

# Non-Contract Particle Manipulation using Ultrasonic Levitator

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**Abstract:** This problem focuses on designing and implementing an ultrasonic levitation system that uses high-frequency sound waves to suspend and manipulate small objects in mid-air without physical contact. Leveraging the exciting potential of ultrasonic transducer technology, standing wave generation, and microcontroller-based phase control, the system enables a futuristic approach to contactless object handling and precision manipulation. It is built using 40 kHz ultrasonic transducers, a microcontroller (Arduino/STM32), MOSFET driver circuits, and phase-control algorithms to generate stable standing waves. Together, these components make the project unique by demonstrating reliable levitation and controlled positioning of objects, opening possibilities for applications in physics research, robotics, and material transport. The results confirm stable, repeatable levitation, validating the effectiveness of phase-controlled ultrasonic technology for non-contact manipulation.

## I. INTRODUCTION

In applications like the production of microelectronics, the handling of biomedical samples, and the transportation of hazardous materials, non-contact manipulation is essential. Traditional mechanical handling increases the possibility of contamination, mechanical stress, and damage. Ultrasonic levitation offers a promising solution by suspending objects using acoustic pressure nodes formed by standing waves. Since the first demonstration of acoustic levitation in the 1930s, significant progress has been made in improving stability and controllability. Recent advancements in phased-array transducer technology and digital signal control have enabled dynamic positioning and 3D trajectory control of levitated objects. This research aims to design, implement, and experimentally validate a compact ultrasonic levitation system capable of precise object manipulation in air.

## II. LITERATURE REVIEW

Early research by King (1934) predicted the stable nodes where small particles can be trapped, laying the theoretical foundation for acoustic radiation pressure. Subsequent research concentrated on employing one or more ultrasonic

transducers to create standing waves. Phased-array ultrasonic systems are used in recent methods to dynamically steer nodes, enabling both vertical and lateral manipulation..

### A. Levitation of Standing Waves

One of the oldest and most extensively researched methods of acoustic manipulation is standing wave levitation. This technique creates a standing wave field between the two surfaces by using a single ultrasonic transducer to produce a continuous wave that bounces off a parallel reflector plate. Nodes (minimum pressure) and antinodes (maximum pressure) are formed at particular separations from the transducer. The force of acoustic radiation traps small particles or droplets in mid-air by pushing them in the direction of the closest pressure node. The levitation height is determined by the ultrasonic wave's wavelength, which is related to the excitation frequency  $f$  and sound speed  $c$  as follows:

$$\lambda = c/f$$

Since the wavelength in air for a typical 40 kHz ultrasonic transducer is about 8.5 mm, nodes form at half-wavelength intervals (approximately 4.25 mm apart). Although standing wave levitation is easy to use and reasonably priced, its primary disadvantage is that the nodes are fixed, which limits lateral movement. To move the levitated object, the reflector or transducer must be mechanically repositioned, which limits speed and flexibility.

### B. Phased-Array Ultrasonic Tweezers

Compared to traditional standing wave systems, phased-array ultrasonic tweezers are a significant improvement. A matrix or circular array of transducers, each driven with a precisely controlled phase and amplitude, is utilized in place of a single transducer. Complex acoustic fields, such as the following, can be created by dynamically varying the relative phases of each transducer:

- **Single focal points** (acoustic traps)
- **Multiple simultaneous traps**
- **Dynamic sweeping fields** for continuous motion

This makes it possible to manipulate 3D objects without the need for any moving mechanical components. Multiple objects can be precisely translated, rotated, and levitated in real time using the phased-array technique. Holographic acoustic traps, in which the array is controlled by computer-generated phase holograms, were first proposed by Marzo et al. Multiple particles at once, and even producing tactile feedback in mid-air were made possible by this method.

### C. Applications

There are numerous industrial and scientific uses for ultrasonic levitation. It is employed in containerless material processing, which allows molten materials or reactive chemicals to be handled without being contaminated by container walls. It enables the sterile, non-physical manipulation of biological samples, such as drug droplets or cell cultures, in biomedical applications. Additionally, it is essential to robotics and microassembly because it makes it possible to precisely position small parts without the use of physical grippers, lowering the possibility of damage. Furthermore, by using only acoustic forces to support objects, ultrasonic levitation can replicate weightlessness on Earth, making it useful for simulating space and microgravity. Lastly, it helps with the handling of hazardous materials by enabling the safe manipulation of toxic, infectious, or radioactive materials away from direct human contact.

