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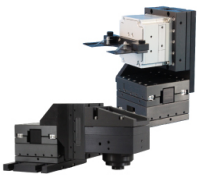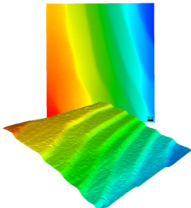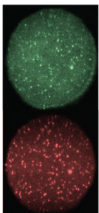Asier Marzo ; Adrian Barnes; Bruce W. Drinkwater

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# TinyLev: A multi-emitter single-axis acoustic levitator

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Acoustic levitation has the potential to enable novel studies due to its ability to hold a wide variety of substances against gravity under container-less conditions. It has found application in spectroscopy, chemistry, and the study of organisms in microgravity. Current levitators are constructed using Langevin horns that need to be manufactured to high tolerance with carefully matched resonant frequencies. This resonance condition is hard to maintain as their temperature changes due to transduction heating. In addition, Langevin horns are required to operate at high voltages (>100 V) which may cause problems in challenging experimental environments. Here, we design, build, and evaluate a single-axis levitator based on multiple, low-voltage (ca. 20 V), well-matched, and commercially available ultrasonic transducers. The levitator operates at 40 kHz in air and can trap objects above 2.2 g/cm$^3$ density and 4 mm in diameter whilst consuming 10 W of input power. Levitation of water, fused-silica spheres, small insects, and electronic components is demonstrated. The device is constructed from low-cost off-the-shelf components and is easily assembled using 3D printed sections. Complete instructions and a part list are provided on how to assemble the levitator. *© 2017 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).* [http://dx.doi.org/10.1063/1.4989995]

## INTRODUCTION

Sound is a mechanical wave and as such it carries momentum that can act on particles due to acoustic radiation forces.[7,9,15,18] When the forces exerted on an object are strong enough and converge from all directions, the particles can be levitated and stably trapped.[6]

Acoustic waves can trap particles of different materials and a wide range of sizes of millimetre dimensions. This is a significant difference with respect to optical trapping in which the particle size range is 0.01-10 $\mu$m and the materials need to be dielectric or optically transparent.[24] Also, acoustic trapping has a ratio of trapping force to input energy orders of magnitude higher than optical manipulation.[21] Magnetic levitation can strongly hold samples in mid-air[10] but it only supports ferromagnetic materials. On the other hand, diamagnetic materials can be levitated by magnets that repel the sample;[14] a frog was levitated in this way[5] since water is slightly diamagnetic. However, this technique requires strong magnetic fields given the weak diamagnetism of most materials of interest. Other forms of levitation such as aerodynamic levitation[53] agitate and alter the samples in the process, and in electrostatic levitation,[23] the required control systems are complex and the sample materials are limited.

The versatility of airborne acoustic levitation makes it a useful tool in container-less transportation,[12,19] pharmaceutics,[4] nano-assemblies,[34] and the levitation of biological samples[29] or even small animals.[36,52] Acoustic levitation of liquids can be used to study new fluid dynamics[39] and measure their surface tension[37,41] or the rheological properties

of surfactant solutions.[38] Other applications include the formation of levitated ice flakes,[3] eutectic crystal growth in molten metals,[49] evaporation of binary liquids,[54] the study of phase transitions,[11] and the rapid crystallization[8] or ionization[35] of samples. Levitated samples do not need to be held in a receptacle, providing benefits in accurate mass spectroscopy[45] and Raman spectroscopy[30] with specific cases for algae,[47] blood cells,[29] or droplet aggregations.[32] In general, acoustic levitation is a useful and versatile tool in biomaterials research[43] and chemistry[31] and enables lab-on-a-drop procedures.[28]

The most common arrangement for acoustic levitators is a single-axis configuration[46] for which there are two main types. The first is based on an acoustic transducer and a reflector, the separation distance and geometry of which are typically designed to act as a resonant cavity. On the other hand, non-resonant levitators can be made using two separated and opposite emitters. Resonant devices are more efficient but are sensitive to changes in temperature and arrangement of the elements. Both resonant and non-resonant levitators are driven with a sinusoidal excitation signal to generate a standing wave between their elements; this standing wave will trap particles at its nodes.

