.

Weighing within levitation systems such as magnetic and optical traps have also been demonstrated by Hill [92] et al. and Dutta [58] et al. as a few examples of weighing objects

without directly touching the object to evaluate the object mass. In the field of acoustic traps, Fushimi [69] explored the non-linear trapping stiffness of acoustic levitation systems to better characterize the dynamics of particles within an acoustic trap. Trinh [195] showed that an acoustic levitator could be used to obtain the density of levitated objects.

In past work, we demonstrated that acoustic levitation systems could be used to weigh objects by modeling the acoustic trapping force as a Hookean system [151]. To account for the levitated object material and shape, a test object was used to obtain the restoring force coefficient. Since publishing this work, other groups have improved upon and taken this step further. Morrell [148] et al. improved upon the acoustic modeling method to better capture the non-linear force of the acoustic trap. Wang [209] et al. improved on the accuracy and precision of the weighing system by applying machine learning models and Fan [63] et al. showed how the acoustic weighing could be applied in contact-less robotic manipulators.

2.7 Launching of Liquid Droplets

Acoustic droplet launching (ADE) is commonly used every day in piezoelectric inkjet printer heads [50, 184], launching picoliter droplets of ink during the printing process. ADE is a non-contact method for transferring small amounts of fluid [154]. This technology is also beneficial for pharmaceutical and biochemistry industries to transfer small volumes of reagents in significantly less time than human or robot pipetting [60, 87]. Unlike inkjet printing, these systems do not need nozzles and have been applied to many fields such as drug discovery [153], compound management [167], genomics [37], synthetic biology [183], proteomics [172], and personalized medicine [178]. ADE systems are composed of three parts, an acoustic transducer, a source well plate, and a target substrate [154]. An acoustic droplet ejection system commercially available and used as a tool in multiple life science industries is the Labcyte ECHO system [2]. The ECHO can transfer liquid of volume amounts from 2.5nL to 1000nL between well plates for high throughput liquid transfer [124].

2.8 Droplet Shaping and Atomizing

As previously discussed, many groups such as Marzo [135, 138] et al. have developed field shaping algorithms to enable levitated object movement in air via acoustic phased arrays. Watanabe [210] showed that mode oscillation could be used to change the shape of levitated droplets and that this shape change could promote mixing withing acoustically levitated droplets during droplet coalescence. Yajie [220] demonstrated that the acoustic levitation system could be used to axially compress levitated droplets and Aoki [11] explored how the viscosity would effect droplet atomizing during axial compression.

Chapter 3

IN SITU SENSING METHODS

3.1 Acoustic Weighing via Hookean Restoring Force

Contact-less manipulation is one of the advantages of acoustic levitation systems, enabling contamination-free transport, processing, and interrogation of levitated objects, including hazardous, biological or precious samples. In conventional laboratory workflows, samples must be stored, transferred, and weighed using physical containers and tools. Each of these steps introduces opportunities for sample loss, cross-contamination, or adhesion to surfaces. Even cutting-edge tools like the Labcyte ECHO, which uses ultrasonic transducers to precisely transfer nanoliter droplets, still rely on traditional containers for sample storage, which can prevent simultaneous manipulation and sensing of samples and potentially introducing surface contact problems into the workflow.

Acoustic levitation systems offer a fully contact-less environment for manipulating diverse sample types, including liquid droplets, granular materials, rigid solids, and even living organisms. To fully realize the benefits of levitation, it is critical that sample sensing and analysis also occur within the levitation system, without requiring scientist to transfer samples or reagents to containment vessels for external sensing or analysis steps. Contact-less sensing modes such as cameras can acquire information about a sample, like color, shape, or structure. Spectrum analyzers can obtain sample material composition. However, one of the most fundamental quantities scientists measure is mass, or how much mass makes up an object. Today, we use calibrated scales to weigh objects, placing the object on the scale or in a containment vessel to hold liquids and powders. These weighing methods require physical contact between the sample and the containment vessel or weighing system, an opportunity for sample loss or contamination when residual material is left behind. For an acoustic lev-

itation system that gains its advantages from contact-less manipulation and containment, the need for a supplemental contact-based sensing tool can create a usability problem.

To address this problem, this section presents a method for contact-less weighing called the acoustic balance [151]. This system leverages the same Hookean spring-like restoration force of the acoustic levitation system to estimate the mass of a levitated object in situ, without requiring physical contact between objects and containment vessel walls or removal of the object from the levitation system. The acoustic balance enables real-time, contamination-free measurement of the levitated object mass, and can also be used to continuously monitor dynamic mass changes, such as the evaporation of liquid droplets. Furthermore, when deployed in a multi-object levitation system, this method enables parallelized mass monitoring across multiple samples, unlocking new possibilities for high-throughput experimentation and autonomous laboratory workflows.

3.2 Levitated Weighing Principles

As discussed in previous sections, acoustic traps manipulate objects through pressure wave gradients. Other groups have shown that multi-channel, phase controlled acoustic elements can manipulate and move objects and overcome gravity. The restoring force acting on the trapped object in this levitation system can be expressed as the gradient of the Gor'kov potential, [33, 54], and methods of finite element modeling can represent the acoustic trapping field.

Objects trapped within an acoustic levitation system are subject to a restoring force that confines the object similar to that of a mass spring system. Omitting damping forces, like drag, the confining force on the object can be a linearly approximated by the equation $m \frac{d^2x}{dt^2} + kx = 0$, where k is the restoring force constant, and x is the horizontal displacement. The relationship between the object's mass, m , and resonance frequency, f can be described by the expression for the natural frequency of a harmonic oscillator, eq. 3.1.

$$m = \frac{k}{(2\pi f)^2} \quad (3.1)$$

By changing the volumetric acoustic field shape via phase delays, the acoustic trapping location can be arbitrarily set. Using this technique, objects can be weighed by suddenly and discontinuously changing the location of the acoustic trap such that the equilibrium location between the acoustic field and gravity also changes. This new equilibrium location pulls the object toward it and the object oscillates as it returns to equilibrium in this new stable trapping location.

3.3 Acoustic Weighing Method

The weighing method works by applying a perturbation to the position of the trapped object and monitoring the object's oscillation frequency as it settles into its new trapping location. This is achieved by changing the location of the acoustic trap minima to a new location in a discontinuous manner, resulting in trapping imbalance. This discontinuous shift in acoustic field necessitates the object to move once again toward lower acoustic potential, first overshooting the acoustic trap equilibrium position, causing an observable damped oscillation.

Fig. 3.1 shows the different types of objects tested. These include polystyrene cubes, ants, hardfiber disks, fr4 disks and mineral oil droplets. The actual mass of each object tested was also recorded using a Mettler Toledo XPR2U balance with a minimum sample

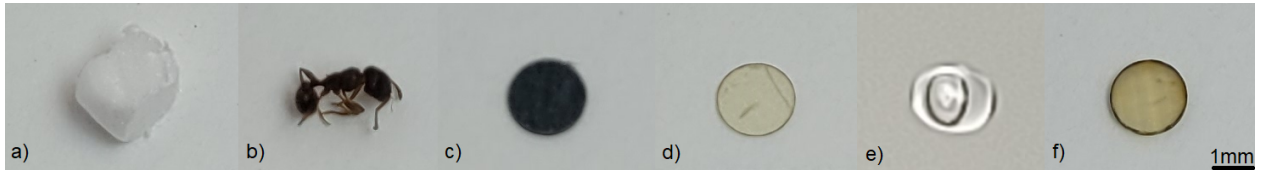


Figure 3.1: The variety of objects used as test masses to validate the acoustic balance: (a) polystyrene, (b) ant, (c) hardfiber disk 5 mil thick, (d) FR4 disk 5 mil thick, (e) mineral oil droplet with air bubble trapped inside, and (f) FR4 disk 10 mil thick

weight of 0.03 mg, precision of 0.001 mg and smallest readable digit (readability) of 0.0001 mg [142].

The acoustic trap displaces the object from position 1 at $x=21\text{mm}$, moving the object to $x = 20\text{mm}$, position 2. This 1 mm step allows for enough trapping discontinuity to cause the object to oscillate while remaining trapped within the targeted acoustic position. A sudden displacement allows the system to quickly record the damped natural frequency to approximate the resonance frequency and calculate the object's mass using the force constant for the acoustic trap. The movement phase from position 1 to position 2 is called the primary displacement. After the object has stopped oscillating, a secondary displacement can be performed, moving the object from position 2 back to position 1. Fig. 3.2a shows both the photoresistor voltages during the primary and secondary displacement steps.

The primary and secondary displacements are performed 10 times each to obtain a better frequency measurement, 20 frequency samples in total. Fig. 3.2 shows the raw photoresistor voltage over the span of all 20 displacements. The Fast Fourier transform is computed for

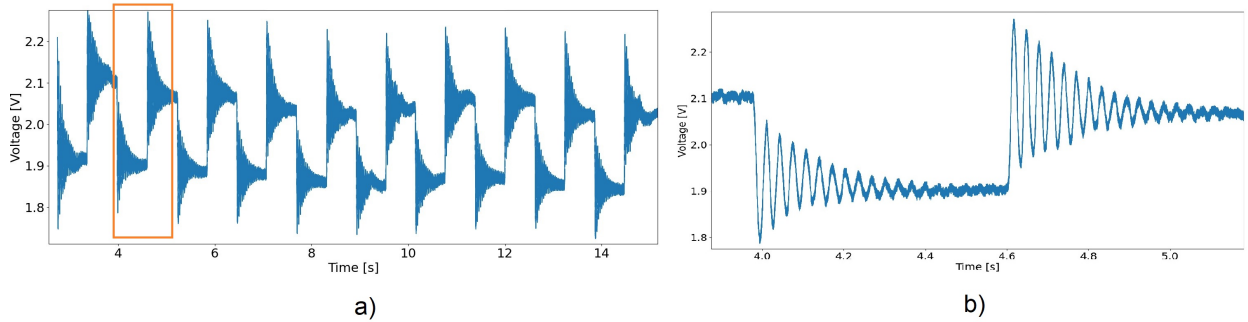


Figure 3.2: **(a)** The voltage signal from the photoresistor corresponding to the displacement and oscillation of the particle in the acoustic trap. The trapped object matches an underdamped oscillating system in both the primary displacement, $t=4.0\text{s}$ to $t=4.6\text{s}$ and the secondary displacement of the object within the trap, $t=4.6\text{s}$ to $t=5.2\text{s}$. **(b)** The full waveform recording for a single test object. The object is displaced 20 times total shown by the 20 damped oscillations. The total time to measure a single object is about 12 seconds.

each primary and secondary displacement wave and the mean frequencies and frequency standard deviation of the primary and secondary displacements are computed to obtain 2 mean damped natural frequencies and 2 standard deviations. The frequency standard deviations for the primary and secondary displacement data sets are represented as a percentage of the mean set frequency. The mean frequencies are then converted to mass values using 2 force constants, one calibrated for primary displacement and another for secondary, avoiding the assumption that both frequencies can be converted to masses using the same force constant. This method compares the test object mass to the calibration object's mass like a balance.

Table 3.1: Acoustic Balance Calibration Masses

Calibration Object	Mass
Polystyrene	0.2552
Ant	0.1726
Hardfiber Disk	0.4369
FR4 5mil Disk	0.5817
Mineral Oil	0.8631
FR4 10mil Disk	1.5267

The acoustic force experienced by the test mass within the acoustic field is dependent on the object's shape and material density, the ambient air temperature and the acoustic pressure field. Therefore, a suitable calibration mass is one that is similar in shape and material composition as subsequently weighed objects. This reduces potential calibration related weighing error attributed to object shape and material properties. At the time of weighing, a sensor measures the ambient air temperature in the acoustic balance and the model used to calculate the phase angles controlling the acoustic emitters is adjusted. This helps to ensure acoustic pressure field consistency between weighing attempts since the speed of sound in air is proportional to the square root of temperature in Kelvin [215]. Factors

that influence the acoustic pressure field, such as acoustic emitter driving voltage or the number of transducers used to form the acoustic pressure field, should be kept consistent after calibration.

Another factor that may indirectly influence the effectiveness of acoustic weighing is the settling time of the object after being displaced. Fig. 3.2b shows how the oscillations of the first response are damped out before the secondary displacement occurs at $t=4.6s$. The settling time is the time the object takes to reach steady state after it has been perturbed. This also determines the rate in which subsequent measurements can be made. For objects with greater air resistance, the settling time can be even less as the oscillations are damped out quicker.

3.4 Calibration of the Acoustic Balance

To calibrate the balance, the reference object is acoustically weighed 10 times to obtain a mean natural frequency, a total of 200 frequency samples. The mean damped natural frequency from the laser-based displacement sensor and the directly measured mass from the XPR2U were then used to compute the linear force coefficient, k , for each calibration mass. Table 3.1 shows the directly measured mass values obtained during the calibration procedure by the XPR2U.

To avoid future calibration steps, force coefficients can be saved as for future reference based on the material of the levitated objects. This look up step can also be automated using a camera and computer vision models to identify both the levitated object material and overall shape.

3.5 Balance Sensing Hardware

Fig. 3.3 shows a cross section view of the acoustic levitation system with the laser beam position in the $x=20mm$ plane and the object positioned at $x=21mm$, referred to as position 1.

The oscillation frequency of the levitated object is measured using a 3mm beam diameter

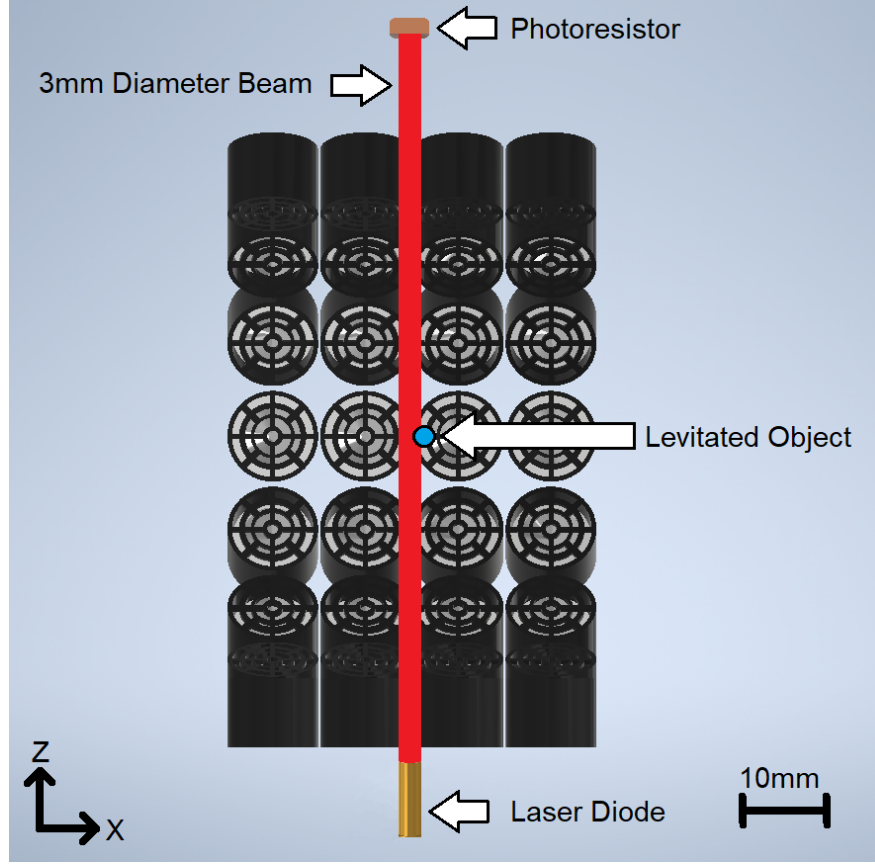


Figure 3.3: Cross section view of the acoustic trap. The laser diode travels through the gaps between the transducers along the $x = 20\text{mm}$ plane and is aligned such that an object positioned in the middle of the acoustic trap will occlude the laser from the photoresistor.

650nm laser diode (LD-5MW-650NM) and a $10\text{k}\Omega$ to $200\text{k}\Omega$ photoresistor (1528-2141-ND) with a detection window of $4\text{mm} \times 3\text{mm}$, shown in fig. 3.3 with the levitated object positioned partially occluding the beam. The variable resistance of the photoresistor is converted to a variable voltage by a voltage divider circuit. The voltage signal shown in fig. 3.2 is recorded by a Saleae Logic 8 digitizer configured to sample at 2.5 mega-samples per second (MSps), a much higher sampling rate than a camera.

The acoustic trap uses a 64 transducer (Murata MA40S4S), cylinder shaped geometry with 4 stacked rings of 16 transducers and a diameter of approximately 47.6 mm. Each trans-

ducer is independently phase controlled. The Cyclone V FPGA (Field Programmable Gate Array) sends time multiplexed output channel waveforms to shift registers which demultiplex each signal into 8 output channels. These output channels are then voltage level shifted from the 3.3V, 40 kHz, square waves to a 32V peak-to-peak square wave by a HEF4104BT level shifting integrated circuit. Phase values for each transducer are calculated by a computer and sent to the FPGA via a USB-to-UART serial connection. The acoustic trap is a standing wave levitator with opposing emitters. This restricts the maximum size of a trapped object to about 2.5mm. By controlling the acoustic trap and performing the displacement maneuver with phase modulation rather than an acoustic emitter on-off method, multiple objects can potentially be levitated and controlled simultaneously with the acoustic weighing procedure.