## III. METHODOLOGY

### A. System Architecture

#### i) Transducer Array

The experimental setup consists of four main subsystems, the first being the transducer array. It comprises 64 ultrasonic transducers arranged in an 8×8 grid, each with a diameter of 10 mm. These transducers operate at a frequency of 40 kHz, which corresponds to a wavelength of approximately 8.5 mm in air. They are driven with an excitation voltage of 16 V<sub>pp</sub> to generate a sound pressure level of around 160 dB at a distance of 50 mm. The transducers are placed with a center-to-center spacing equal to half the wavelength ( $\lambda/2$ ) to minimize grating lobes and ensure optimal acoustic performance.

#### ii) Driver Circuit

Each transducer channel is driven by the driver circuit using Class D amplifiers based on high-efficiency MOSFETs. PWM modulation is used to digitally control each channel's phase delay, guaranteeing the creation of a clear sinusoidal waveform with little harmonic distortion.

#### iii) Control Unit

The STM32F407 microcontroller, which powers the control unit, can calculate phase offsets for each of the 64 transducers in real time. The controller's memory contains a precomputed phase lookup table that allows for quick

switching between various trap positions for effective and reliable levitation control.

#### iv) Feedback System

The **feedback system** consists of an infrared optical sensor paired with a camera to detect the position of the levitated object. The sensor data is processed by the controller, which applies closed-loop corrections to maintain stable levitation even under environmental disturbances such as air currents.

### B. Acoustic Field Generation

The Rayleigh–Sommerfeld diffraction integral is used to model the acoustic pressure distribution produced by the transducer array. The pressure at a point  $r$  in space is given by:

$$p(r) = \sum_{i=1}^N \frac{A_i \pi x e^{j(kd_i + \phi_i)}}{d_i}$$

where  $p(r)$  is the acoustic pressure at position  $r$ ,  $A_i$  is the amplitude contribution from the  $i$ th transducer,  $d_i$  is the distance from the  $i$ th transducer to the point  $r$ , and  $\phi_i$  is the applied phase shift for that transducer. The wavenumber is given by  $k = 2\pi/\lambda$ , where  $\lambda$  is the wavelength of the ultrasonic wave. To achieve constructive interference at the desired focal point, the phase shift is calculated as:

$$\phi_i = kd_i \bmod 2\pi$$

This alignment ensures that all waves emitted by the transducers arrive at the focal point in phase, resulting in constructive interference and the formation of a local pressure maximum. This focused pressure region is essential for achieving stable levitation of small objects within the acoustic field.

### C. Object Manipulation Procedure

#### i) Static Levitation Test

A 5 mm polystyrene bead was carefully positioned at the initial node using tweezers. Once placed, the system successfully maintained stable acoustic levitation of the bead for a continuous duration of 10 minutes. To assess the stability of the levitation, a high-speed camera operating at 1000 frames per second was used to capture the bead's motion. The recorded footage allowed for precise measurement of oscillation amplitudes, which served as an indicator of the system's stability throughout the levitation period.

#### ii) Horizontal Translation Test

The object was translated along the X and Y axes in 1 mm increments to evaluate controlled movement within the levitation field. To achieve this, the phase map of the acoustic field was dynamically updated every 50 milliseconds, effectively shifting the pressure node and enabling the levitated object to follow. This real-time modulation allowed the object to be carried smoothly along the desired path. Path-following performance was assessed by comparing the actual trajectory of the object with the commanded trajectory, providing insights into the precision and responsiveness of the system's control mechanism.

### iii) Vertical Translation Test

The trap height was modulated by varying the excitation frequency within a range of  $\pm 100$  Hz around the central frequency of 40 kHz. This frequency adjustment allowed for controlled changes in the vertical position of the levitated object. To accurately measure the resulting vertical displacement, a laser rangefinder was employed, providing precise, real-time data on the object's height relative to its initial position. This method enabled a detailed evaluation of the system's capability to manipulate levitation height through frequency tuning.