For resonant levitators, it was shown that a concave reflector produced stronger trapping forces than a planar one[27] and that using a large radiation plate attached to the front of the emitter provided more stability[40] allowing the levitation of liquids and study of samples in microgravity; these results have been validated in later research.[48,50] Using a concave emitter increased significantly the efficiency of the levitators,[1] by locally concentrating the acoustic energy. However, a change in temperature affects the speed of sound and thus detunes the resonance and reduces trapping strength;[51] also

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introducing large samples in the levitator can shift its resonant frequency,[44] leading to the need to adjust the system (e.g., the cavity size or excitation signal). Also, non-linear behaviours such as second harmonic generation can reduce the trapping force of resonant levitators.[2] For improving the adaptability of emitter-reflector levitators, a morphing reflector made of water or elastic materials has been demonstrated.[13,16]

Researchers employ non-resonant systems for versatile and more stable levitators. These systems are typically composed of two emitters opposed to each other.[42] Using this approach, a levitator with an operating temperature range of −40 to +40 °C was developed that required no calibration for the separation of the opposed emitters.

All these previous levitators are based on single or opposed pairs of Langevin horns which are made of piezoelectric disks clamped between a backing material and a resonating horn.[20] They have the advantage of supporting high-voltages (typically 100-1000 V) leading to the generation of high acoustic pressures with a single emitter. However, they have several disadvantages that limit the widespread use of acoustic levitation. First, Langevin horns are hard to tune to a specific resonant frequency, for instance, Weber *et al.*[42] reported that dozens of horns were built and then the two with the closest frequency were picked. Second, the high-voltage required to drive them is potentially dangerous. Third, as Langevin horns typically heat up due to transduction inefficiency and their resonant behaviour is sensitive to temperature, they must be left to "warm-up" prior to operation and lose power after intense functioning.

On the other hand, phased arrays made of hundreds of ultrasonic transducers have been demonstrated to levitate small electronic components.[25] However, their capability to levitate a wider range of liquids and solids is still unproven and current phased-arrays require complex custom electronics available only to a few research laboratories.[17,21,25]

Here, we present TinyLev, a single-axis non-resonant levitator made with off-the-shelf low-cost components (Fig. 1). This levitator produces stable trapping, is robust to changes in temperature and humidity, functions with low-voltage, is easy to operate, and can operate for extended periods of time. Instead of using one or two Langevin horns, we use 72 simple ultrasonic emitters. This is analogous to the translation from a single powerful lamp to an array of light-emitting diodes (LEDs) that is now seen in, e.g., traffic lights, projectors, and spotlights to make devices durable, inexpensive, and reliable. In the sections titled Design and Results, we show the procedures followed to design TinyLev and evaluate its performance.

## DESIGN

We will describe the design considerations for making a single-axis levitator using an array of small ultrasonic emitters. First, we analyse the available transducers which are the elements that transform the electric signal into acoustic power. Second, we study how to spatially arrange the transducers to maximize trapping forces and the number of traps as well as reducing parasitic reflections. Third, we present simple and effective electronics to drive the transducers.

### Field and force simulations

For simulating the generated complex acoustic pressure (i.e., amplitude and phase) emitted by each transducer, we used the piston source model,[26] the contribution of each transducer in the array is then summed to obtain the total field. The force was calculated as the gradient of the Gor'kov potential.[15] More details of the method can be found in Sec. 1 of the supplementary material.