3.6 Discussion of Acoustic Weighing Results

Table 3.2 shows the percent error of the acoustic balance measurements compared to the Mettler Toledo balance measurement. The percent error for all the various test mass objects are either 5.56% or better except for the polystyrene and ant test masses. Additionally, fig. 3.4 shows the acoustic balance did not accurately weigh the polystyrene and ant objects less than 0.2mg. This would indicate that the minimum mass the acoustic balance can measure is about 0.2mg and that the balance was not sensitive enough to accurately weigh the least massive objects. Considering the test object group with the greatest mass, the FR4 10 mil data has the largest absolute mass variance relative to the other samples, even of similar shape and percent error. Combined with the low frequency standard deviation at 2.91%, the FR4 10 mil thickness test object likely has the lowest linear force coefficient compared to the other test masses. This indicates that the FR4 10 mil disk is near the upper limit of mass this levitation system is capable of sufficiently trapping and weighing. The range of accurate measurement for this specific acoustic levitation device is then between 1.5mg and 0.2mg.

Table 3.2: Acoustic Balance Results

Test Object	Mean % Error	Mean Freq Std Dev %
Polystyrene	20.17	7.97
Ant	13.17	13.27
Hardfiber Disk	4.70	4.44
FR4 5mil Disk	4.39	2.94
Mineral Oil	4.18	15.76
FR4 10mil Disk	5.56	2.91

3.7 Measurement and Standard Deviation

Even though the acoustic levitator was capable of levitating the various objects, some objects were more difficult to measure than others. The frequency standard deviation percentage indicates the fluctuation of the frequency measurement relative to the test object mass. Mineral oil, for example, has a mean frequency standard deviation percentage of 15.76% indicating the frequency samples obtained when measuring the mineral oil samples varied by about 15.76% of the sample mass. The ant samples also had high deviation percentages as well. A contributing factor to the higher deviation is the additional noise due to mineral oil droplets refracting the laser and the ant shape causing spinning in the acoustic trap. However, the acoustic balance measured samples above the minimum mass amount with a percent error of less than 5.56%, and only 4.18% for oil. While some materials and object shapes can cause increased noise, these challenges can be compensated for by increasing the number of frequency samples and applying acoustic field shaping techniques to minimize object spinning within the trap.

By increasing the number of samples required to obtain a confident measurement, the time to measure increases. The time to perform a mass measurement is also determined by the settling time, or the waiting time required between perturbations to allow the test object

to stabilize in the acoustic trap. In general, the settling time is determined by the damping force, air resistance, and therefore makes objects with greater drag forces easier to measure as frequency measurements can be performed in quicker succession. This also means that for certain objects, perturbation direction also matters since some objects have a greater air resistance when move horizontally versus vertically.

3.8 *Acoustic Balance Performance*

The measurement results indicate that the acoustic balance can measure objects with a percent error of 5.56% or better in the range of 1.5mg to 0.2mg. The acoustic system was also tested with object sizes ranging from a 2.5mm long ant to a 0.5mm sized cube. A variety of types of objects were also tested including liquid mineral oil, ants, and FR4. While the acoustic balance was able to measure objects at the high end of its mass levitation capabilities, it lost performance at the lower end as the mass decreased, yet the weighing variance did not decrease proportionally with the decrease in mass.

While additional precision and performance can be obtained by averaging a greater number of samples, this comes at the cost of increased time to weigh individual objects. Shown in the lower left corner of fig. 3.4, for the specific laser-photoresistor sensing method, there exists a limit to the smallest measurable mass due to the noise floor present in the measurement. Section 3.9 will discuss methods for decreasing this noise floor and obtaining better weighing performance.

Acquiring the weight of an object while being manipulated can enable interesting and new techniques for acoustic manipulators. By using the acoustically obtained weight as a closed-loop feedback mechanism, material can be incrementally added to and combined with droplets, powder, or other objects in the acoustic manipulator. This sensing method is especially useful in mass-based sorting and dispensing of precise quantities of material in applications like automated laboratory processes and additive manufacturing. These techniques can be applied to the development of robot end effectors or contact-less laboratory automation systems which can enable a general purpose robot to perform precise chemical and contamination-free, reagent mixing tasks.

3.9 *Discussion of Acoustic Weighing Capabilities and Improvements*

While acoustic balances can add a new sensing method to acoustic levitation systems and robotics, some future directions of work can potentially increase the repeatability and accu-

racy of this weighing method or remove the need for a calibration object. Future changes to the hardware can also improve the minimum and maximum size and mass limitations by reducing the measurement variance introduced by noise. Some of the directions for improving performance of the acoustic balance are changes to the measurement steps and procedure for calibration, while other methods for reducing the noise require changes to the hardware and software.

The acoustic balance leverages two trapping positions 1mm apart that the object is displaced between. The two positions are treated as having different force coefficients and thus the calibration object needs to calibrate for two acoustic positions. This means that the object is measured using two potentially different force coefficients which could have different levels of sensitivity. Equation 3.1 shows that for higher k values, or higher acoustic trapping forces, the same object will have a higher squared resonance frequency, f^2 . This also means that for higher k values, 0.1mg in mass is represented by a wider frequency range, relative to lower k values.

Rather than performing the displacement of the object horizontally along the axis of the cylindrical shape of the levitator, the system can take advantage of the symmetry of the levitator geometry and displace the object along a series of nodes formed around the cylinders axis. Since the radial symmetry of the acoustic field means each node about the center is of similar trapping force, the calibration object would only need to calibrate for one trapping node and the force coefficient can be potentially reused for each node about the ring equidistant to the central axis.

One of the weaknesses of this approach to weighing is the required calibration step needed to derive the force coefficient. To reduce the number of steps needed to calibrate the system, the weighing process can be improved is by characterizing the dynamics of specific shape and material combinations within the trap and using this information to create a reference library or model which would give a force coefficient based on the levitated material. The model could also further be improved with computer vision. By using a camera to identify the object, the overall shape and volume of levitated object can be estimated to further refine

the force coefficient model. Another direction for improvement would be to train a machine learning model. The model would learn to recognize the levitated object's material and shape to estimate a force coefficient or transfer function that correlates the raw oscillation waveform data to a mass.

The acoustic balance was tested using inanimate objects and insects that could not fly, shown in fig. 3.1. A direction for future work and improvement is validation adapting the calibration and weighing system for insects capable of flight and other living organisms like the ones levitated by Xie [217]. It is very likely that the added movement capabilities of the living organisms in the levitator could lead to calibration or measurement variation that would need to be removed during calibration.

In the presented acoustic model and framework for a hookean force constant, the acoustic levitation force is assumed to be a linear force. However, the acoustic levitation force is non-linear for high intensity sound fields. The relationship between the mass and the levitated object dynamics within the acoustic field is likely also non-linear. A machine learning model could also better estimate the non-linear dynamics of the acoustic trapping field and help to increase the accuracy and precision of the acoustic balance, replacing the calibration step with training a machine learning model.

Hardware changes can further improve weighing performance. By increasing the number of acoustic emitters or changing the type of emitter to a more powerful transducer, the new hardware system could manipulate objects of larger mass, also increasing the force coefficient. As mentioned previously, by increasing the force coefficient, the acoustic balance gains additional mass resolution as the same mass step is represented by a larger frequency step. Changes to the acoustic emitter geometry or phase profile could also increase the range of object sizes.

Additional hardware changes can also be made to the object displacement and oscillation sensors. Instead of using a laser and photoresistor combination, a lidar, time of flight sensor, camera, or other sensor can be used to obtain more accurate tracking of the levitated objects. For transparent droplets, a different type of sensing method could yield a higher signal-to-

noise ratio, reducing the noise floor and making the noise easier to digitally signal process.

3.10 Contact-less Camera-based Sensing Methods

Unlike traditional laboratory setups where analyzing a sample involves containment vessels, probes, or mounting harnesses, levitated systems derive an advantage from their touch-less manipulation capabilities and therefore complement sensing modalities that preserve the sample's isolation in midair. Touch-less sensing modalities, like the weighing system previously discussed, also enable acoustic levitation systems to perform direct measurements on samples.

This section presents the development and integration of several complementary touch-less sensing methods for acoustic levitation systems. The sensing systems presented will focus on camera-based image feature extraction processing and optical sample tracking of clear liquid droplets. Each approach addresses different aspects of sample characterization that will be used to collect the results presented in later sections that describe acoustic levitation system control and manipulation methods. These sensing methods can enable future implementation of real-time monitoring and closed-loop control of samples and reagents in experimental workflows without introducing contamination. By choosing to use touch-less sensors like cameras with acoustic levitation systems, operators can preserve sample integrity and fully leveraging the contact-less manipulation capabilities of acoustic levitation systems.

3.11 Colorimetric Sensing of Levitated Liquid Droplets

Camera-based sensing is a well research field [190, 197] that has been used in a variety of applications including robotics [62] and particle image velocimetry [169] to name a few. Modern imaging sensors, like high resolution cameras and scientific-grade CMOS sensors, can provide real-time touch-less visual data about levitated objects within acoustic traps. Using image processing and computer vision algorithms, these raw images can be processed to extract sample features such as position, shape, size, color, and other dynamic behaviors. This data can be processed to extract quantitative information relevant to scientific experiments and

leveraged by both the acoustic levitator’s controller and in experiment workflows.

Another application of camera-based sensing in levitated systems is colorimetric analysis. In biology and chemistry, the color or intensity of a sample can be used as an indicator of indicator of relative chemical, biological, or physical changes. Colorimetric assays are widely used in diagnostics, bio-sensing, and chemical analysis due to their simplicity, low cost, and ease of interpretation [181, 107]. A common application of colorimetric readout is the chemistry used in pH testing [22]. The result of the test is indicated by the change in color of the testing implement. When combined with acoustic levitation, colorimetric sensing allows for in situ analysis of reactions or processes occurring within levitated droplets without the need for physical sampling or contact with measurement tools.

Image feature extraction for colorimetric readouts typically involves capturing a video or series of image frames of the levitated sample under controlled lighting conditions and background environment. Software algorithms can then process these images to isolate the region of interest (ROI), correct for background noise and extract color values. These color metrics are often calibrated against known standard or reference reaction results for normalization or relative comparison between experiments [180]. This color change can be evaluated quantitatively [84] in terms of color change over time, comparing the color development of two experiments as indicators of reaction kinetics [203], for example.

When applied in acoustic levitation systems, camera-based colorimetric sensing offers several advantages. Levitated liquids and solids can be touch-lessly monitored in real-time and end-to-end without interfering with the acoustic field. It can enable automation and high-throughput workflows that may depend on simultaneous tracking of multiple levitated samples or reagents used in a reaction. The continuous data available can help inform control systems that can take advantage of real-time data for actuation or experimental parameters at both the acoustic levitation control level and the experimental workflow control stage. This same data can also be used to monitor dynamic processes such as evaporation, mixing, or reaction kinetics directly.

However, the accuracy and effectiveness of these camera systems are dependent on fac-

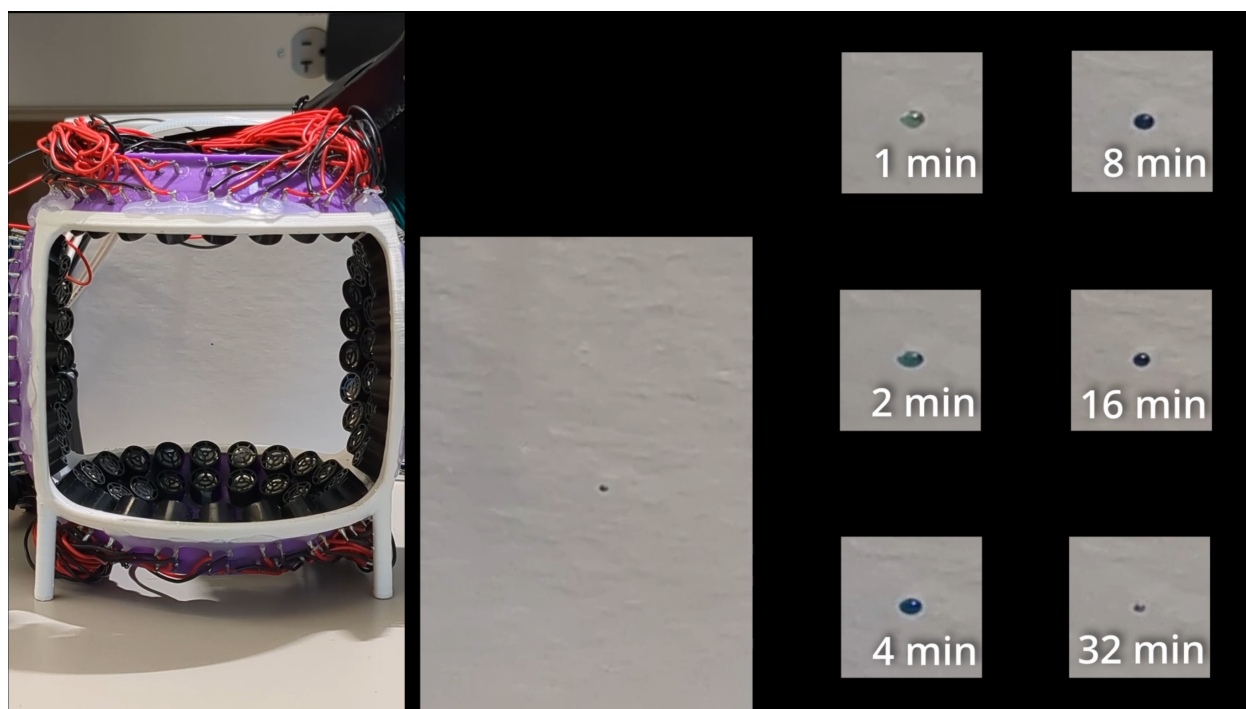


Figure 3.5: Colorimetric sensing of acoustically levitated mixing of peroxidase-mimicking DNA-zyme reaction showing the reaction progress as the droplet darkens and evaporation reduces the volume of the droplet and concentrates the contents. To turn this system into a complete colorimetric sensing system, the brightness would need to be extracted from the image and calibrated.

tors such as lighting stability, camera calibration, perspective distortion, and acoustic wave-induced sample motion. Addressing these factors often involves error compensation, implementing controlled illumination setups, mounted camera positioning and object tracking algorithms. Specifically, tracking and visual feature extraction of transparent liquid droplets can be difficult no matter the lighting conditions. While lighting techniques for increasing the contrast between levitated droplets of clear liquids like chemical reagents exist, droplet localization during movement can lead to loss of tracking

Ideally, levitated aliquots of transparent liquid can be localized within the acoustic levitation system using a camera as the primary method since camera-based solutions provide a

multipurpose solution for data gathering. Additionally, visual feature extraction techniques need to be effective in a variety of ambient lighting conditions and cannot directly affect the contents of the liquid sample. Factors such as sample sensitivity to high intensity light can prevent usage of lighting techniques that increase sample and background contrast ratio. The next section presents a solution to enabling camera-based localization of levitated transparent droplets of fluid by taking advantage of background patterning seen through the droplet.

3.12 Visual Feature Extraction and Localization of Clear Droplets

Accurate localization of levitated samples is critical for estimating the position and velocity of one or multiple levitated objects. The data derived from image feature extraction can be used in feedback control loops, automated manipulation, and quantitative analysis in acoustic levitation systems. However, while opaque or colored objects are readily detected using standard image processing techniques, transparent or near optically clear droplets present unique challenges for visual feature extraction and localization. Low contrast between levitated objects and background make transparent objects difficult to detect against typical backgrounds, especially in uncontrolled or changing lighting conditions.

Localizing and performing visual feature extraction on transparent droplets can pose a couple of challenges, primarily due to the refraction and distortion of environment background or the reflection of light into the camera. Both problems can cause unrecoverable loss of tracking or even cause tracking algorithms to track the wrong object. Often times, clear droplets of liquid are most easily identified in images through distortion of background patterns, edge highlights due to specular reflections, or lensing effects. Effective localization can sometimes rely on enhancing and detecting these secondary visual features rather than directly detecting the droplet body with camera imaging.

There are several strategies and methods that can be used to improve the detection success of transparent droplets in acoustic levitation systems. These methods may include improving lighting conditions and lighting angles, using edge detection algorithms like a

Sobel operator to emphasize droplet perimeter features, or choosing a machine learning-based detection approach. To track the motion and measure the velocity of transparent droplets, droplet data was collected using a combination of controlled illumination for better contour-based localization and by improving tracking reliability by using a checker board background pattern.

To overcome the inherent challenges of visually detecting and tracking a transparent droplet within the acoustic levitation system, we developed a localization method based on a neutrally lit environment combined with a high contrast patterned background. This approach exploits the optical distortion caused by the transparent droplet, acting like a lens when placed in front of the background pattern. Rather than directly extracting the outline of the droplet itself, our method focused on tracking the distorted background pattern seen through the droplet. As the droplet moved, the pattern would change, but there was enough continuity between the distorted pattern in each frame to enable a contour-based tracking algorithm to follow the changes in background pattern contour without losing tracking. To help improve the reliability of this method, the levitator and droplet trapped within, were front-lit using a diffused light source and the background was printed with a matte finish. This maximized the contrast of the white and black checker board pattern distorted by the droplet while also reducing bright reflections from the droplet and background surface which could cause continuity loss.