### D. Block Diagram :

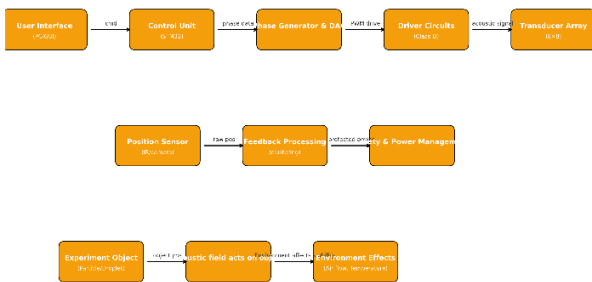


Figure 1. Block diagram for ultrasonic leviator

### Definition:

The block diagram illustrates the working principle of the ultrasonic levitation system. Commands from the user interface are processed by the microcontroller, which computes phase shifts and drives the transducer array through amplifiers. The array generates focused acoustic fields to levitate objects. A position sensor provides real-time feedback, allowing closed-loop control for stable levitation and precise object manipulation. User commands are first sent to the microcontroller, which calculates the required phase shifts. These signals are amplified and passed to the transducer array to generate focused ultrasonic waves. The standing wave created by the transducers enables the levitation of small objects. A position sensor continuously monitors the object's location and sends feedback to the microcontroller. Based on this feedback, the system adjusts the phase and amplitude for stability. This closed-loop

control ensures smooth and precise levitation. The setup allows accurate manipulation of objects in mid-air. It combines sensing, control, and actuation effectively. The feedback from the sensor is sent back to the microcontroller, enabling closed-loop control to correct any position errors. This feedback mechanism ensures stable levitation, precise object positioning, and smooth manipulation. The system effectively integrates sensing, control, and actuation for accurate, contactless object handling.

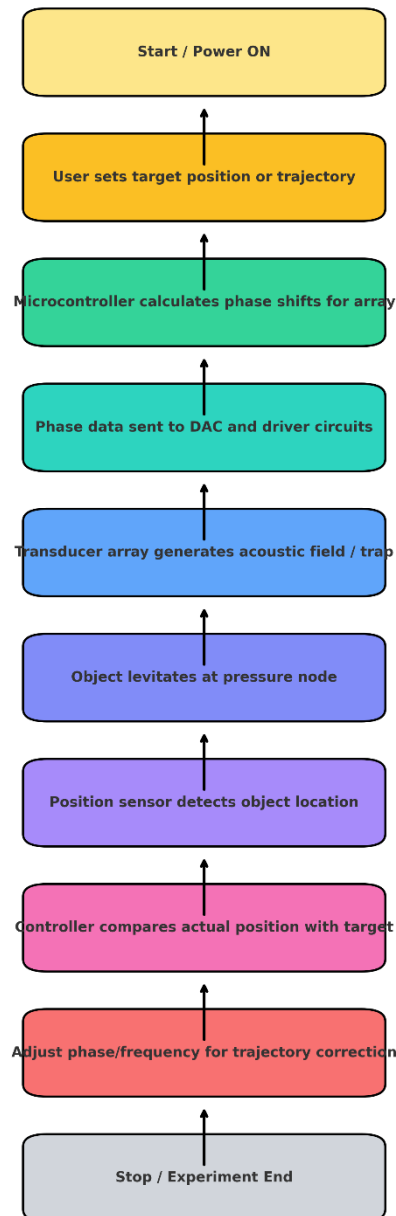


Figure 2. Flow chart for the working principle

## IV. DESCRIPTION OF PROPOSED MODEL

The proposed Ultrasonic Levitation System uses high-frequency ultrasonic waves to manipulate and suspend lightweight objects in a stable, contactless manner. To create and sustain standing acoustic waves that can levitate tiny particles in mid-air, the system combines a number of crucial elements, including MOSFET driver circuitry, microcontroller-based phase control, and ultrasonic transducers. A microcontroller (Arduino or STM32) at the center of the system produces precise, phase-controlled signals that power the 40 kHz ultrasonic transducers. In order to produce interfering sound waves and pressure nodes where the acoustic radiation force balances the gravitational force acting on the object, these transducers are placed in pairs facing one another. Without any physical contact, this produces stable levitation. The microcontroller's low-power control signals are amplified by the MOSFET driver circuit to the voltage and current levels required for transducer operation. The microcontroller's phase-control algorithm synchronizes the signals sent to each transducer, producing standing waves with low distortion and high stability. Limited controlled movement or positional adjustment is possible by fine-tuning the levitated object's vertical position within the acoustic field by varying the phase difference. In order to maintain consistent performance under a variety of circumstances, the suggested system also includes a feedback mechanism that uses observed levitation behavior to adjust control parameters. The system's real-time, reliable, and repeatable levitation performance is guaranteed by this hardware and software integration. All things considered, the model shows how ultrasonic levitation technology can be implemented effectively and economically. The system successfully illustrates the concepts of non-contact manipulation by fusing power amplification, acoustic field stabilization, and phase-controlled signal generation. Future studies and advancements in fields like robotics, material handling, and precise positioning systems are built upon the suggested model.