We note that there is an additional effect due to reflections that is not considered in this model but we consider that it can be ignored. To explore this assumption, a pulse-train of 4 cycles was generated on the top array; the amplitude measured in the bottom array had decayed to 86% (SD = 0.5%, 4 repetitions) after the first reflection on the top array (i.e., pulse emitted from the top, reflected on the bottom, reflected on the top, and measured at the bottom). The negligible influence of reflections is further supported by the good correspondence between the simulated and experimental levitation forces (Fig. 2), the small difference in current consumption at different phase differences between the top and bottom array (Sec. 2 of the supplementary material), and the ability to move the levitated
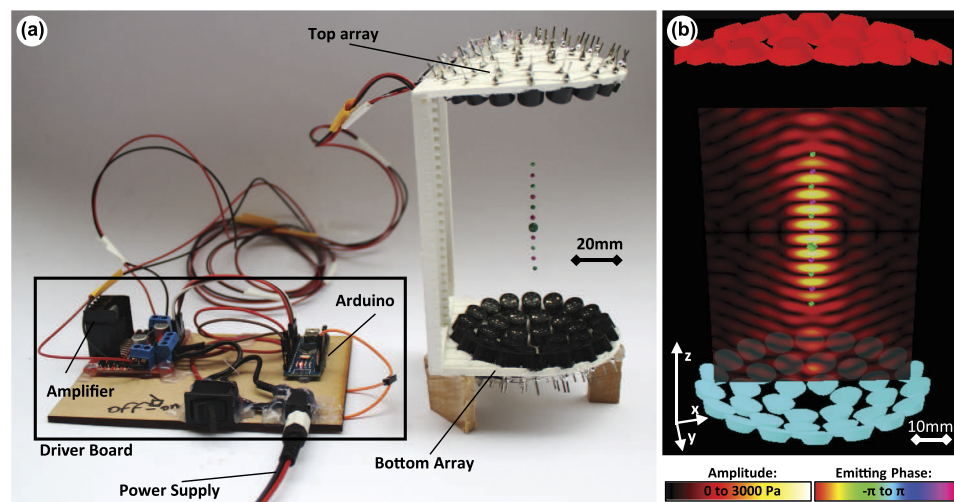
FIG. 1. (a) TinyLev system composed of the driver board and the single-axis levitator with 72 transducers (arranged as two surfaces, each containing 36 transducers). Expanded Polystyrene (EPS) particles are trapped at its nodes. (b) Simulated acoustic field; each circle represents a 10 mm diameter transducer and the colour represents the emitting phase of the transducers (two driving signals are required to produce vertical movement of the traps).
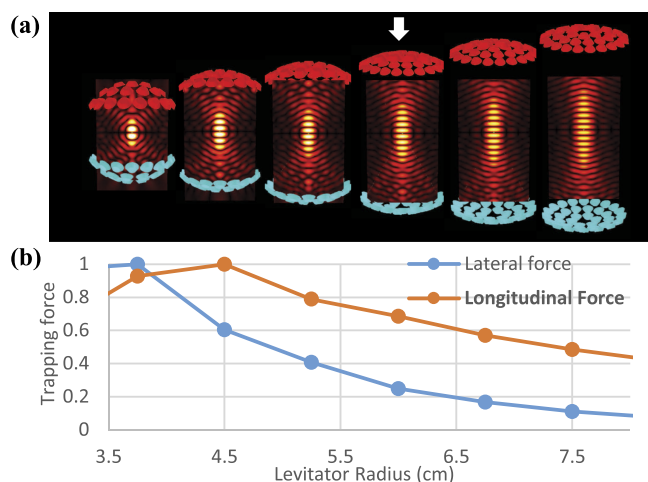
FIG. 2. Simulated trapping strength performance as a function of the array separation. Note that in all cases each array surface consists of 36 close-packed transducers and the surfaces are curved to achieve a central focus. (a) Maps of acoustic pressure for different array separations. The same colour scale is used for each separation. Each circle represents a 10 mm diameter transducer. (b) Trapping force as a function of array separation.

samples across several nodes (Movie 1 of the supplementary material).

## Transducers

The main components of the levitator are the transducers, elements that transform the electrical input signal into acoustic waves. For operating in air, transducers for distance measurement were found to provide good acoustic power, consistent resonant frequency, and are available at a low-price. Most of the commercially available transducers operate at 40 kHz. Air-borne acoustic waves at that frequency have a wavelength of 8.65 mm at 25 °C which allows the levitation of samples of up to ≈4 mm (half-wavelength).

We evaluated a selection of commercially available transducers and these are listed and evaluated in Sec. 2 of the supplementary material. The key factor measured was the pressure generated at a fixed distance under the same excitation signal. Another important measure is the standard deviation of the phase; transducers were found to output slightly off-set signals even if they were fed with the same signal and the acoustic pressure recorded at the same distance; this is probably due to manufacturing differences even within the same batch.

Most transducers we evaluated are available in either 10 mm or 16 mm diameter. We decided to concentrate on the 10 mm variants to reduce the experimental burden and produce a compact device. Murata transducers are the best option for 10 mm with the highest acoustic pressure levels and the smallest phase deviation; however, Ningbo or Manorshi 10 mm transducers minimise cost and would only incur in a 3% reduction in trapping force due to their phase deviation (SD = 14°). In Sec. 4 of the supplementary material, we show how the standard deviation of the phase (assuming a zero mean Gaussian random variation) affects the trapping force of the device shown in Fig. 1.