When processing the video frames, the scale and two dimensional coordinate system can be defined using the background pattern. By using a high contrast pattern to make the transparent liquid more identifiable, the droplet remains visible whether it is in front of a black or white tile. Additionally, while the droplet is moving in front of the background, the distorted pattern seen by the camera changes as the droplet refracts the different parts of the background behind the droplet, but tracking still remains possible because the pattern difference is small enough between frames. As the droplet movement speed increases, the tracking and localization reliability and consistency can decrease and become more noisy as the similarity of the droplet pattern is greater between frames and the image of the droplet

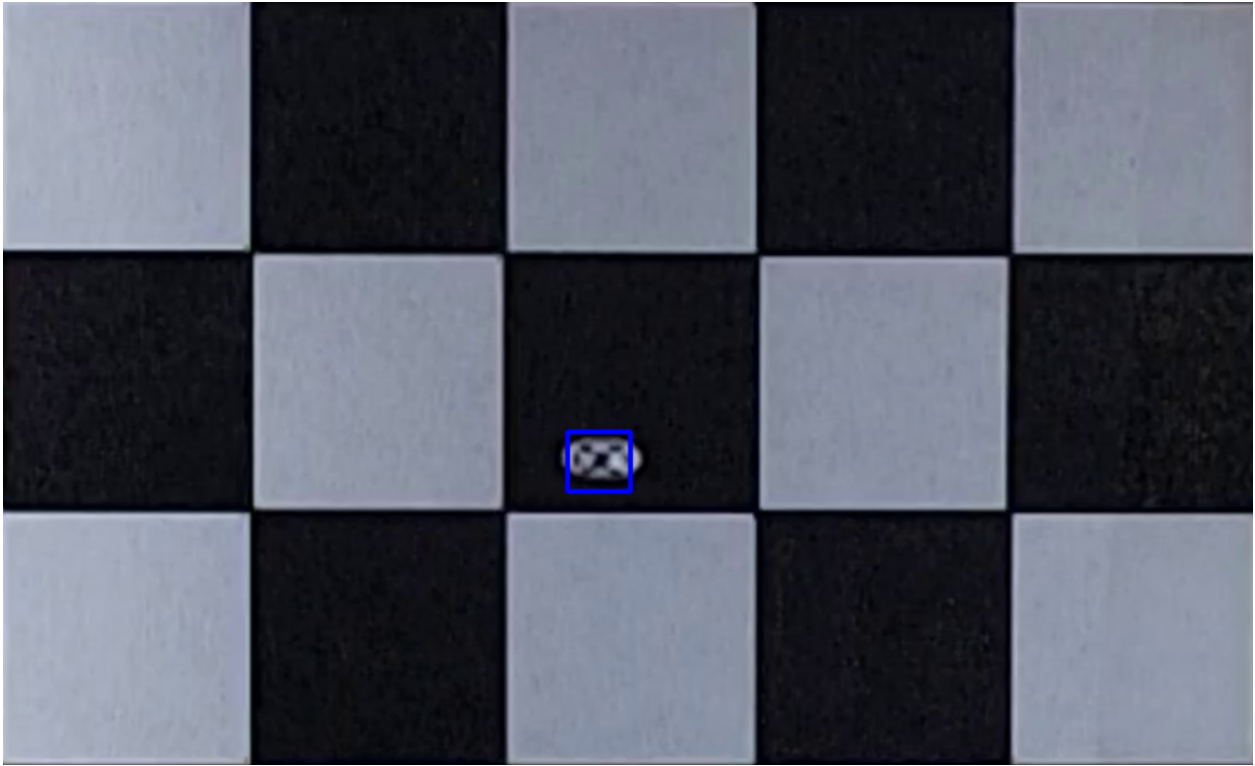


Figure 3.6: Tracking and localization of a transparent liquid droplet by targeting distorted high contrast background patterns when viewed through the droplet.

becomes more blurry.

In later chapters, this camera-based method for localizing and tracking the object will be used to monitor the speed of the droplet movement as it is controlled by the acoustic levitator. While this method for applying a visible pattern to the droplet enables droplet tracking, the added background pattern is an additional factor to consider when attempting to use camera-based image processing techniques to gather additional points of data. When gathering color data, the pattern needs to be considered during colorimetric readout. The high contrast pattern can change the hue of the colors and makes shape recognition of droplets during droplet compression difficult since the distorted pattern interferes with edge detection. With multiple camera perspectives, this method for localizing transparent fluids can enable three dimensional closed-loop control and trajectory planning of liquid droplets in

the levitator. Similar to computer vision applications in robotics, the addition of two or three cameras can enable tightly integrated data collection and object control for multipurpose sensing.

3.13 Improving the Camera-based Feature Extraction

The camera-based localization and visual feature extraction can be used to identify the colorimetric state of experiments and to localize and monitor the position and velocity of moving objects within acoustic levitation systems. There has already been work outside the contextual application of acoustic levitation that could be applied to improve the system. Camera-based imaging techniques have a number of error sources such as particle lag, illumination, and image recording. Improvements to the camera sensing system can be broken down into colorimetric improvements and object tracking improvements. The camera used to track the object position and velocity is a Sony IMX179 sensor. The resolution, distortion, and sub-pixel arrangement of the camera can have an effect on the position and velocity measurement. Additional accuracy and performance can be derived by calibrating and characterizing the camera's intrinsic and extrinsic parameters.

Improvements to the colorimetric measurement method in the acoustic levitation system fall into two main categories. The first is controlling the illumination and lighting environment of the levitated objects and background. Second, the camera itself needs to be characterized. To obtain an image of the levitated objects, the levitated objects and background in view of the camera need to be illuminated to increase the contrast between the background and the levitated objects. Since colorimetric results compare color development between two or more experiments, illumination of the acoustic levitation volume should be kept consistent between experiments but also across the acoustic levitation space, avoiding shadows or differences in brightness. Lighting methods should aim to reduce glare and reflections from the surface of levitated objects and reflective components in view of the camera. To keep illumination of the acoustic levitation space consistent, white led lights with diffusers can be fitted inside the acoustic levitation system attached to the chassis.

A direction for future work and development is testing and quantifying how droplet evaporation and condensing of the material contained within the droplet affects the appearance and brightness of the droplet color. As the droplet changes volume and decreases in size, the droplet’s optical properties might also change causing a change in appearance, including how illuminating light is refracted and reflected by the liquid surface. A control experiment to test this would be to measure how a colorless transparent droplet with known material properties (pure water) changes in brightness as the droplet evaporates. As the droplet decreases in size, light could refract and reflect differently along its path to the camera, including internal reflections within the droplet.

In addition to improving the lighting environment consistency and brightness calibration, the camera sensor can be characterized to improve color accuracy for future colorimetric experiments. By using calibrated LED lights at known wavelengths, the camera sensor color space can be mapped to the LED wavelength. With consistent lighting conditions and characterized camera color sensor mapping, the rate that an experiment color change develops can be captured and compared across samples within the same camera frame (multiple samples in camera view) and between different trials (multiple image recordings). Finally, by adding tinted side panels to the acoustic levitation chamber, the lighting conditions within camera view can be kept more consistent. This would improve colorimetric comparison by enabling consistent experimental data collection regardless of lighting conditions external to the acoustic levitation system. By creating a consistent lighting and camera sensing environment, quantitative measurement of colorimetric results could be used to compare and track color development of samples during experiments, even across different acoustic levitation camera capture systems.

The object tracking and localization system uses background patterns to make levitated transparent liquid droplets easier to track. As a tool for precision position and velocity measurement, cameras have sources of error that need to be accounted for to increase the position measurement certainty. Accurately processing of camera data information requires estimation of the intrinsic camera parameters such as focal length and skew, and lens distortion

parameters like radial and tangential distortion. It is also necessary to estimate the extrinsic parameters of the camera which include camera position and orientation. Sometimes the estimates of camera parameters can be baked into the image processing pipeline. Image capture parameters like frame rate limit the accuracy of velocity measurements. The camera system parameters, and the errors in the estimation of these parameters, will lead to propagated errors in the system's ability to measure the droplet position and velocity. In future work, the camera system's precision and accuracy will need to be characterized to better measure the droplet position, velocity, and color. These camera attributes will affect the minimum and maximum resolvable object displacement and uncertainty [100]. Improvements to the camera system can come from using a sensor with a higher resolution, frame rate, shutter speed, or changing the recording setup. Additional proposed improvements to the camera-based levitated object tracking system include collecting ground truth motion data using a calibrated precision 3-D motion stage and changing the background in view of the camera to enable localization based on the background pattern viewed through the droplet. These improvements could be applied in addition to camera hardware improvements.

The current camera sensing system could be characterized using a motion stage to identify the minimum and maximum resolvable object displacement and positioning certainty. The motion stage can be used to move and position a target object through the acoustic levitation system volume (with the acoustics turned off) in view of the camera. The camera recorded and processed position and movement velocity of the target object can be compared with the motion stage output position and movement velocity to obtain a ground truth measurement of the camera system and assess the camera tracking error. The uncertainty of the ground truth and also the camera error measurement would be dependent on and greater than the positioning accuracy of the motion stage. Another potential method of localizing the levitated transparent liquid droplet is by treating the droplet like a lens and designing a background for the two dimensional view of the camera. This background could be designed such that each pattern viewed by the camera through the droplet would be unique. If the camera position and background plane is known, the unique pattern in focus and visible to the

camera could be used to identify the exact location of the droplet in a two dimensional plane. Additionally, if the volume of the liquid and the optical lens behavior of the liquid versus the droplet volume is known, the amount of the background pattern visible and in focus through the droplet could also be used to estimate the droplet distance away from the camera, similar to positioning a lens based on focal distance. This method for localizing the droplet would depend on the camera and lens setup used. The lens would need to be able to keep the droplet background pattern in focus and the camera would need a high enough resolution and frame rate to clearly resolve detail in the pattern as the droplet moves. The background could also take advantage of multiple colors to communicate a unique locatable pattern. Future work on camera-based tracking and velocity measurement of levitated transparent liquid droplets can be improve through hardware upgrades and further characterization of the camera sensor used. The object tracking method can be validated with motion stage of background based approaches to ground truth data collection to quantify the object localization error.

Chapter 4

ACOUSTIC CONTROL METHODS

Precise control of levitated objects is essential for advanced acoustic levitation systems as scientific instrumentation and tools for laboratory automation. While basic levitation can be achieved with simple standing wave fields or static phase transducer array configurations, more sophisticated applications, like droplet transport and dynamic object manipulation, require more advanced control strategies that account for complex acoustic interactions and environmental influences.

Two challenges arise in practical acoustic manipulation systems. First, the presence of acoustically reflective surfaces, such table and wall surfaces, can reflect and distort the intended acoustic field shape, leading to trap instability and loss of levitated object control. Managing acoustic fields in these real world environments demands control algorithms that can adapt and compensate for reflective interference while still maintaining stable levitation and manipulation.

Second, controlling the dynamic movement of levitated objects, especially when smooth translation or velocity control is required, necessitates methods beyond phase-based trap position control. Conventional phased array field shaping often results in abrupt changes in acoustic pressure nodes. In section 3.1, this same abrupt change in trap position was used to weigh objects as they oscillate. While discontinuous motion can be leveraged for sensing advantages and also the negative effects mitigated through small enough step sizes, the motion can risk instability. Additionally, a phased-based movement system might not be possible with certain hardware configurations since movement speeds of objects depend on the rate that the acoustic phase array can be updated limiting the type of controller used to compute and output acoustic emitter signals. By contrast, a frequency modulation approach

would enable velocity control of objects through beat patterns. A velocity control approach would offer a promising way to achieve smoother, more predictable object movement by leveraging the time varying beat effect that results from two waves of different frequencies interfering.

This chapter presents work on control methods developed to address these challenges. It will describe techniques for achieving stable acoustic trapping in environments containing reflective surfaces, including experimental approaches and field shaping strategies. It will also introduce a frequency modulation approach for velocity control of acoustically levitated objects. The section on velocity control aims to enable smooth, controlled translation of levitated objects without the need for complex beam steering or field shaping algorithms and differs from the more popular approach of using phase controlled acoustic arrays to control levitated objects. Together, these methods advance the practical usability of acoustic levitation systems in real world laboratory and automation settings.

4.1 *Picking of Objects from Acoustically Reflective Surfaces*

One challenge when controlling acoustic levitation systems is modeling and compensating for acoustic reflections. These reflections make picking up objects from solid surfaces particularly difficult as the surface is like a mirror reflector for acoustic waves. During picking manipulations, objects are pinned to the surface rather than lifted by the acoustic system. Therefore, the control system needs to consider both the incident and reflected waves in the acoustic control model during picking tasks. In our work on contact-less picking [152], we demonstrated that a *method of images* similar to that used in electrostatics, could represent the incident wave and the reflected wave to successfully enable acoustic levitation system to pickup objects from acoustically reflective surfaces.

4.2 *Acoustic Trapping Force*

Acoustic levitation systems manipulate objects by modulating air particles via ultrasonic waves. The ultrasonic waves create a spatial distribution, a time average acoustic energy

pattern. Objects inside the acoustic field move from positions of high energy potential to areas of low energy potential. These energy potentials can be estimated using the Gor’Kov potential. The Gor’kov potential is an approximation of the acoustic potential felt by a spherical test object within a time averaged acoustic pressure field. The acoustic pressure and particle velocity distributions can be calculated based on the acoustic emitter positions, amplitudes, and phase values. Given the acoustic pressure distribution (p), and acoustic particle velocity distribution (v), Gor’kov potential (U) field can be obtained by applying the expression in Eq. 4.1, [33],

$$U = 2\pi R^3 \left(\frac{\langle p^2 \rangle}{3\rho_o c_o^2} - \frac{\rho_o \langle v \cdot v \rangle}{2} \right) \quad (4.1)$$

where R is the radius of the levitated object, ρ_o is the density of air and c_o is the speed of sound in air. The acoustic radiation force (F_a) can be obtained by taking the gradient of the of the Gor’kov potential, shown in Eq. 4.2.

$$F_a = -\nabla U \quad (4.2)$$

The acoustic radiation force vector field for a acoustic trap is shown in Fig. 4.1. The vector field convergences to a trapping point with both vertical and horizontal stability. The stable location for the object is located in the air at a local minima of the Gor’kov potential where the force of gravity (F_g) equals the upward acoustic lift force. The expression for acoustic radiation force and Gor’kov potential enable finite element modeling to be used as a method for controlling the system during object picking.

4.3 Field Modeling

Since the picking task requires an object to be lifted off an acoustically reflective surface, the model must represent both the incident and reflected acoustic waves. This allows the model to predict object behavior and picking outcome given the input set of acoustic emitter phase values.

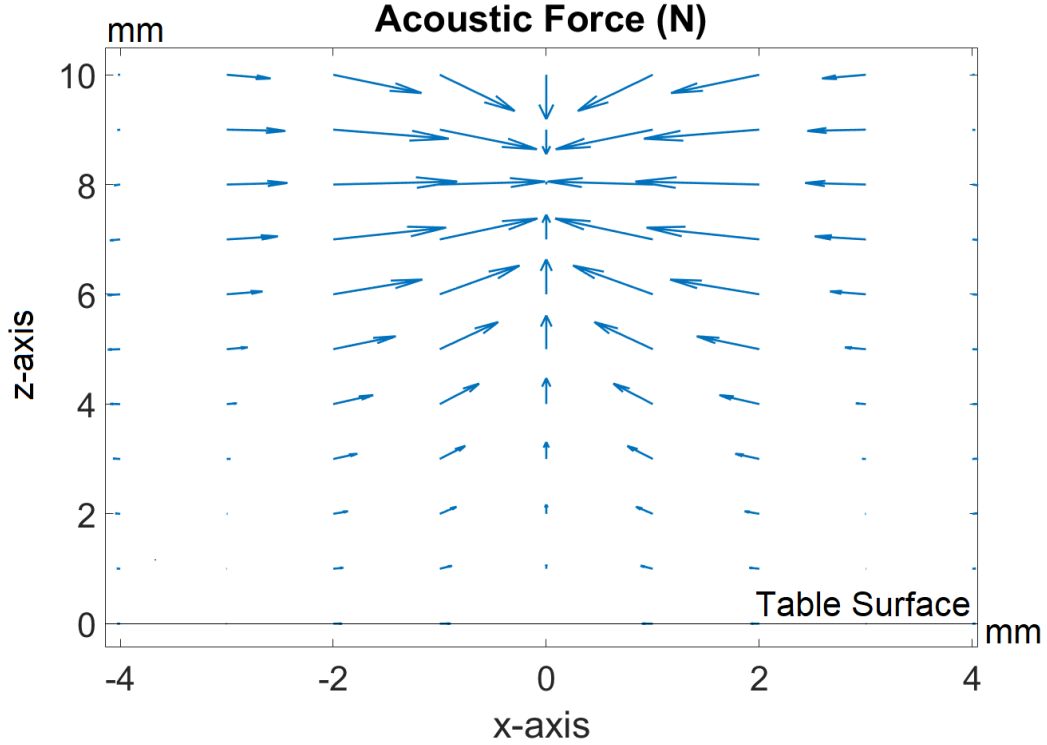


Figure 4.1: Quiver plot showing the simulated acoustic force field exerted on an object 2mm in diameter during object picking. The object is pulled upward to the stable convergence point located 8mm above the table surface.