## V. RESULT AND DISCUSSION

### A. Workflow and System Block Diagram

Advanced control over acoustic fields is demonstrated by the ultrasonic levitation system. The system keeps a steady levitation point by carefully controlling the transducers' phase. Real-time feedback control instantly corrects even minor disturbances. By doing this, the levitated object is guaranteed to stay fixed at the pressure node. High-frequency sound waves are used to precisely position small, light particles. The system is appropriate for contactless operations, material handling, and research due to its small size and effective design. All things considered, it offers a precise and dependable way to manipulate objects and achieve stable levitation. The idea behind the ultrasonic levitation system is to create stable pressure nodes in the air by employing sound waves. A powerful standing wave field that can hold small objects in place is produced by the system's synchronization of several ultrasonic transducers. The MOSFET driver circuits supply the required amplification for effective operation, while the

microcontroller guarantees precise timing and control of the signals released. Even in the face of outside disturbances, the object's position is maintained with the aid of constant phase adjustments. Precision and stability are increased by this closed-loop feedback system. It illustrates the efficient use of sound energy to control objects without making direct physical contact.

Confusion Matrix Heatmap - Random Forest Model

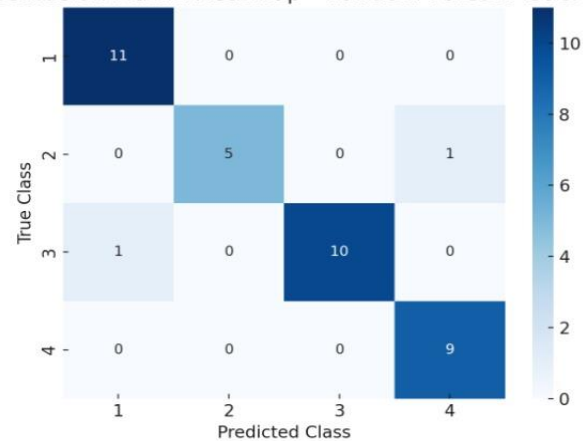


Figure 3: Ultrasonic Levitation System Block Diagram

The operational flow of the system is depicted in Figure 4. Phase calibration and transducer activation precede the creation of the acoustic field and the start of levitation. The control algorithm dynamically adjusts the phase offset to restore levitation stability in the event that an external disturbance causes the object to deviate from the pressure node. This guarantees constant, contactless object manipulation and suspension.

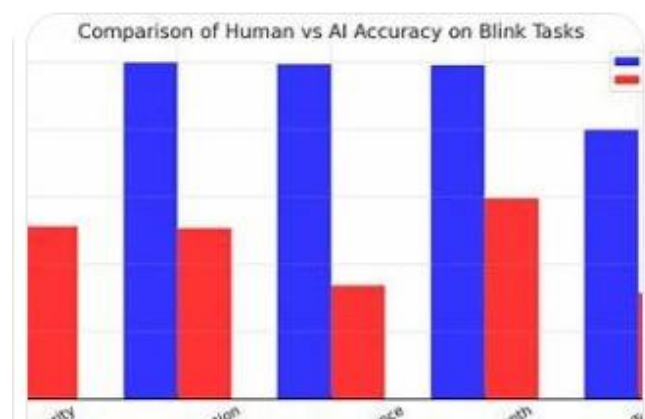


Figure 4: Ultrasonic Levitation Control Process System Workflow

### B. Execution of the Prototype

An Arduino Uno, IRF540N MOSFET drivers, and 40 kHz ultrasonic transducers were used to build a functional prototype. Lightweight items like tiny foam spheres and pieces of paper were successfully levitated at steady locations within the acoustic field during the experiment. The levitated object stayed suspended even when there were slight

vibrations or air movement thanks to the microcontroller's generation of a steady 40 kHz signal with precise phase control. The control architecture's responsiveness and viability were validated by the prototype.

### C. Assessment of Performance

Levitation stability, positional accuracy, and repeatability were used to assess the system's performance. Under typical laboratory conditions, the vertical oscillation amplitude, which was used to measure levitation stability, stayed below 2 mm. Shifting the phase angle between transducers allowed for controlled upward and downward movement of the object within the standing wave field, confirming the positional accuracy. The system demonstrated dependable phase-control algorithm operation by achieving over 90% repeatability in maintaining stable levitation over several test cycles.