## Number of transducers

After exploring some of the possibilities, we decided to use 36 transducers at each side (72 in total) as a compromise between trapping force and cost/complexity. These transducers are arranged in rings of 6, 12, and 18 transducers which come from the optimal circle packing in a hexagonal pattern (Sec. 5 of the supplementary material); we removed the transducer in the centre to leave a hole for inserting a camera or injector and alternatively as an exit route for falling drops. As it will be seen later, this number of transducers generates enough force to levitate samples of interest and keeps the manufacturing process simple. More transducer can be added, and the next ring would consist of 24 transducers. However, whilst this will increase the trapping forces, it brings additional cost and complexity. Also, it makes the spherical cap on which the transducers are placed more closed, resulting in a more resonant device.

## Arrangement of the transducers

Langevin-horn levitators radiate sound from large surface area horns or curved reflectors that naturally focus the acoustic waves. In contrast, TinyLev is made of arrays of small transducers that achieve an acoustic focus by their orientation and distance. We analysed 4 focusing strategies as shown in Fig. 3. Laying the transducers in flat surfaces allows for a very simple construction, e.g., using a laser cut base-plate, but the trapping force is too low for most applications (i.e., 2% of the trapping force performance compared to the best configuration we explored). It is possible to focus the acoustic energy of an array by electronically adjusting the phase of the signals to increase the trapping force (i.e., 50%), but this approach requires complex electronics capable of producing many independent signals. It is also possible to introduce fixed physical phase-delays by placing the transducers at set
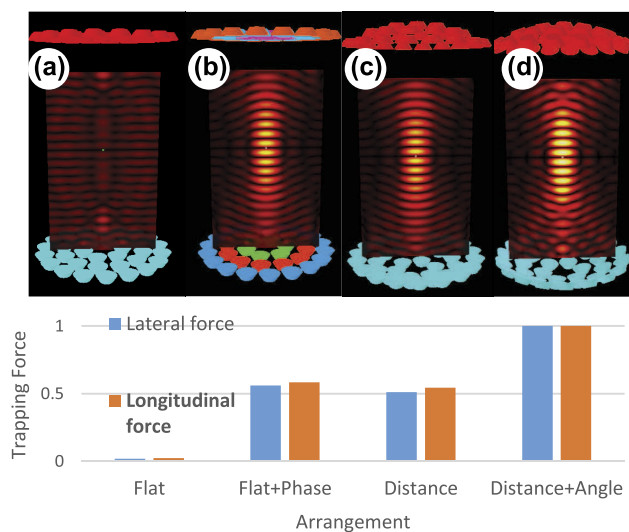


FIG. 3. Simulated effect of different focusing methods on the acoustic field: (a) no focusing, (b) electronic phase focusing, (c) focusing by distance offsets, (d) focusing by distance offset and transducer orientation angle. Scale is the same; each circle represents a 10 mm diameter transducer. (Bottom) Normalized trapping forces obtained with each arrangement.

vertical distances;[22] this strategy leads to the same performance as the electronic phase control approach. However, the best performing configuration is achieved by moving the transducers vertically to obtain the focusing effect, then orienting the transducers so that their normal points towards the focus. This final option ensures that a focus is achieved and the transducers insonify this focal point with maximum intensity.

The separation of the upper and lower array surfaces also affects the trapping forces that the device generates. In Fig. 2, we show how different array separations affect the generated forces. In each case, the array surfaces are curved to achieve a geometric focus in the centre of the cavity. This means that, as the array surface separation increases so does the radius of curvature of the arrays surfaces. Note that in all cases, the transducers are close-packed over each array surface. We found that spreading out the transducers to produce a larger array surface reduced the z-force trapping force and increased reflections, so this was not explored further. Note that the z-force needs to be the highest as it provides the levitation against gravity; the x and y forces may be smaller but are still important as they provide lateral stability.

To manufacture the frame in which the transducers are mounted, we analysed various options. We selected 3D printing since it easily allowed us to obtain accurate sockets for the transducers that fix their position and orientation angle. 3D printing the frame in one piece provides stability and simplicity. The only way of 3D printing the frame in one piece is laying it on the bed with the bowl-shaped array surfaces pointing upwards (Sec. 6 of the supplementary material). This restrains the curvature of the bowls as excessive overhang proved difficult to print. Although, the maximum longitudinal trapping force was obtained with an array surface radius of curvature of 4.5 cm, we selected the arrangement with 6 cm radius to minimize undesired reflections, overhang, and to obtain more functional traps. The realization of other arrangements can be seen in Sec. 7 of the supplementary material.