Each acoustic emitter is modeled as monopole acoustic sources which superimpose linearly. The rigid table surface is treated as a boundary with the condition that the particle velocity normal to the table must be zero, since the air cannot penetrate the table. The rigid table surface acts like a ground plane in electrostatics. Fig. 4.2 shows this table ground plane at the x - y plane. To accurately model the reflected acoustic field from the table, we utilize an electrostatics idea, *the method of images*, in which the ground plane is removed but its effect is modeled by a new set of so-called "image" charges. The method of images can be applied to acoustics [75]. Similar to the charges, we can remove the table surface by introducing "image" acoustic sources located below the table surface. If a real charge is at coordinates (x, y, z) , its image will be located at $(x, y, -z)$. Similarly, we model the acoustic

particle velocity by placing "image" acoustic sources of equal amplitude below the table at the $(x, y, -z)$ location such that the net vertical particle velocity at $z = 0$ is also 0.

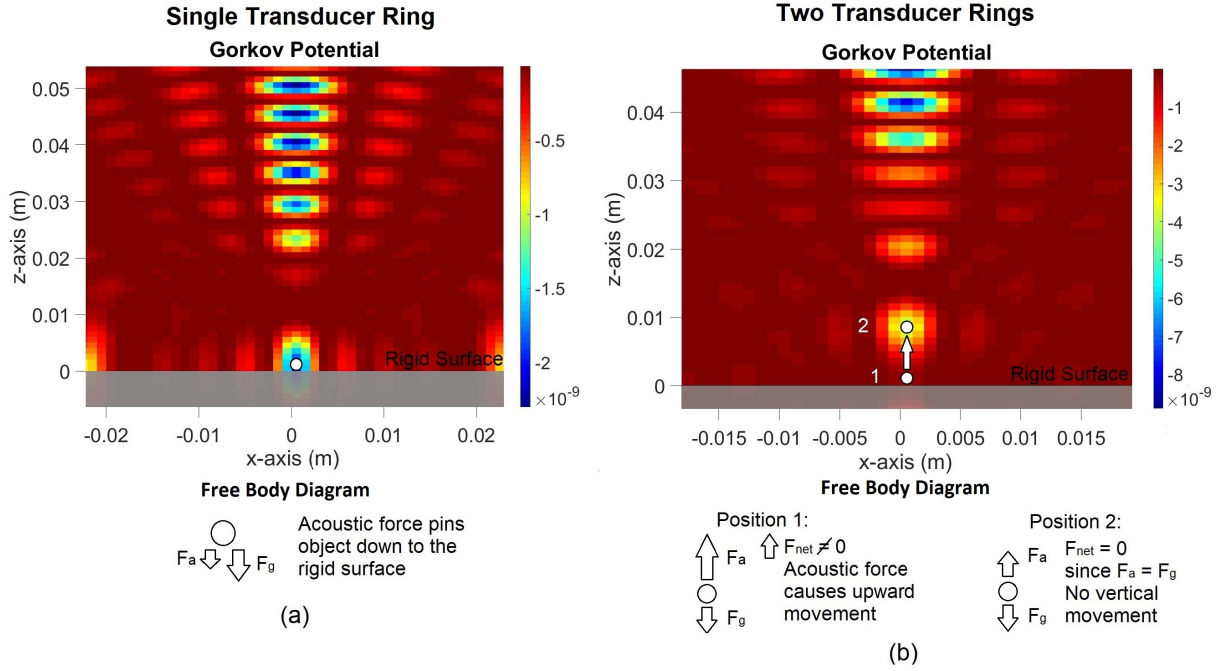


Figure 4.2: (a) A Gor'kov potential distribution incapable of lifting an object due to the stable node located on the rigid surface. A particle initially resting on the table top experiences a downward acoustic force, pinning it to the table. This potential is due to a single ring of transducers above a rigid reflecting surface. (b) A Gor'kov potential distribution capable of lifting an object off a table top. Under the influence of this potential, a particle that is initially resting on the table top (position 1) experiences a net upward force. As illustrated in the force-body diagram, at position 1 the upward force due to the acoustic field exceeds the downward force of gravity. Once this potential is enabled by turning on the ultrasound field, the particle rises until it reaches position 2, a stable local minimum at which gravity balances the upward acoustic force. This potential is due to two stacked rings of transducers above a rigid reflecting surface.

By including the reflected field in our modeling process, we discovered that it was necessary to introduce a second ring of transducers located above the first to enable the acoustic levitation system to pick up objects from the rigid surface. Fig. 4.2 shows the modeled Gor'kov potential with and without the second ring of transducers. The force body diagrams also show how the object in the single transducer case goes from being pinned to the table top, to lifting off the table surface once the second ring of transducers are enabled. By modeling the reflected acoustic field, the Gor'kov potential shows that the acoustic field must be shaped such that an upward vertical lift force is generated to lift the object off of the rigid surface. This is shown in the Gor'kov potential plots by the shift in local minima. The second transducer ring cancels the Gor'kov node located on the reflective surface, creating a region of vertical instability at the reflective boundary and pushing the object into the new stable Gor'kov minima.

4.4 Manipulator Design

By designing acoustic levitation system into form factors general purpose robots can use as manipulation tools, we can enable robots like the PR2 to gain additional dexterity through contact-less object manipulation.

To help maximize acoustic trapping force and enable dexterous manipulations, we designed an inward facing cylindrical array of 56 transducers arranged in into four rings. This geometry focuses the acoustic energy into the center axis of the cylindrical array, exerting a higher degree of force and can lift objects further away from the surface of the table than a planar transducer design. While only the bottom two rings of the manipulator are necessary to achieve object picking, the top two rings lift the object further off the reflective surface, securing the object at a higher position. This reduces the effect of the "image" acoustic sources on the object, allowing the whole levitation system to be lifted without displacing the object from the trap.

This robot picking tool consists of 4 stacked transducer rings with a diameter of five times the in air 40 kHz acoustic wavelength, shown in Fig. 4.3a. This trap geometry

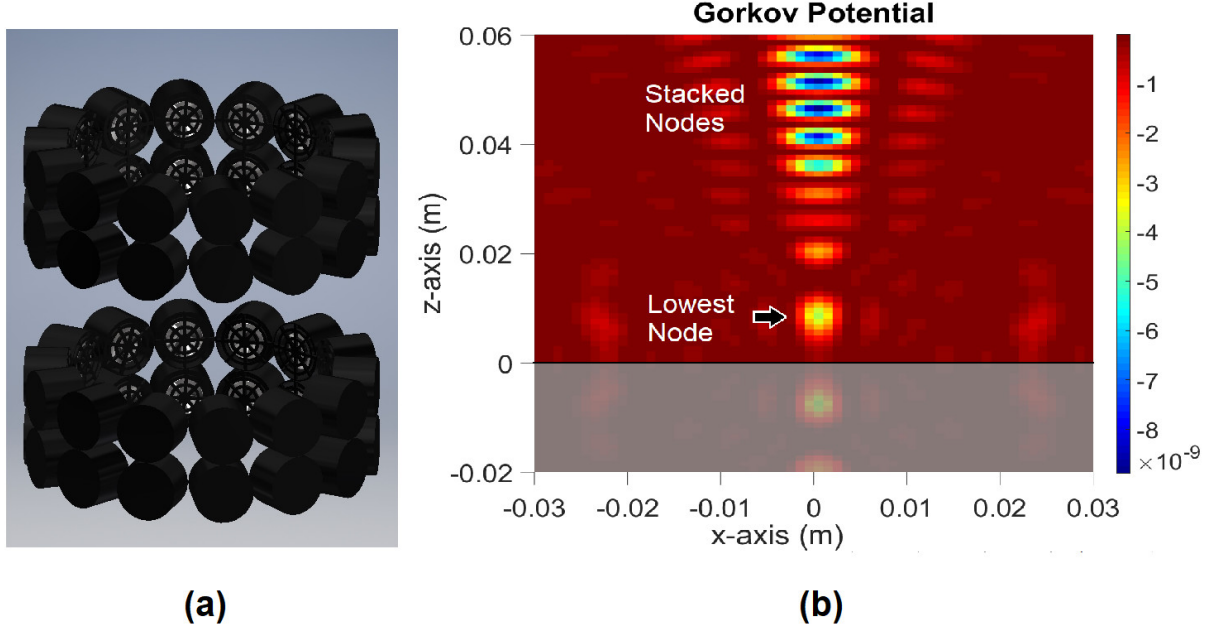


Figure 4.3: (a) The ultrasonic transducers are arranged in a cylinder consisting of four ring levels, numbered 1 to 4 from bottom to top. (b) The four level ring geometry generates a stacked node structure with stable points located along the axis of the cylinder. These stable points trap objects and can be easily translated along the central axis of the cylinder. The acoustically reflective boundary is shown as the black horizontal line.

generates multiple standing waves which intersect to form a stacked node structure shown in Fig. 4.3b. This geometry prioritizes acoustic levitation strength and dexterity along the cylinder central axis and aids in the system's specialized task of picking and vertical object translation, translating the object upward from node to node.

To generate each individual output channel waveform, a field programmable gate array, FPGA, generates 56 channels of independently phase controlled square waves. Each output channel has a phase resolution of 2500 steps or approximately a 0.15° phase step. The FPGA allows all channels to be updated simultaneously on the same clock edge for precise transducer clock timings. The FPGA outputs are level translated from 3.3V to 12V logic

Table 4.1: Mass of objects picked up by device

Object	Flower Bud	Plant Piece	Mosquito	IC	Potato Chip	Polystyrene
Weight (mg)	3	3	3	12	5	1

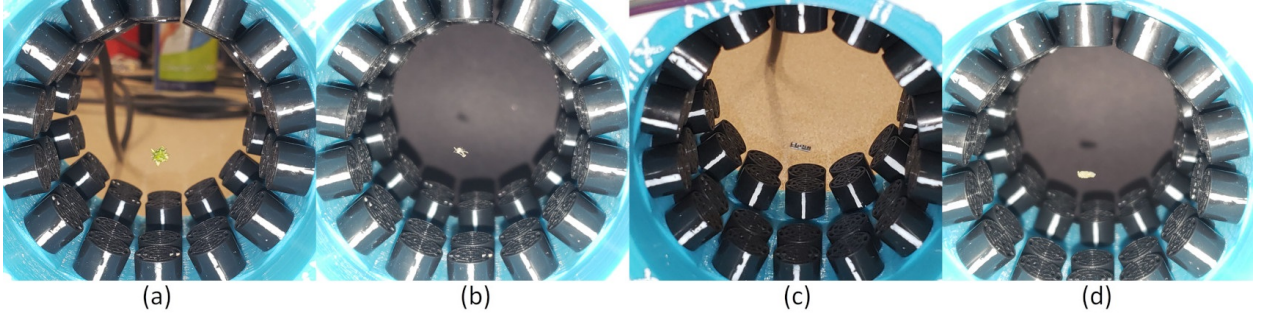


Figure 4.4: The ultrasonic levitation device is a material agnostic manipulator capable of suspending (a) plant pieces, (b) small insects [mosquito], (c) integrated circuits, and (d) food [potato chip crumb]. Unlike magnet based levitators, the levitated object is not restricted to specific materials. Objects stay suspended in the middle of the trap, with the force of gravity directed downward in the frame of the pictures.

and a second signal with inverted phase is generated. The original and inverted phase signals differentially drive each transducer such that the 56 Murata MA40S4S transducers see a $24V_{pp}$ signal. With this design each individual transducer channel outputs a constant amplitude, but overall acoustic trapping pressure and force control can be adjusted by either increasing or decreasing the number of contributing sources.

4.5 Discussion of Manipulation Results

The acoustic manipulator can pick up objects with a maximum dimension of 2mm or less. We tested our picking device using polystyrene balls ranging from 2mm to 1mm in diameter. The polystyrene balls are an example of an object which is small and fragile enough to

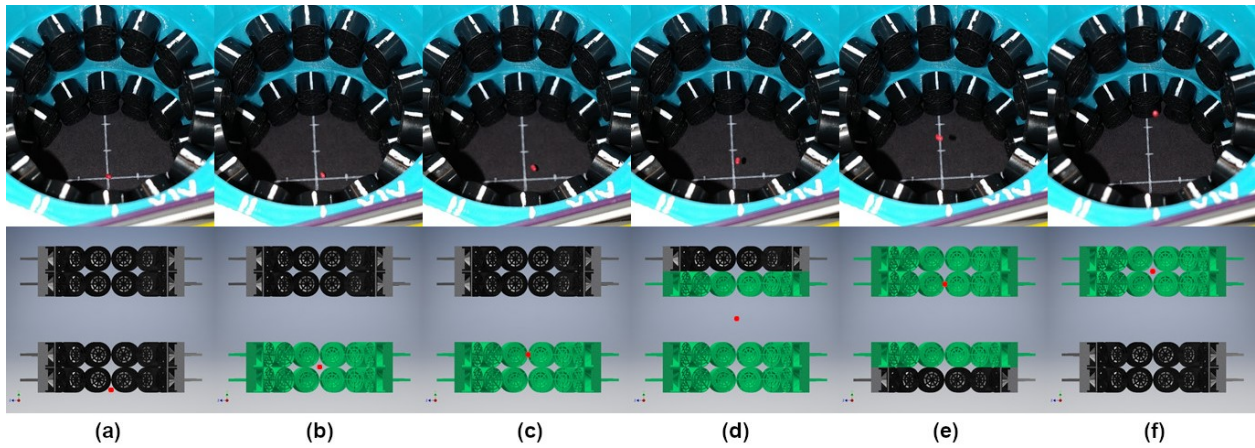


Figure 4.5: The picking action is performed in 6 steps. In the figure, green represents activated transducers involved in the picking process. At each step, additional phase shifts are applied to move the object higher before control is handed off to the next pair of transducer rings. At 50mm from the table surface, the levitation device can be lifted away from the table.

be crushed, missed and occluded by the PR2's jog gripper. The PR2 grasps the cylindrical acoustic manipulation system via a handle, resembling a coffee mug.

Some of the other types of objects tested in our acoustic levitation system include plants, small insects, integrated circuits chips, and potato chip crumbs. Table 4.1 shows the mass of each object picked up by the levitation system. By grasping the acoustic levitation system, the PR2 is able to manipulation objects much smaller than its end effector positioning uncertainty of about 10mm. The PR2 also avoids crushing the objects shown Fig. 4.4 since the acoustic levitation system has a grasping (trapping) force that will not damage the sample objects.

The picking procedure for the levitation system takes advantage of of both phase manipulation and selective activation and deactivation. Fig. 4.5 shows the sequence of ring activity and phase shifts which allow the object to be picked up from the surface of the table. Once the object is trapped in the upper ring, the acoustic levitation system can be picked up and move by the PR2 without displacing the object within.

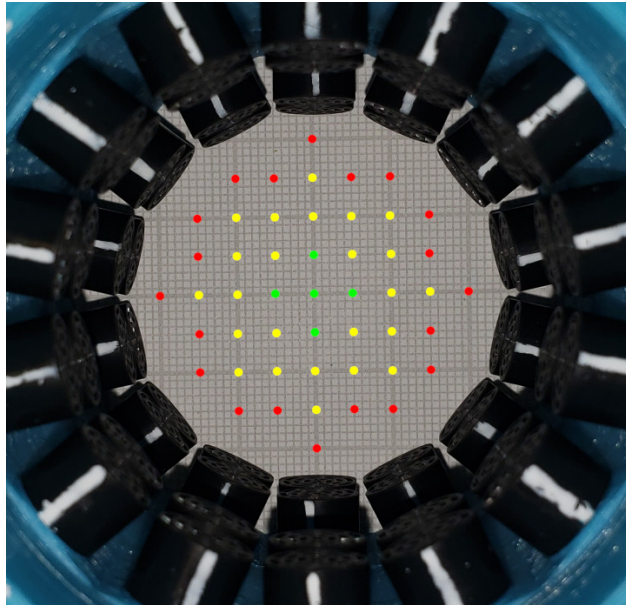


Figure 4.6: This chart represents the acoustic manipulator’s *basin of attraction*, the area that objects can be levitated or translated from to be levitated. The acoustic manipulator has been tested to successfully perform the picking action on objects at test point positions represented by the green dots and pull objects from the yellow dots to the center to be levitated. The red dots represent positions that were tested where objects could not be pulling into a position capable of picking. Each grid unit is 1mm and each dot is spaced 5mm apart.

In an ideal scenario, the robot would be capable of positioning the acoustic manipulation device with the object directly in the center of the cylindrical transducer array, however, robots designed for larger manipulation tasks, such as the PR2 used for testing, have a positioning error larger than the size of the target object. The acoustic manipulation device compensates for positioning error by increasing the “grasping” range of the robot. For contact-less manipulation via acoustic levitation, we call this the *basin of attraction*, shown in Fig. 4.6.

This basin refers to the area in which objects inside the cylinder can be either picked up

or pulled by the acoustic field toward the inner area where the picking action via acoustic levitation is possible. The extent of the basin of attraction is shown in green and yellow. The green area denotes positions that the acoustic levitation device can directly lift without lateral manipulation and the yellow denotes the area where the manipulator can laterally move objects into the green area from. To compensate for the 10mm positioning uncertainty of the PR2, the basin of attraction is about 30mm in diameter, an area of 706.86mm^2 , allowing for objects to be picked up despite positioning misalignment.