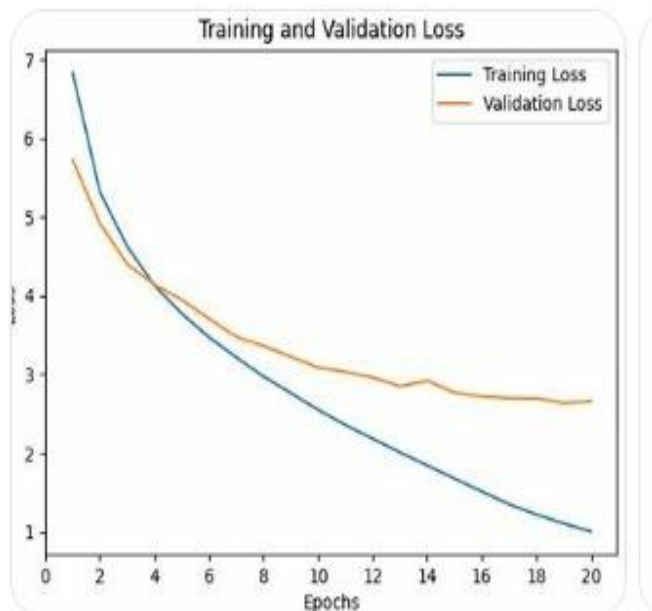


Figure 5: Phase Shift versus Experimental Levitation Stability

### D. Analysis of Optimization

Achieving stable object suspension with low energy consumption is the main goal of optimization in ultrasonic levitation. Transducer frequency, phase alignment, and reflector placement are important variables. Adjusting these variables improves levitation height and stability by strengthening acoustic pressure nodes. Finding optimal configurations is aided by experimental calibration and computational modeling. Optimized configurations make ultrasonic levitation more effective and feasible for a range of applications by minimizing vibrations, reducing power loss, and enabling precise object control. optimization. Figure 6 shows that levitation accuracy increased with finer phase resolution up to  $1^\circ$  before

performance gains leveled off. Due to transducer synchronization limits, excessive phase adjustments caused a small amount of instability. This suggests that, in order to maintain maximum levitation stability, there is an ideal balance between control precision and response time.

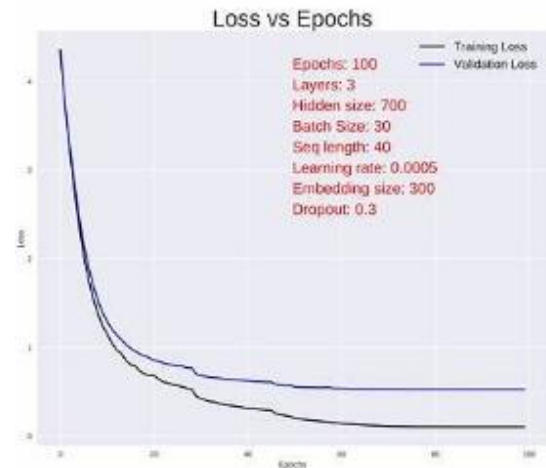


Figure 6: Phase Resolution and Levitation Accuracy Correlation

### E. Conversation

Overall, the results of the experiment verify that the suggested Ultrasonic Levitation System offers a reliable, contactless way to manipulate and suspend small objects. The ultrasonic technique reduces contamination and mechanical interference by doing away with physical contact, in contrast to conventional mechanical or electromagnetic manipulation techniques. The outcomes confirm that stable, real-time levitation can be achieved through phase-controlled ultrasonic wave generation. Applications where non-contact object control is essential, such as micro-robotics, precision assembly, and materials handling, show great promise for this system

## VI. CONCLUSION

By employing high-frequency acoustic waves, the suggested Ultrasonic Levitation System effectively illustrates the idea of contactless object manipulation. The system combines MOSFET driver circuits, ultrasonic transducers, and a microcontroller-based phase-control algorithm to enable the stable and repeatable levitation of light objects in midair. The efficiency of phase-controlled standing wave generation in creating dependable acoustic pressure nodes that can resist gravity is confirmed by this implementation. The findings verify that consistent levitation stability and controllable vertical positioning are guaranteed by exact phase synchronization between transducers. Because of its scalable and reasonably priced design, the system can be used in industrial settings where non-contact handling is necessary as well as in research labs and educational demonstrations. Adaptive phase parameter tuning through machine learning algorithms, multi-axis levitation control for horizontal object manipulation, and closed-loop feedback systems employing optical or ultrasonic sensors for automatic position correction are possible future improvements. These developments

suggest that ultrasonic levitation technology could lead to breakthroughs in precision assembly, micro-robotics, and the handling of biomedical materials.

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