During PR2 usability testing with the acoustic levitation tool, the robot was able to grasp the system and pick up a red polystyrene ball, extract the color using a camera, and place the red polystyrene ball in the red target location. This experiment suggests (1) the weight and size of the acoustic manipulation tool does not impact the robot arm's normal functionality, (2) the acoustic levitator is strong enough to resist air turbulence while the PR2 moves the system, and (3) the contact-less grasping provides unoccluded view of the trapped object for better visual feature extraction.

While the acoustic levitation system can perform picking and sorting, the system has limitations and can be improved. A primary improvement to the system is adding a camera system for object localization and visual feature extraction at the point of object picking instead of using cameras mounted on the robot. This allows objects to be localized within the levitator local environment and can be used by the levitator to enable multi-object sorting and storage within the levitator itself. Additionally, a camera system will enable localization of one or more objects, creating opportunities for object motion planning and closed-loop motion controllers. With more robust control frameworks phase shifting can be used to increase acoustic field efficiency, trapping force, maximum object size and field shaping resolution to better adjust to different object shapes.

Another improvement that would affect performance is sensing the temperature and humidity of the air within the acoustic levitation volume. The speed of sound is dependent on temperature and humidity. To account for air environment changes, we have implemented a closed-loop control system which accounts for the effect temperature and humidity have

on the speed of sound when calculating output channel phase values.

Acoustic levitation systems can help assist general purpose robots by expanding the manipulation capabilities of robots equipped with large jog-gripper style manipulators or have a high degree of positioning uncertainty relative to the size of the object. The method of images helped improve the acoustic model and further informed the acoustic levitator geometry and design to enable object picking from an acoustically reflective surface.

4.6 Frequency Modulation for Velocity Control

Control algorithms for acoustic levitation systems primarily focus on field shaping through phase-base control. As demonstrated in previous sections, by changing the phase delay of each acoustic emitter, the volumetric structure of the acoustic field that results from the superposition of each acoustic wave can be used to form and control the position of the acoustic traps [138]. By changing the phase angle and the volumetric acoustic field, objects can be moved through discrete points along a trajectory [136]. If the distance between each discrete point is small enough, the discontinuity of motion is not visually discernible, and the velocity of object movement can be controlled either through the distance between points of the trajectory or the rate of which the phases and acoustic field is changed. However, to control the motion of levitated objects using a discrete system, each change in phase would required the acoustic field controller to calculate new phase angles for each transducer and update each channel. Since the smoothness of motion and the maximum velocity are both dependent on the number of points along a given levitation movement trajectory. There is a practical maximum limit to the smoothness of motion and the maximum stable movement velocity, limited by the phase angle calculation time and update rate of the hardware.

If a levitator with C acoustic channels moves an object along a stable trajectory that consists of N points, the levitator's controller must then solve for $C * N$ phase angles to execute the trajectory. To achieve a constant trajectory speed, it will take T seconds to complete N movements. If the controller cannot solve for the C phase angles in T/N seconds the object might either move slower than the specified speed or be dropped. As a result,

shortening the time, T , to execute a trajectory (ie. increasing movement speed) or increasing the number of points, N , along a trajectory given the same time (increasing smoothness), decreasing the time the controller has to calculate each set of C phase angles. This can be a practical problem when working with microcontroller-based acoustic levitation systems with limited computation speed, or when controlling a large number of individual acoustic channels.

To solve this issue, we developed a frequency modulation-based approach to levitated movement that enables velocity control of levitated objects. At the start of a trajectory, a single update is required to change the frequency of the relevant acoustic channels. To stop object movement, a second channel update is performed to set the frequency back at the end of the trajectory. This method of levitated object motion control enables smooth motion without discontinuous steps which might appear in sensor data, reduce controller computation requirements and update rates, and move levitated objects when exact object position is unknown.

This section presents work on frequency modulated acoustic channels for velocity based movement control of levitated objects. It will discuss beat frequencies and the force principles, outline the acoustic levitation system hardware, and present results showing the relationship between frequency modulation and speed. This section will also discuss potential applications and use cases for frequency modulation over phase-based control and how the control schemes can be used together to gain the benefits of both methods.

4.7 Beat Frequency and Force Principles

Beat frequencies or beat rates, commonly experienced in audible traveling sound waves are an amplitude modulation or envelope modulation resulting from two acoustic tones [193]. Through the interference of two tones with frequencies f_1 and f_2 a listener would perceive two tones, one higher, and one lower, [90] and [191]. The interference of the two acoustic frequencies would produce a side band frequency, or beat frequency Δf equal to $f_1 - f_2$.

Within the context of an ultrasonic standing wave, for an object between two sources, the

beat frequency allows for a time varying shift of the standing wave. In a simple 1-dimensional pressure wave example, two acoustic sources of equal amplitude, one located at $x_1 = -\Delta x$ and $x_2 = \Delta x$, create a standing wave. Δx is always an integer multiple of the wavelength λ . $p(x, t)$ is the the acoustic pressure with respect to space and time.

$$p(x, t) = 2A \cos(xk + \frac{2\pi(f_1 - f_2)}{2}t) \cos(\Delta xk - \frac{2\pi(f_1 + f_2)}{2}t) \quad (4.3)$$

If f_1 and f_2 are the same frequency, f , $p(x, t)$ approximately evaluates to a standing wave, $p(x, t) = 2A \cos(xk) \cos(\frac{2\pi f}{2}t)$. However, if $f_1 \neq f_2$, then eq. 4.3 evaluates to the product of a traveling, time-varying wave with frequency $\Delta f/2$ and a stationary time varying wave with the average frequency of f_1 and f_2 .

$$f_{primary} = \frac{f_1 + f_2}{2} \quad (4.4)$$

$$f_{beat} = \frac{f_1 - f_2}{2} \quad (4.5)$$

To generate the beat pattern pressure wave in a standing wave acoustic levitator, the output frequency of one of the transducer arrays is increased by 0.1 Hz (Δf) to 40000.1 Hz. This forms an interference pattern referred to as a beat pattern between the 40000 Hz and 40000.1 Hz waves as a result of the superposition of the two waves. The result is a time varying carrier wave and traveling wave that varies with both space and time.

Since objects levitated within an acoustic trapping location are at equilibrium, the change from the beat pattern wave shifts the location of equilibrium in the direction of propagation of the wave such that there is a small difference in acoustic trapping force on opposite sides of the levitated object, carrying the object to a new equilibrium position.

4.8 Frequency Modulation Hardware System

The test system uses two, 24 Murata MA40S4S concave transducer arrays. The 24 transducers that make up one array are wired in parallel. The system is controlled by an Arduino

Uno that communicates via serial with two AD9833 direct digital synthesis (DDS) signal generators to produce the 40000 Hz or 40000.1 Hz waveforms. Both AD9833 chips share a signal from a single 25Mhz clock. In our case, the clock oscillator was de-soldered from one of the two boards and a jumper wire was soldered connecting the clock signals. By tying the clocks of the AD9833s, each DDS comes out of reset on start up and are synchronized enough for 40 kHz output. The two DDS output signals are connected to a 74HC04D hex inverter to generate the inverted waveforms and both the original DDS output and the inverted signals are connected to a L298 h-bridge to drive the transducers.

Rather than using a field programmable gate array (FPGA) to handle many individually controllable output channels, a simpler levitator design was used built from off-the-shelf, easy to obtain parts like the Arduino Uno. This makes the levitator both easy to build and more accessible to program since coding languages like C++ or Python can be used instead of Verilog. While FPGA acoustic levitation systems can leverage the frequency modulation for object translation, frequency modulated translation is more desirable for acoustic levitation system designed around a microprocessor because it requires fewer commands for movement and does not require the computation complexity and output channel quantity to support individual transducer phase control and acoustic field shaping.

The acoustic levitation system is built to take inputs from a pipette tip such as a fixed volume 4uL pipette or a syringe. To reduce positioning issues and inconsistency with human hand movement, the pipette or syringe can be mounted at a fixed position pointing into the levitation volume.

4.9 Frequency Modulation Velocity Results

The levitation control system is able to control the movement of levitated droplets by changing the frequency of one or groups of output acoustic elements. The traveling beat pattern wave propagates at a speed much slower than the speed of sound. This beat pattern wave propagation speed is also the speed that levitated objects are moved. We tested beat frequencies of 0.1 Hz, 0.2 Hz, 0.5 Hz, 1 Hz and 2 Hz and recorded the average velocity that the

acoustic levitation system could move a $4\mu\text{L}$ droplet of water up and down along the vertical axis.

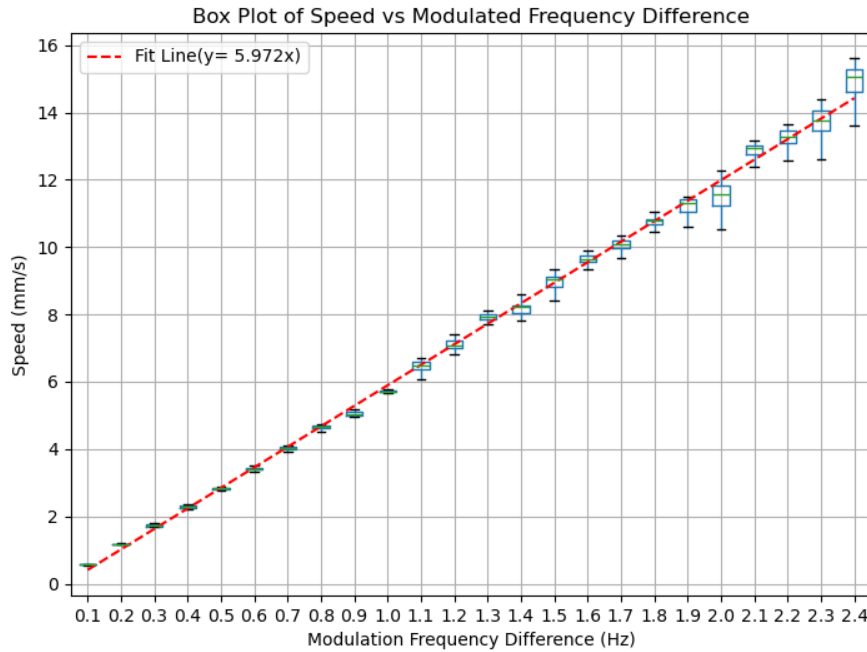


Figure 4.7: The modulation frequency has a linear relationship with the speed that the object moves. As the beat frequency is increased, the speed increases until around 2.5 Hz where the object stability and trapping reliability of the acoustic field diminishes enough that the object escapes confinement and drops.

The object velocities were gathered using a camera to record the droplet of water as the beat pattern pressure wave translated the object vertically in front of a checkerboard with 10 mm squares. Each beat frequency and translation direction combination were recorded 10 times at 30 frames per second (FPS). The final velocity for each frequency and translation direction combination was obtained by averaging the number of frames each droplet took to move one 10 mm checkerboard square over the 10 trials and converting the average number

of frames into a time. Then dividing the 10 mm by the traversal time.

The relationship between the beat frequency and the movement velocity is approximately linear. The 0.2 Hz beat frequency droplet move roughly 2 times as fast as the 0.1 Hz droplet, and the 1 Hz droplet moved roughly 10 times faster than the 0.1 Hz droplet. The moving acoustic pressure field was strong enough to separate the liquid droplets from the pipette tip, overcoming the surface tension force between the droplet of water and the plastic tip.

4.10 Discussion of Frequency Modulation

In a standing wave acoustic levitation system, objects can be smoothly translated through the modulation of acoustic emitter frequencies. The speed of movement is proportional to the frequency difference between the standing wave frequency and the modulation frequency, called the beat frequency. The hardware described in this work uses a 40kHz design but the same frequency modulation technique can be applied to other acoustic levitation frequencies. Similar to velocity-based control in robotics, velocity focused movement of levitated objects through frequency modulation is smooth and continuous. Unlike other acoustic levitation control schemes that move objects with quantized position states represented through the phase angles of an acoustic emitter array, a velocity control approach would focus on controlling and maintaining velocity of levitated objects. Depending on the levitation system hardware, velocity focused movement of levitated objects might be more desirable.

In situations like pipetting or liquid dispensing, the dispensing location might be inconsistent or slightly changing in the case of manual human pipetting. To help assist liquid droplet inputs into the levitator, the frequency modulation can be used as an acoustic funnel to provide a low frequency moving pressure wave front that translates dispensed objects along a single axis at a constant velocity. The result of this small frequency difference is all (previously stationary) acoustic trapping locations and objects trapped within are continuously translated at a constant velocity in the same direction of propagation as the 40000.1 Hz wave, like floating objects on a conveyor belt. To stop the translational motion, the control system changes the signal generator frequency from 40000.1 Hz back to 40000 Hz,

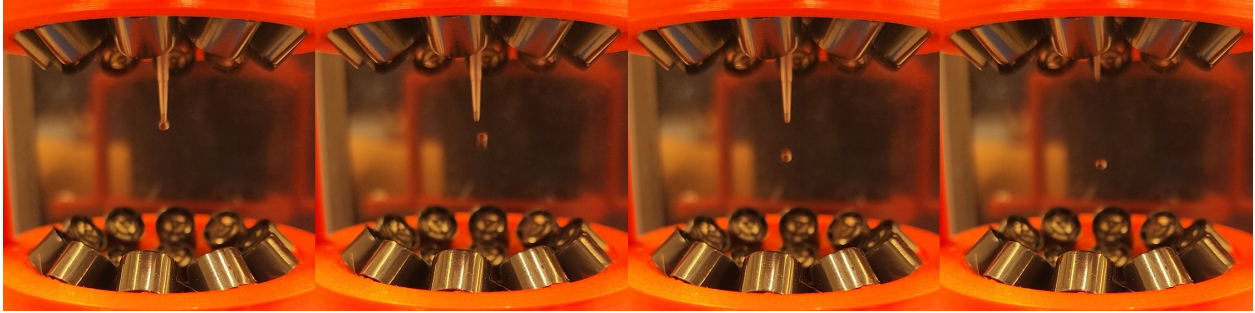


Figure 4.8: Using the frequency modulation to apply a constant downward acoustic force for mechanically pipette dispensing a $2\ \mu\text{L}$ droplet of water into a 1 Hz beat-field. The droplet is pulled down directly off the pipette tip without allowing the droplet to move across the outside tip surface

thus stopping the acoustic traps and levitated objects.

Compared to phase-based object translation, this method for translating objects simplifies the controller requirements, issuing a single command to change the signal generator frequency to achieve continuous translational movement. Phase based translation would require the controller to send a new set of phase values to the signal generator for each position step change.

Considering the benefits and drawbacks of each control system, the phase controlled system would enable an acoustic levitator to independently control multiple levitated objects with precise position control. The maximum speed an object would be able to travel would be limited by the rate a controller can send new phase values and update the signal generator's acoustic output channels. Levitated objects also need known initial positions to solve for the phase values. Known initial position requirements can be compensated for by either having fixed automated dispensing locations, camera or other sensor enabled object localization, or experienced users capable of repeatedly dispensing into known input acoustic trap locations.

The frequency modulation, or constant velocity, control system enables group control of one or multiple levitated objects with precise velocity, translating objects within different

acoustic traps at the same constant velocity as a group, like a conveyor belt. While the speed of translation is based on the beat frequency and the frequency precision of the signal generator, the position precision is limited by the rate a controller can send new frequency values. The constant velocity control system can be applied to objects as long as they are dispensed into the levitation volume. However, camera or other sensor systems are needed to localize and detect presence of levitated objects. The position and orientation of the acoustic transducing elements can be designed to continuously translate levitated liquid droplet or other objects into a smaller space for localization or other sensing tasks, like an acoustic funnel.

To get the advantages of both phase control and velocity control previously discussed, levitation systems can implement a hybrid approach that uses both phase and frequency changes in different parts of the levitator. For example, to enable easier pipetting into the levitator, the constant velocity approach can be used when pipetting into the acoustic levitation system, compensating for location precision constraints when pipetting. The levitator carries the droplet to a predefined location and is detected via beam break sensor, like an acoustic funnel. From this point on, the levitator can then translate the droplet via phase control now that it is at a known location.

Acoustic funneling can be applied to the user object input method, providing an easier interface experience for novice users of acoustic levitation systems. Since acoustic trapping locations have neither visual nor strong tactile location indicators, less experienced users of acoustic levitation systems have a difficult time finding and injecting droplets into stationary acoustic trap locations. By designing acoustic levitation systems with an acoustic funnel, positioning uncertainty for human and robot to levitator interfaces can be compensated for during object input steps into the levitator.

4.11 *Pipetting Challenges*

In the current levitation system, mechanical pipettes are used as a method for inputting liquid droplets into the acoustic field. The tip is loaded with a liquid and placed in the

center of an acoustic trapping location. The plunger is pressed, and the droplet is expelled into the acoustic trap. The user then carefully extracts the pipette tip visually confirming that the levitator has separated the droplet from the tip.

In a perfect scenario, the acoustic levitation system always successfully receives the droplet from the pipette tip. However, in reality the user usually has difficulty locating the levitation node at first since there is no visual or even tactile feedback to the user. To find the levitation node, users typically dispense the droplet in the approximate location they think is correct. The droplet can sometimes stick to the tip. In some situations, droplet will even travel up the outside of the tip in the opposite direction of desired pipetting as the user's hand and arm deviate or stray from the original dispensing location. The potential for the droplet to travel along the outside of the pipette tip is a problem as this increases the chance of contamination and sample loss.

By modulating the frequency of the acoustic field, the acoustic field itself could be used to provide a constant downward force to remove liquid droplets from the tip of the pipette or syringe. This guides the droplet in a single direction, preventing the droplet from traveling along the outside surface of the pipette tip and automatically separating the droplet from the tip once the plunger of the pipette is actuated. The frequency modulated droplet guide can help assist human users during manual pipetting and interface with automated liquid dispensing systems. Droplet separation from the tip is facilitated by the acoustic force similar to surface tension when pipetting against a well plate wall. Fig. 4.8 shows a mechanical micro-liter pipette dispensing a droplet into a downward propagating 1 Hz beat-field, generated by the levitator. The top set of acoustic emitters are producing a 40001 Hz field while the bottom set are producing a 40000 Hz field. The resulting net acoustic field is a traveling acoustic radiation force wave which moves down the length of the pipette tip and detaching the droplet and preventing the droplet from traveling in the upward direction across the tip outer surface.

To help position the pipette during human operation, a mechanical pipette tip guide can be attached to the levitator such that the tip is consistently positioned in an optimal

location and orientation within the acoustic field. When interfacing with a robotic liquid handling system, these machines have a positioning uncertainty of less than a millimeter and therefore can be programmed to consistently position the tip in approximately the correct spot at which point the beat-field guide will compensate for millimeter scale positioning variation.

Additional exploration and testing needs to be done to identify the range of droplet volumes this method can dispense. Most likely, there exists an upper and lower limit for droplet volumes this method is capable of guiding as the beat-field acoustic radiation force must overcome surface tension between the tip plastic and aqueous solution.

4.12 Additional Testing and Improvement of Frequency Modulated Control

While phase control of acoustic fields require the controller to change the acoustic drive signal for each object position change, frequency modulated movement of an object requires updates when the object velocity is changed. A direction for future work is to evaluate the smoothness of motion for phase controlled and frequency controlled object motion for the same acoustic levitation hardware system by tracking the object while it is levitated along a trajectory, evaluating the object position and velocity deviation relative to the trajectory for a range of object velocities and changes in path direction. While FPGA systems with high clock frequencies and parallelized channel outputs might not see as large if any improvement by using a frequency modulation to obtain object translation smoothness instead of phase control. Hardware like microcontrollers with lower clock speeds and less parallel output capabilities might see a greater degree of smoothness and would benefit from the lower acoustic output update rate.

Another direction for future work and improvement is validating and exploring the effect of frequency modulated movement on a variety of objects. Comprehensive testing might include various sized object of the same material, similar sized objects of different mass and density, and objects with large flat surfaces. This testing would aim to look at how object with different size, mass, and geometric profiles can be controlled using a velocity control

approach. One hypothesis could be that velocity control could help improve movement stability of objects with higher mass since the velocity can be gradually and continuously increased or decreased.

When designing standing wave acoustic levitation systems, the transducer arrays are usually separated at wavelength multiples to create a standing wave interference pattern. When frequency modulating one of more transducers, the carrier wave frequency becomes the average frequency of the interfering waves. For a beat frequency composed from a 40000 Hz wave and another wave with a frequency of 40010 Hz, the carrier frequency would be 40005Hz. As a result, would the overall levitation force decrease now that the carrier frequency is not the 40000Hz that the hardware geometry was designed for and will the force further decrease as the beat frequency increases? One direction for exploration and future work is looking at the effect the carrier frequency has on the levitation force and object stability during movement. A constant carrier frequency but changing beat frequency implementation might use two frequency modulations like $f_1 = 39995Hz$ and $f_2 = 40005Hz$, maintaining a 40000Hz carrier but moving an object using a 10Hz beat wave.

Chapter 5

LEVITATOR TOOLKIT DEVELOPMENT

The previous chapters presented work on sensing and movement control methods for acoustic levitation systems. Sensing and movement control are the core functions for an acoustic levitation liquid handling system. They are the fundamental and most commonly used features of acoustic levitation systems which apply most broadly to system applications. Building upon the techniques for sensing and motion control, this section presents manipulation capabilities that build upon acoustic levitation control and sensing systems to perform more specific applications and manipulation tasks such as droplet launching and shaping.

5.1 Acoustic Droplet Launching

In a laboratory, scientists usually store reagents and liquid samples in test tubes or well plates. To reduce the risk of contaminating the entire storage of sample or reagent, a subset of liquid is transferred via pipette to another tube or well plate for use during an experiment. The samples and reagents are then organized spatially in a well plate so that a human or robot can perform the liquid mixing using step-by-step instructions called a pick list [213]. For humans and most robots, the pick list is executed using pipettes with disposable tips to move small volumes of liquid between wells of the plate. In traditional laboratory workflows, the pipettes, well plates, and tubes are the containment vessels that mark the beginning of an experiment and facilitate the transfer of samples and chemicals from long term storage to short term containment vessels for immediate use [145]. Since acoustic levitation systems perform touch-less liquid sample containment and mixing, would it be possible to also transfer liquid droplets from long term storage containers into the levitator without needing a pipette?

In a past chapter, this manuscript presented how frequency modulation could be applied to pipetting, to assist humans and robots when injecting droplets into the levitator. In this chapter, we will first review related examples of liquid transfer and then present an acoustic method for transferring aliquots of liquid by launching droplets directly from a long term storage container, like a test tube, into the levitator, eliminating the need for a pipetting step to transfer the liquid. Acoustic droplet launching aims to aid in enhancing the acoustic levitation liquid handling and automation capabilities by removing another contact surfaces that can cause contamination and precious sample loss.

5.2 Related Examples of Liquid Transfer with Acoustics

One specific solution for automating laboratory workflows is call the ECHO developed and sold by Labcyte. The ECHO system uses ultrasonic acoustics to launch nanoliter droplets through the air, sending one or multiple droplets from the well of one plate to the well of a receiving plate.

The ECHO system uses ultrasonic pulses to move nanoliter droplets between micro well plates. Liquid is transferred between two well plates, an upside down receiving well plate and a transmitting well plate. Droplets in the receiving well plate are able to stay in the well via surface tension. Droplets are launched from the transmitting well plate via carefully timed ultrasonic pulses. To achieve this, the ECHO measures the volume of liquid in the transmitting well plate using an ultrasonic transducer as a speaker and microphone. Then, this same transducer applies a pulse of sound to eject a droplet from a well in the plate, transferring a droplet to a receiving well plate.

This method of liquid dispensing enables nanoliter droplet manipulation for chemistry that require a high degree of droplet volume precision. This launching maneuver requires careful calibration of the ECHO to maintain acoustic impedance matching between the transducer and the micro well plate. The ECHO is also only compatible with custom well plates that are designed with an acoustic impedance matching layer on the well plate bottom. These well plate materials can cause the meniscus of the sample to climb the well wall,

preventing droplet transmission. This requires users to modify chemistry to account for these process challenges.

The ECHO system can be described as a ultrasonic nanoliter droplet transfer robot which replaces the pipette with a novel droplet launching system. Like other automated liquid handling platforms, the ECHO still uses a motion stage to reposition the well plates and ultrasonic transducer. This system requires careful calibration and is sensitive to small variation in both acoustic dynamics, sample material and sample position within the well plate. Before performing plate-to-plate droplet transfer, the ECHO must measure the amount of liquid in the transmitting well. Error in this measurement process can lead to variation in the volume of the dispensed droplets.

Improving on this launching technique, this section presents a method of acoustic droplet launching which uses audible spectrum surface transducers to launch droplets into the acoustic levitation volume from a test tube. Once launched, the acoustic levitation system would catch the droplet at the apex of motion, trapping the droplet. Rather than measuring the volume of liquid in the tube, the acoustics are pre-calibrated to the resonant frequency modes of the tube such that the same acoustic waveform can launch the entire contents of the tube one droplet at a time, without dead volume (liquid leftover in the tube).

5.3 Principles for Droplet Launching

Acoustic droplet ejection (ADE) is used outside of life science instrumentation every day. ADEs are commonly used in inkjet printing heads which use piezoelectric transducers to launch picoliter droplets of ink from an ink cartridge to a paper surface [154]. ADEs are also used in the life science instrumentation industry to transfer reagents in high throughput workflows. However, the current solutions for ADE focus on launching droplets between well plates [124]. This section outlines the method for acoustically launching droplets from a polystyrene micro test tube as an input mode for acoustic levitation systems. This method for launching droplets was tested on water-like solutions of samples and chemical reagents [79] to eject droplets from a tube into the air, enabling direct transfer of droplets from storage

containers into the acoustic levitation system. The application of acoustic droplet ejection tools as an acoustic levitation input method aims to reduce or removes the use of pipettes and tips when injecting fluids into the acoustic levitator. An automated method for object input into the levitator also helps to improve system usability by removing human manual pipetting into the levitator.

Unlike the ECHO system, this method uses acoustics in the audible spectrum to launch a single droplet into the air. By using audible acoustic waves, this provides a number of benefits, including broad spectrum frequency output. Unlike highly resonant ultrasonic transducers, a transducer designed for audible spectrum can produce a broader range of frequencies, and by extension a larger range of wavelengths, which allows the launching system to tune the acoustic driving frequency to match the resonant mode of the test tube and trigger the launching process with two frequencies. At these frequencies, the test tube is semi-acoustically transparent due to the size of the acoustic wavelength in the material of the launching harness and test tube.

Like the wave pool waterspout and even in vibration haptic systems, this acoustic-based launching system uses the superposition of multiple waves to constructively interfere and create a location on the liquid surface of high amplitude. The target location will therefore have enough energy to overcome the surface tension forces holding the surface of the liquid together, separating a droplet from the bulk liquid media.

The launching process starts with identifying the resonant frequency and harmonics for the liquid contained within the specific tube containment vessel. Generally, tubes of the same geometry (withing a range of tolerance), containing liquids with similar viscosity, will have the same or nearly the same resonant frequency. An easy and quick method of identifying the fundamental frequency and harmonics is with a camera to monitor the surface of the liquid inside the tube; the drive frequency of the launch transducer is swept from 1Hz to 1khz at 10hz step intervals. Using the camera footage aligned with the frequency sweep, the potential ranges for resonant frequencies can be identified by frequencies which trigger chaotic eruption of liquid from the mouth of the tube. For each frequency range that the

eruption occurred, the center frequency is recorded. Generally, the fundamental frequency and the 2nd and 4th harmonics are captured. These frequencies will be used in both the pre-launch, surface conditioning step, and the launching step. A more rigorous and complete method of identifying the fundamental and harmonic frequencies of the launching structure would be to measuring the resonant modes of the launching harness and test tube by using the transducer as a time multiplexed speaker and microphone.

Before launching a droplet, the surface of the liquid within the test tube is not always perfectly flat. Instead the surface of the water can be concave from the liquid climbing up the side surface of the tube wall. This liquid surface concavity is also not always symmetrical and can be caused by the launching process itself. If the surface is not symmetrical, a droplet might be launched sideways missing the acoustic levitation trap that will catch the droplet or even launched into the side of the test tube, lodging it onto the side of the container. To avoid this, the transducer vibrates the liquid surface at the fundamental frequency, but at a low enough amplitude to not cause droplet eruption like in the calibration step. This creates a standing wave pattern on the liquid-air interface and normalizes the surface to a symmetrical and repeatable geometry.

With the standing wave pattern still driving the surface of the liquid, a single period of the 2nd or 4th harmonic is played synchronously with the fundamental surface preparation signal. Through superposition of a 2nd or 4th harmonic impulse wave with the fundamental standing wave, the traveling acoustic waves will overlap at the center of the circular liquid surface and create a maxima, a rising spout that ejects a single droplet into the air. This launching method can be repeated to launch multiple droplets in succession.

5.4 Acoustic Droplet Launching Hardware

The acoustic launching system consists of an off-the-shelf 4 Ω , 25W surface transduction loudspeaker with a 3D printed test tube harness. Figure 5.1 shows the launching hardware. The speaker is driven using a L298N H-bridge for amplification connected to a MAX10 field programmable gate array (FPGA) for arbitrary waveform generation. A variety of centrifuge

tubes, micro tubes, and PCR tubes made from polystyrene were tested successfully with different calibration settings.

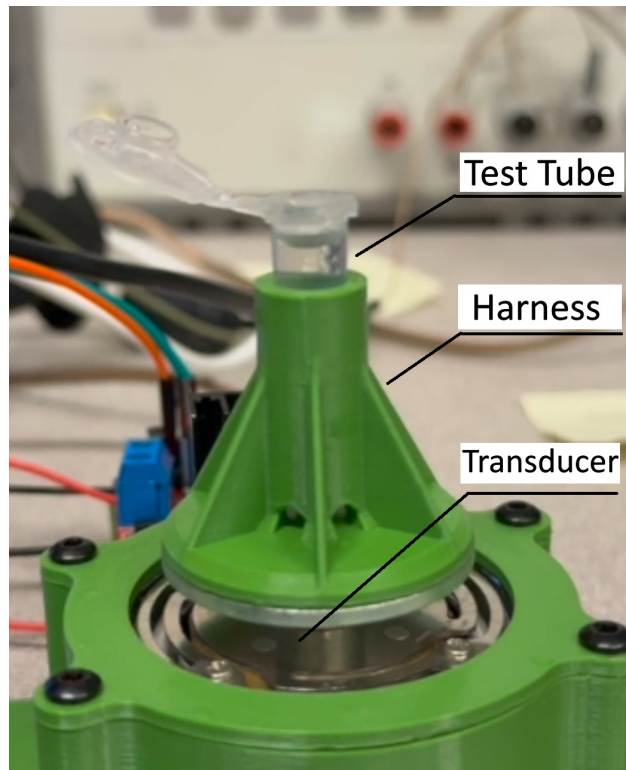


Figure 5.1: The launching system consists of a surface transducer, 3D printed tube harness, H-bridge, and FPGA clamped to a table surface to avoid movement of the launching system.

To avoid uncontrolled movement of the launching system, the surface transducer is clamped to a table surface. Since the L298N is an H-bridge that acts like a class-D amplifier, the drive amplitude of the liquid surface preparation wave is changed by varying the duty cycle of the square wave produced by the FPGA. To avoid over heating of the transducer and melting of the printed plastic parts, the surface preparation wave was used for five seconds before triggering a droplet launch. However, between launches, the surface preparation wave was not deactivated. Since the L298N is a full bridge, this allows the transducer to be driven using two drive signal 180 degrees out of phase to obtain a bi-phasic drive output. Figure 5.2 shows a frame-by-frame of the droplet begin launched.

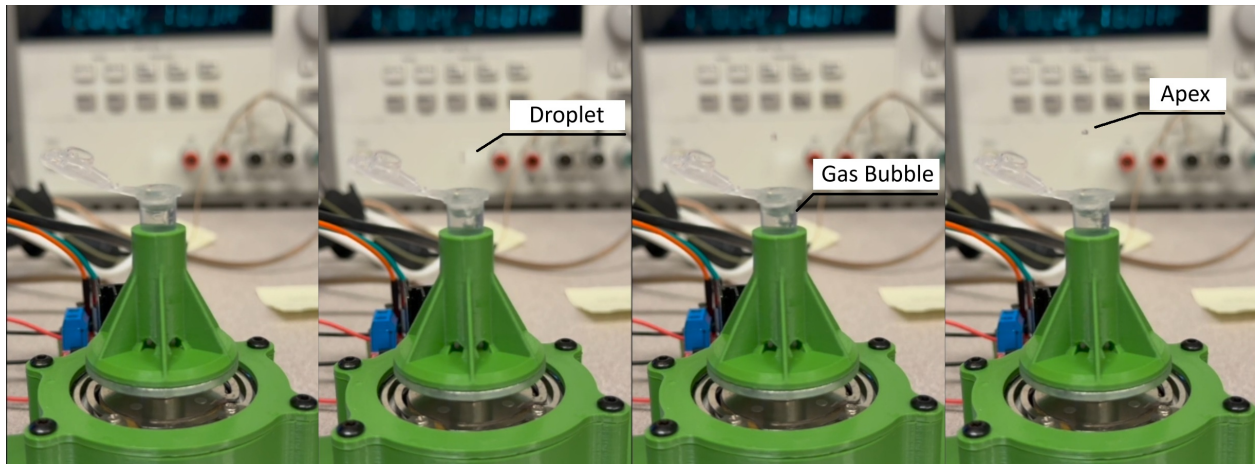


Figure 5.2: The acoustic launching system dispensing a droplet of water into the air using the fourth harmonic causing a droplet to launch with the formation of a gas bubble as a result of cavitation at the bottom of the tube

5.5 Launching and Acoustic Weighing

Once launched, the liquid droplet can be caught by the acoustic levitation system at the apex of the droplet trajectory. By using the acoustic levitation system, each droplet can be weighed to determine the exact volume of liquid dispensed. Given a target droplet volume, additional droplets can be launched and combined together within the levitator to obtain a desired volume of liquid. When launching droplets, with the second and fourth harmonics, the volume (and weighed mass) of the droplet launched decreases as the launch frequency is increased.

Launching with the second harmonic frequency, 150 Hz, the launcher produces a mean droplet volume of $0.7\mu L$ with a standard deviation of 3.2%. When the frequency was doubled to the fourth harmonic, 300 Hz, the launcher produces droplets with a mean volume of $0.14\mu L$ and standard deviation of 6.3%. The launching system has a success rate of about 90% occasionally launching a droplet into the side of the test tube wall or producing no droplet at all.

5.6 *Droplet Launching Limitations*

The launching system was tested using only water and water-like buffer solutions [65] and specific containment vessels, the launching technique is dependent on the geometry of the containment vessel and can perform poorly especially when launching from the tapered section of the tube. While some tubes have smaller tapers or are round bottomed, the initial calibration settings obtained for the straight walled section of the test tube might not work properly for the tapered bottom. To overcome issues associated with tapered bottom micro tubes, a calibration profile can be used to determine the pre-launch and launch frequencies based on the water level within the tube.

To mitigate a miss-launch due to liquid volume inside a containment vessel. Custom tubes can be created with a flat bottom. However, this will likely lead to dead volume, a portion of liquid that cannot be launched by the system. For precious or rare samples that are difficult to obtain significant volume of, this launching method might leave too significant of a dead volume for use. Currently, the solution for launching the entire contents of a containment tube is to use a camera to estimate the height of the liquid within the vessel and adjust the launch frequency based on a known frequency curve for the containment vessel geometry.

Even though the tube and harness are acoustically transparent at the frequencies we currently drive the surface preparation wave at, the high amplitude impulse used for launching the droplet can cause cavitation at the bottom of the tube. This is visible in figure 5.2 as a gas bubble produced by the cavitation process floats to the water surface. While gas production is not necessarily bad, cavitation might be undesirable for applications such as cell or DNA handling since cavitation bubbles could potentially lyse cells and break DNA structures. Further experimentation and evaluation needs to be done to better understand the effect of cavitation during launch and the methods for preventing cavitation. One direction which could reduce the intensity of the launching impulse, and the likelihood of cavitation, is to use multiple periods of the launch frequency rather than a single impulse. This would reduce the peak instantaneous pressure at the water-container interface, spreading the energy

out over multiple periods.

5.7 Droplet Launching Directions for Future Work

The droplet launching work discussed in this chapter focuses on launching droplets from micro tubes and was tested on only water solutions. To improve and validate the usability of the droplet launcher in the laboratory, additional testing is required to characterize the droplet launching droplet volume consistency and behavior for different liquids. Additional testing and directions for future include testing the droplet launching system with different water-like buffer solutions which might include chemicals to maintain pH, salts, and detergents which could have an effect on the liquid surface tension and viscosity. Taking this testing a step further, the droplet launching system should also be tested with liquids that are not water-like to generate profiles for liquids that are more viscous or have different surface tension properties to identify the effect that these fluid properties have on the pre-launch and launch steps.

In addition to testing the effects of different liquid launches, another direction for future work includes developing and testing a launching systems capable of launching droplets from both micro test tubes and well plates. Some potential directions for testing could include developing a launching stage with multiple launching transducers that act as a phased array, and can target specific wells within the plate to trigger droplet launches.

This method for launching droplets of liquid samples and chemical reagents into the air for capture by an acoustic levitation system brings laboratory automation a step closer to contact-less scientific workflows. By eliminating an intermediate contact surface, the likelihood of contamination or sample loss decreases and without the use of pipette tips, the cost for automation also decreases. In addition to the contamination-free and sample loss prevention, the launching system in combination with the acoustic balance weighing can improve the accuracy of liquid handling by providing an initial droplet dispensing method with multiple dispensable droplet volumes and a direct measurement of the dispensed droplet mass. The launching system can be used to provide a contact-less, automated method for

dispensing aliquots of liquid into the levitator.

The droplet launching system can be taken a step further and improved in many directions. This could include increasing reliability by designing the containment tube geometry to always work with the same calibration frequencies as the initial fluid level. However, other directions for improvement also include expanding the launching ability to well plates, acoustically changing the launch height and precisely controlling the volume of the launched droplet by using different combinations of higher order harmonics to obtain more precise or smaller droplet volumes.

5.8 Shaping and Atomizing Levitated Liquid Droplet

The actions performed when working in a laboratory can be broken down into manipulation tasks like dispensing, containment, transport, mixing, splitting, and sample evaluation. Within the context of traditional wet labs, a scientist would use a pipette to dispense, transport, mix, and split liquid samples or chemical reagents. Glassware or plastic vessels would contain the samples. Sample progress, performance or output would be evaluated based on a variety of characteristics like color change, fluorescence, spectroscopy to name a few.

As previously discussed, acoustic levitation systems can dispense, contain, transport and mix levitated droplets of liquid without making physical contact with the samples. With a camera system and a suite of sensing techniques, acoustic levitation systems are able to weigh, track, monitor, and extract a variety of useful data points about samples during acoustic manipulation. When performing visual feature extraction, it might be desirable to flatten and change the shape of a levitated liquid sample from a sphere to a flattened platelet shape, increasing the amount of light that can pass through the sample and illuminate the contents trapped within the droplet.

This section will discuss work on droplet shaping, methods for changing the shape of a droplet from a sphere to a circular platelet (pancake) and the effect of over-compressing a droplet, atomizing. While controlled splitting of a droplet into two sub-droplets of equal volume has not been accomplished, droplet shaping and atomizing are steps toward unlocking

this functionality.

5.9 Equatorial Expansion of Levitated Droplets

When levitated by a uniform acoustic radiation force, acoustic droplets take on a spherical shape due to equilibrium between the surface tension and the acoustic force. In cases where the trapping radiation force is not necessarily uniform over the surface of the droplet the droplets can take on non-spherical shapes, [196]. Since liquids like water are generally non-compressible fluids, droplets can be shaped by the acoustic radiation force. Trinh [196] et. al found that the extent that the droplet can be deformed depends on the size of the droplet and its material composition. The material of the droplet affects the surface tension force and influences how easily droplets deform. Yajie [220] explored the effect that acoustic intensity has on droplet equatorial expansion rate.

5.10 Principles of Droplet Shaping

Acoustic field shaping has its roots in holography and human interface devices, like display technology. In previous chapters, we discussed work on field shaping algorithms for acoustic emitter arrays. Using phase-based field shaping techniques, the intensity of the acoustic force field can be modulated through the constructive interference of acoustic pressure waves. However, another option for modulating the intensity of the acoustic trapping field is through the modulation of the acoustic emitter output intensity, too. While it is more common to phase shape the volumetric acoustic field to cause changes in intensity and acoustic trapping force, this section will present another method for causing equatorial expansion and changing the output intensity of the acoustic emitters by changing the duty cycle.

Many acoustic levitation systems take advantage of the band pass filter-like frequency response of the piezoelectric transducers that make up the acoustic emitter arrays. Generally, transducer elements like the Murata MA40S4S commonly used in acoustic levitation setups have a bandwidth of about 1kHz to 2kHz. Since the attenuation of frequencies outside of this band centered at 40kHz is so high, acoustic levitation systems will drive them using

a class D amplifier (or something like one), relying on the piezoelectric transducer to filter the out of band frequencies. This makes it easier for microcontrollers and FPGAs since the driving waveform can be a square wave rather than a sine wave. To control the effective output amplitude of the 40kHz acoustic wave with a digital signal, the digital controller can vary the duty cycle of the square wave to change the acoustic emitter intensity.

Since the acoustic radiation force trapping the object is a time averaged force, the duty cycle change can also be seen as a time averaged decrease in the energy of the wave. Decreasing the duty cycle, decreases the energy of the wave. This methodology can be taken another step further to decrease the time averaged acoustic radiation force. By driving the acoustic emitters with a square wave with a period of no activity (duty cycle equal to zero), the time averaged acoustic radiation force is further decreased.

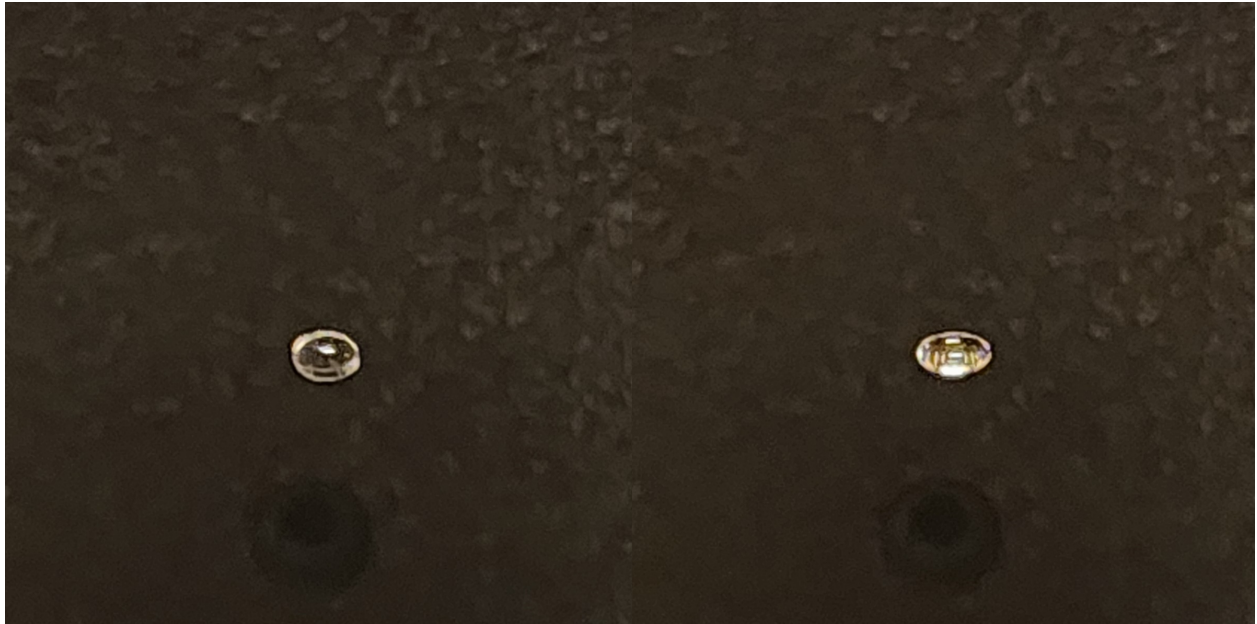


Figure 5.3: Equatorial expansion, or pancaking, of a levitated droplet of water resulting in a wider, more disk like shape rather than a sphere

Acoustic levitation systems can cause equatorial expansion of levitated droplets by applying an acoustic force with a much higher magnitude along a single axis, allowing the

droplet to expand along the other two axes. The acoustic levitation system must therefore be designed such that when the acoustic field is at maximum intensity and constructive interference, the droplet is compressed along this single axis. Then, to contract the equatorial expansion, the duty cycle of the driving square wave signal is decreased, reducing the intensity of the acoustic emitters that are forcing axial compression. Figure 5.3 shows the acoustic levitation system forcing a levitated droplet of water into a state of equatorial expansion, pancaking.

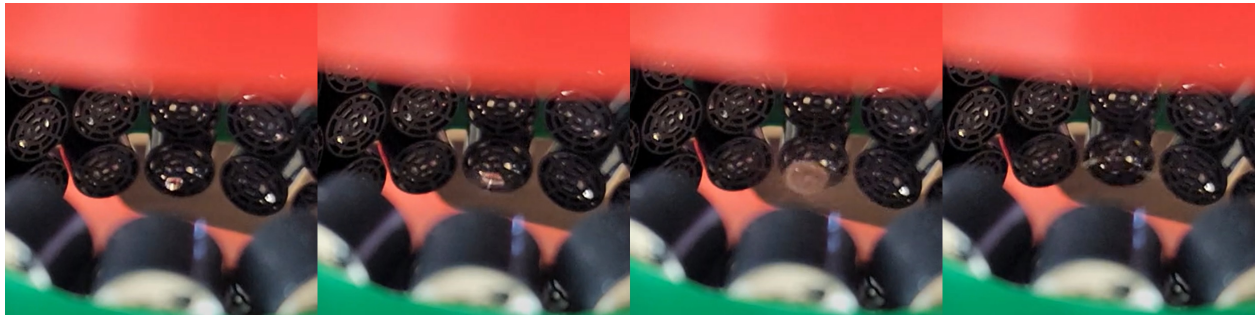


Figure 5.4: High speed video of equatorial expansion with over compression of the droplet causing atomizing of the levitated droplet and resulting in fractured droplets escaping the acoustic trap

Acoustically driven pancaking of droplets has a limit to the smallest size and degree that the once spherical droplet can be flattened. As a droplet gets smaller, the surface tension maintaining the spherical shape of the droplet becomes greater than the acoustic radiation force, preventing the droplet from deforming. However, if the acoustic radiation force pancakes the droplet such that the surface puckers and becomes slightly concave, the surface tension holding the droplet together can break down and cause the droplet to atomize. Figure 5.4 shows a high speed camera capture the over-compression of a droplet resulting in surface tension breakdown and droplet fracturing. The sub-droplets escape the acoustic trap. Some fractured droplets are captured in adjacent trapping locations and regroup.

5.11 *Applications of Droplet Shaping*

Acoustically driven shaping of liquids can be applied to a variety of use cases. Since the levitated droplets of liquid are stable within the acoustic levitation system, examining the droplets with a suite of sensors can further enhance the capabilities of an acoustic levitation-based liquid handling and automation platform, but also provide interesting benefits in other applications such as optics and variable focus lenses.

Equatorial expansion of levitated droplets allow for cameras and other touch-less sensors to examine a droplet with the contents spread out and dispersed across a semi-flat surface. Pancaking droplets allow cameras and sensors to view the contents trapped within the droplet with less distortion than if the droplet was a sphere. It also allows the sample to be back lit and further illuminate possible structures within the droplet.

Transparent liquids, for example water or oil, can be deformed to act as a variable convex lens in an optics systems. By performing equatorial expansion on optically clear liquid droplets, the focal length of the droplet as a convex lens can be modulated. The shortest focal distance would exist in the spherical droplet state, and the largest focal distance would exist in the most expanded, flattest state. Within an acoustic levitation liquid handling system, a variable focus lens might allow a fixed focus camera to magnify the contents of another levitated droplet, making microscopic structures or organisms visible. However, other applications of a variable focus lens might be for focusing collimated beams or lithography.

Another application of droplet shaping within the context of acoustic levitation systems for laboratory automation is acceleration of mixing. Usually, when two droplets are mixed in the levitator, the speed of mixing is based on the rate of diffusion. However, the mixing process can be sped up by repeatedly compressing and expanding the droplet.

5.12 *Axial Over-Compression and Atomizing Droplets*

When a droplet is axially compressed to the point that the opposite flat surfaces become concave, an atomizing wave can form that propagates across the surface of the liquid droplet,

causing a breakdown of surface tension forces holding the droplet together. As a result of surface tension breakdown, the droplet fractures into thousands of small droplets, some escaping the acoustic trap. Levitated droplets of higher viscosity require higher intensity acoustic fields to atomize. Atomizing also only affects levitated fluid droplets, not solids.

An interesting application of atomizing levitated droplets is the separation of fluids based on viscosity and the separation of fluids from solids in heterogeneous mixtures. An interesting example is a levitated droplet mixture consisting of two fluids. One is a low viscosity fluid like water, and another is a high viscosity fluid like resin. If the acoustic trap forces the droplet to atomize, the first fluid to atomize is the water, the fluid of lower viscosity, leaving only the resin. Similarly, for a levitated mixture consisting of both liquid water and a solid such as ice, atomizing enables the subtraction of liquid water from the solid ice, leaving only the solid. While the more viscous material is left behind, one of the drawbacks of this method of material separation is the unconstrained sputtering of fluid droplets throughout the levitator. One solution to this problem could be through containment. By building a dedicated chamber for atomizing fluids, the stray droplets can be contained and isolated from other levitated samples.

5.13 Acoustic Levitation Toolkit Remarks and Future Work

This chapter outlined advanced acoustic manipulation techniques that built upon and apply the fundamental methods of controlling and shaping the acoustic levitation field. It presented a contact-less liquid droplet input solution for the levitator that removes the need for pipettes and plastic tips. In addition, by using pulse width modulation to change the acoustic field intensity, levitated droplets of fluid can be shaped for better camera-based inspection, changeable optical properties, and mixing of liquid droplets. These functions could further reduce the need for disposable liquid handling tools and other contact-based manipulation methods. They could also augment the sensing capabilities of touch-less sensors like cameras or spectrometers. As acoustic levitation systems mature and develop, new methods and manipulation strategies will further expand the manipulation capabilities

of these systems to target specific sample and material handling applications.

While this work tested droplets consisting of water and water-like liquids, additional directions for future work and improvement include additional testing of droplet shaping and atomizing related to different liquids of various surface tensions and viscounties. Liquids containing detergents or other additives could have affect the liquid shaping dynamics. Additional experiments testing liquid properties could include quantifying the degree or starting point of atomization during axial compression and also comparing the magnitude of force needed to be applied to levitated liquid droplets with different viscounties.

Additionally, droplet mixing using the droplet shaping technique needs to be further tested and explored to further quantify the mixing dynamics of levitated droplets through shaping. High speed cameras and coloring additives in droplets could be used to visualize diffusion and fluid movement during mixing. Colorimetry or spectroscopy could also be used to quantify the development rate of droplet mixing, comparing the mixing rate of droplets in a single micro plate well versus in an acoustic levitator setup.

Chapter 6

ACOUSTIC LEVITATION: CONTACTLESS MANIPULATION PLATFORM

Acoustic levitation systems provide many desirable manipulation benefits as a platform for contact-less automated liquid handling. From a manipulation perspective, it is capable of non-contact sample containment, transport and mixing. In the previous chapters, this thesis presented how imaging techniques can localize and interrogate sample in acoustic levitation systems since no manipulator or containers occlude the levitated sample. Based on the vibration frequency of objects in the acoustic field, objects can be weighed without the need for conventional contact scales. Solid objects can be picked up from a table top and brought into the levitator. However, to enable automated liquid handling, additional base functionality needs to be proven.

Like current generation automated pipetting systems, the acoustic levitation liquid handling system, must be able to dispense droplets into the acoustic trap, maintaining compatibility with both human pipetting interactions and robotic systems. Past chapters presented methods for liquid input into acoustic levitation systems including using acoustic frequency modulation and droplet launching. However, to take full advantage of the acoustic levitation tool kit, acoustic levitation systems must be able to split droplets into sub-droplets without atomizing samples, creating potential contamination events or loss of samples. This chapter presents future directions of work which may improve upon acoustic levitation systems. These directions for future work fall into three larger categories for improvement, sensing, software-based control, and hardware changes.

6.1 Acoustic Levitation System Improvements Leveraging Artificial Intelligence and Machine Learning

Acoustic levitation systems combine many cross-disciplinary ideas from physics, robotic control algorithms, sensing systems and other application specific concepts. As acoustic levitators evolve into versatile tools for scientific workflows, use cases will drive the demand for more intuitive and robust systems capable of more complex sensing and manipulation tasks. Traditional approaches to levitation system design, based on analytical models, manual tuned control parameters, and predefined scripts, will struggle to handle the variability and complexity encountered in real world applications especially when integrated into automated laboratory environments. AI and ML models can be leveraged to help improve sensing system accuracy and provide pattern recognition despite challenging high noise sensing environments. Machine learning can also help to improve the acoustic field shaping and control systems to increase levitation confidence and system productivity. Artificial intelligence can also be applied to help compensate for acoustic levitation weaknesses, specifically reducing interface and knowledge deficiencies that make using the system challenging even for experienced operators. Acoustic levitation platforms provide a unique combination of manipulation and sensing capabilities which can enable intelligent closed-loop automated handling solutions to problems in a variety of fields.

6.2 Machine Learning Models for Improving Sensing Systems in Acoustic Levitation Systems

To enable real time monitoring of levitated samples and provide data for feedback control and support experimental analysis, sensing systems are an important part of an acoustic levitation tool designed for automation. Factors such as changing ambient lighting, real world acoustic field variance, and droplet dynamics can add to overall noise in sensing systems. To mitigate noise effects and help boost sensitivity, machine learning can be applied to enhance the performance of sensors integrated into acoustic levitation systems.

ML-based image analysis can be used to improve the detection and characterization of

levitated samples. Unlike image processing techniques such as thresholding or edge detection, convolutional neural networks (CNNs) and other deep learning models can learn to recognize complex patterns despite transparent droplets, distorted backgrounds or suboptimal lighting environments. For example, these models can be trained to track and localize levitated droplets or as previously discussed, extract the resonant frequency of levitated objects to more precisely estimate the object mass despite a non-linear acoustic trapping force.

The sensing techniques presented in this manuscript can further be improved upon by applying machine learning and artificial intelligence to extract a greater level of performance out of integrated sensing hardware. As a platform, acoustic levitation can leverage a plethora of sensing techniques. One interesting example of using a sensor fusion approach to machine learning that builds upon the weighing system would be to use forms of spectroscopy to identify the material of levitated objects prior to weighing, then based on the determined material, a force coefficient can be retrieved from a library to perform weighing. This can be taken a step further by directly feeding the spectroscopy output into a neural net that determines the levitated object mass.

6.3 Data-driven Acoustic Field Shaping and Software Control

In addition to improvements to sensing fidelity, machine learning can potentially provide a faster solution for real-time phase, frequency, and amplitude control. A model could be trained to execute acoustic field shaping control functions based on user defined trajectories and even anticipating error or levitated drop states that might occur in risky acoustic field shapes. The the controller can then repair and provide an alternative control action to avoid high risk levitation paths. With sensor inputs like camera images, new models with optimized control strategies can reduce the need for manual tuning.

Analytical models attempt to anticipate and control the acoustic levitation systems by capturing the dynamic acoustic field using mathematic models for the acoustic transducers, sound propagation through the air and superposition of multiple waves. Earlier, this manuscript discussed a method of modeling the reflected acoustic field which enabled the

acoustic levitation system to pick up object from a table surface, and another method for velocity-based control. However, a data driven approach that relies on iterative solvers and sensing systems to provide ground truth could help develop more robust and efficient acoustic levitator control systems.

Some of the benefits of developing data driven acoustic levitator controllers include better real world performance, increased dynamic performance and speed of manipulation, and a higher degree of multi-object parallelized control. This approach has the advantage of compensating for unit to unit variability, edge cases that are hard to model analytically and potential robustness in changing environments. As hardware continues to accelerate and improve the performance of neural networks, a neural network will have long term advantages over physics-based solvers that require finite element analysis and large amounts of memory. Also, by shifting the control system to a data driven approach, it reduces the need for domain specific expertise, minimizing the reliance on domain expert tuning and manual calibration. This would likely translate to broader accessibility and faster adoption in research and industry as a tool for scientific experimentation.

6.4 Liquid Droplet Rotation via Frequency Modulation

A previous chapter presented acoustic frequency modulation to enable smooth, linear motion of levitated objects in standing wave traps. When transducers are driven together at the same beat frequency, levitated objects move at higher speeds with higher frequencies. Translational movement of levitated objects can also be achieved using phase changes to shape the acoustic field, and with small enough position changes, smooth motion can also be achieved. Therefore, for smooth movement of objects, there is a limit to the maximum rate that the acoustic field can be changed. This would also limit the speed of levitated objects with phase control. To rotate an object, the phase values are rotated via a transform such that the acoustic field is also rotated. Similar to the position scenario, the rotation rate would also be limited by the speed in which the acoustic field and phase angles could be changed. To increase the maximum rotation rate of a levitated object, frequency modulation could be

applied to current acoustic levitation system hardware.

Using the same acoustic emitter hardware detailed in past chapters for frequency modulation, acoustic emitters of the same array could be divided into subsets of transducers which would output different modulation frequencies while the opposing array side would remain unchanged. A simple example would be dividing the array of acoustic emitters in half. One half would output a 40000.1Hz wave, the other half would output 40001.0Hz, while the opposing emitter array would output the nominal 40000Hz. Would the difference in moving wave cause the object to spin?

6.5 Liquid Droplet Splitting via Stored Droplet Motion

In the previous chapter on droplet shaping and axially compressive acoustic forces, the result of equatorial over-expansion of a droplet was atomizing of the droplet. This prevented the acoustic levitator from splitting the droplet into two sub-droplets of equal volume by forcing the droplet to change shape. However, in the chapter on droplet launching, this work presented methods for preparing the surface by driving the liquid surface within the micro test tube at its fundamental frequency, but with low enough magnitude that launching was not initiated. The effect of this was the surface, while no longer flat, was made consistent with periodicity due to a known repeating motion. This also stored energy within the oscillating liquid surface to reduce the energy needed to initiate the droplet launch at one of the harmonic frequencies.

In situ splitting of levitated droplets could be possible by combining the amplitude driven method of axial compression of liquid droplets with the stored surface oscillation using during the prelaunch process. If thought of as a rubbery ball, the droplet would have a resonant frequency for compression and expansion that the acoustic levitator could drive the shape change at. By oscillating between the modes, sphere and pancake, the droplet could be driven to overshoot the pancake to sphere state, to create a droplet separation event. Splitting without atomizing is possible because during the pancake to sphere transition, liquid is moving in opposite directions pulling apart the droplet at its equator. Instead of requiring

the levitator to provide enough momentary power to rip the droplet in two, energy for the split is stored in the droplet's kinetic change of shape motion. The atomizing surface wave that would normally break the droplet, now aids in the separation of the droplet at the equator since now the liquid is in motion moving in 2 directions rather than radially in all directions.

6.6 *Acoustic Levitation Specific Hardware*

While control software and sensing systems have seen an increase in attention associated with high speed computation and field control algorithms, many acoustic levitation systems repurposed hardware designed for other applications which has led to imperfect part selection. This includes parts such as the FPGAs, amplifiers, and the transducers themselves. Two areas of hardware-based improvement that could greatly benefit acoustic levitation systems are acoustic levitation purpose built channel drivers and transducers with better thermal performance.

Since the phased arrays used in acoustic levitation use hundreds or even thousands of transducers, many systems are built using FPGAs to handle the large quantity of individual channels with FPGA general purpose output pins. However, acoustic levitation systems would benefit from many independently controllable channels that were not only phase and frequency controlled but also precisely amplitude controlled to enable advanced manipulation functions like controllable droplet atomization and splitting.

Additionally, currently available ultrasonic transducers designed for air can heat up during continuous and prolonged usage. This can cause performance changes over time and raise the temperature of the gas within the levitation volume. While high performing transducers with greater air volume displacements would increase acoustic levitation forces per transducer, a greater improvement for acoustic levitation specific applications would be thermal stability and energy efficiency. Transducers with better thermal consistency would reduce the amount of heat released into the surrounding air and reduce convective gas effects in the acoustic levitation manipulation volume during prolonged continuous usage.

6.7 Intuitive Interfaces and Natural Language Processing for Application Specific Levitation Systems

Large language models (LLMs) can act as intermediaries between users and complex control systems and software. It would allow a user to explain an objective or task in plain language, and have that intent translated into executable steps for an acoustic levitation systems. Not only could this help to lower the barrier for non-programmers to interact with the acoustic levitation platform, but also help to accelerate the startup, discovery, and execution rate of scientist and even expert users.

Natural language processing would enable users to describe experimental goals and procedures that would get translated by the LLM into executable control sequences, scripts or parameter settings for the machine. This would make starting an experimental process easier, but also help to troubleshoot and diagnose problems with the experiment, explaining issues, offering suggestions and providing explanation for system behavior. This would be an extremely useful tool for an acoustic levitation system that many scientist would be unfamiliar with and unable to know how to troubleshoot. It would also help accessibility when it comes to on-boarding and training users on how to use an acoustic levitation system, and can automatically document and log experimental results. This would not only support reproducibility but also collaborative research.

6.8 Artificial Intelligence-driven Closed-Loop Experiment Optimization

Acoustic levitation automation platforms could open the door to new AI-driven workflows in biology, chemistry, material science and scientific discovery. Since acoustic levitation platforms already combine manipulation and real-time sensing capabilities, it can enable LLMS to help streamline and automate the experimental process by providing closed loop experimental optimization.

Since acoustic levitation systems can provide contactless manipulation capabilities and abundant data gathering opportunities, LLMs can help on a macro level by providing coher-

ent summaries about data collected which can inform next steps in a scientific experiment or discovery process. In this case, a human can make executive decisions and plan consecutive actions based on the data collected and summarized.

Another way LLMs and acoustic levitation automation systems can help scientist is through closed-loop experimental optimization. Closed-loop experimentation refers to a system that can adjust experimental parameters dynamically based on ongoing results. This kind of system could analyze experimental outcomes in real-time and change experimental parameters that the acoustic levitation platform would then execute. The system would monitor the experiment using the suite of sensors on the automated manipulation platform and iteratively improve an experiment based on a human directive or task input into the LLM.

LLMs can serve as an expert scientific research assistant that has been thoroughly trained on how to best operate a laboratory automation platform like the acoustic levitation system. Users can provide high level hypothesis driven goals and the LLM can translate them to executable code or instructions for the acoustic levitation system. Based on sensor data, LLMs could even provide error detection and recovery recommendations when unexpected results occur and the whole process including data and decisions stemming from the data can be automatically documented for future understanding and reproducibility.

6.9 Data Visualization and Human-Levigator Interfaces

Natural language processing and artificial intelligence could be future avenues for changing how humans interact and execute assays and workflows in the laboratory. For a system that emphasizes contact-less liquid handling and automation, the acoustic levitation system programming, user interface, and experience would potentially look and feel different than the experiment planning, pipette liquid transfer, and data gather used in scientific workflows today. For acoustic levitation systems, this could also mean that workflow planning and data representations also need to change. The human computer interface system would need to be able to represent workflow ideas and data differently. For example, the acoustic

levitation system can contain and move droplets in three dimensional space rather than the two dimensional well plate array. This could create possibilities for parallel mixing and sensing events all happening in different spaces within the levitator, but the workflow needs to be able to capture the parallelism during the planning stage.

While LLMs can enable speech based communication of workflow steps and laboratory objectives from the human to the acoustic levitation controller, another direction for planning and user input can also be spatial input. Work like LeviCursor [18] allows users to move acoustically levitated objects by indicating the object path via finger tracked movement. By using spatial input, users could define laboratory workflows in 3-D space by tracing out the trajectory of levitated droplets with a finger tip. Then, as a verification or debugging step, the levitator could play back the trajectory, allowing the operator to "pinch-and-pull" the levitated object to make adjustments to the droplet movement path in real-time. This playback and adjustment function could also be used in concert with workflows that originate from natural language models or code generated workflows to make in situ trajectory and workflow adjustments.

Acoustic levitation systems could also be used as a method for visualizing and representing data and information in 3-D [74]. Acoustic levitation liquid handling platforms could also be used to display workflow relevant data during workflow execution. In a previous chapter, colorimetric readout was discussed as a visual metric that could be used to indicate the state of chemistry within a liquid droplet. This same concept could be used by the acoustic levitation system to communicate data about the levitated object state by projecting colors onto levitated samples. For example, if a 3-D array of droplets are levitated in the liquid handling system and each droplet contains a different concentration of DNA, an operator would normally see an array of clear colorless droplets. However, a projector system could be implemented to illuminate each droplet with a color indicative of the DNA concentration, providing direct visual feedback to the operator. Similarly, in situ levitated object data visualization strategies like this could enable at a glance experiment progress representation by communicating data through projected color or by spatial positioning such as indicat-

ing higher concentrations with a higher positioning within the levitator. Data representation strategies like positioning and coloring could both be implemented to simultaneously provide two experimental points of data for multiple levitated samples.

Chapter 7

THESIS CONCLUSION

This thesis presented work on sensing and manipulation methods for acoustic levitation systems, using control and sensing techniques to develop higher level manipulation capabilities that could serve as a toolkit for an acoustic levitation-base contact-less object handling platform. As the demand for chemistry miniaturization and laboratory automation increases, contact-less methods of liquid sample and chemical reagent handling will become increasingly more appealing. With this motivation for development in mind, this work presented solutions for in situ sensing including touch-less weighing and object tracking of commonly levitated items such as transparent liquid droplet. It outlined control methods for acoustic levitation systems that take advantage of phase, frequency, and amplitude manipulation, enabling more robust and control of acoustic fields by accounting for acoustic reflections and realistic hardware engineering limitations. Finally, the sensing and control methods were combined to enable dispensing and liquid shaping functions that will help to make acoustic levitation systems more appealing as a contact-less liquid handling platform capable of automated and high throughput workflow in the future.

7.1 Closing Thoughts on Acoustic Levitation Sensing and Control

Acoustic levitation systems can enable new manipulation and sensing possibilities as a scientific research instrument and programmable laboratory or automation platform. This thesis has presented explorations in acoustic levitation sensing methods, control systems, and manipulation techniques, detailing the fundamental principles, techniques, and use cases. When paired with touch-less sensors, acoustic levitation can reach its full potential. This work discussed sensing techniques like weighing and other camera-based sensing techniques to localize

and extract other visual features useful to understanding sample state and behavior. These techniques can enable real-time, dynamic sample monitoring in parallel with manipulation.

On the control side, it presented methods for modeling and controlling acoustic fields in the presence of acoustically reflective surfaces and a frequency modulated approach to velocity-based control of levitated objects instead of the phase oriented position control. The control methods help to increase the robustness of acoustic traps and provide new manipulation options to increase acoustic levitation system manipulation capabilities and flexibility. This thesis outlined the methods and advantages of combining these sensing and control methods, developing manipulation capabilities like droplet shaping and droplet launching into the air from a micro test tube. These are easily stage advances toward creating a base feature set for an acoustic levitation platform toolkit that can be useful as a scientific tool.

As a scientific tool, machine learning and artificial intelligence can improve the sensing and control capabilities of acoustic levitation systems through sensor data processing and a data driven approach to acoustic field shaping. Artificial intelligence can also help to further improve acoustic levitation user interfaces and specific laboratory workflows by closing-the-loop on processing real-time experimental data and provide suggestions for automated optimization steps while automatically documenting experimental results. Acoustic levitation systems have a variety of applications and niches. Although the technology has many benefits there are limitations that also exist. These limitations are potential directions for future work and improvement.

Acoustic levitation systems can be a high impact platform level technology than has the potential to change how scientists approach automation and scientific discovery in the lab. In addition to accelerating the iterative design processes, the accessibility that acoustic levitation systems provide to informative sensor data and liquid handling capabilities could enable the growth and pursuit of new ideas that might have otherwise been impossible. With tightly integrated sensing systems, comprehensive and informative data can be collected from samples to best inform next steps during discovery. Contact-less sensing also means that

precious samples are never lost or contaminated. As acoustic levitation systems mature as a technology and contact-less liquid handling platform, these systems will continue to become more complex and capable of more advanced laboratory tasks. While acoustic levitation-based liquid handling systems can be a contact-less alternative to manual pipetting and a scalable solution to laboratory automation, features like the tightly integrated sensors, the easy of deployment, and the expanding toolkit of manipulation capabilities will potentially enable acoustic levitation to mature into a life science instrumentation platform for ubiquitous scientific discovery that could impact fields ranging from biology and pharmaceuticals to material science.

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