## Driving electronics

We use square waves as the excitation signal since they are somewhat easier to generate digitally compared to sinusoidal waves. We note that exciting air-borne ultrasound transducers with square waves is a common practice;[21,33] since the transducers have a resonant behaviour, they act as notch filters and the output is near-sinusoidal. In Sec. 8 of the supplementary material, we show the excitation signal and the corresponding transducer output for both a sinusoidal and the square wave driver excitation signal.

We used an Arduino Nano to generate the square wave signals and a L297N Dual H-Bridge motor driver to amplify the signals. We use a push-pull configuration so the peak-to-peak voltage that the transducers receive is double the input voltage. The electronics can drive two channels with up to 70 Vpp and a phase resolution of $\pi/12$. One channel is kept at a constant phase, while the other channel's phase can be shifted to move the trapped particles upwards or downwards. Further details on the circuits are provided in Sec. 9 and Movie 1 of the supplementary material.

## RESULTS

### Trapping force

The main performance measure of the levitator is the maximum density of the particles that it can levitate. If the particles are in the Rayleigh regime (i.e., smaller than half the wavelength), then the trapping force is proportional to the volume so only the density limits the samples that can be levitated. Samples were placed in the levitator and the voltage of the excitation signal reduced until the sample fell from the trap. In Fig. 4, we show the required voltage for samples of different densities, i.e., isopropyl alcohol (0.79 g/cm$^3$), water (1 g/cm$^3$), sugar (1.5 g/cm$^3$), and fused silica (2.2 g/cm$^3$).

Denser objects were levitated (Sec. 10 of the supplementary material), i.e., moulding sand (1.76 g/cm$^3$), Blu Tack (2 g/cm$^3$), pieces of ceramic (2.4 g/cm$^3$), SOIC8 MOSFET (3 g/cm$^3$), and sapphire spheres (3.9 g/cm$^3$). However, the agreement between the simulations and experiments decreased notably. We hypothesized that this was caused because the shape of the objects was irregular, the transducers were operating above its 20 Vpp maximum (i.e., outside the linear voltage-to-amplitude regime), and some of the samples were sound absorbers. Some of the levitated samples are shown in Fig. 5.
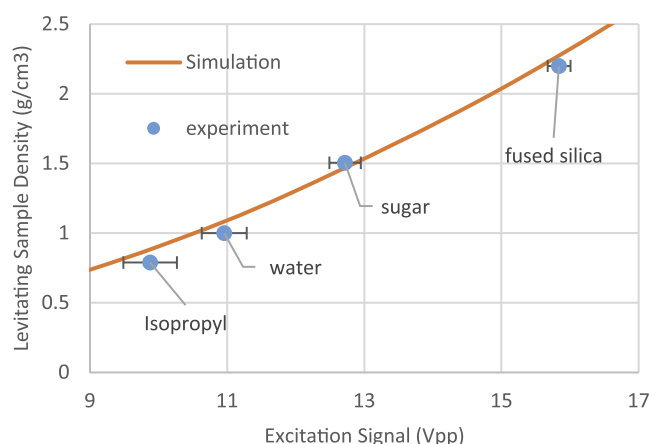


FIG. 4. Minimum excitation voltage for levitating samples of different densities. Error bars represent standard deviation measured over 4 drop tests.
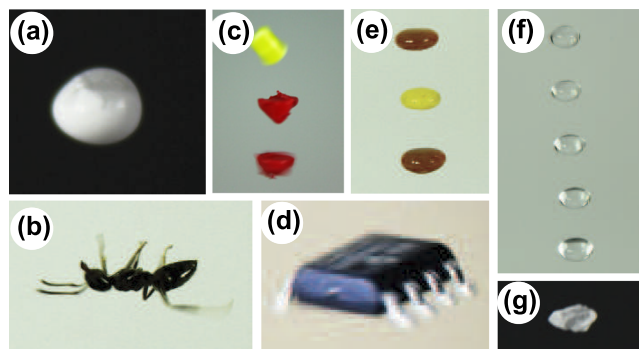


FIG. 5. Levitated samples using TinyLev. (a) A 40 $\mu$l supersaturated solution of isopropyl and tin dioxide, 2.5 mm in diameter. (b) Ant, 6 mm long without the antennas. (c) Polylactic acid, 2 mm width fragments. (d) MOSFET TC4427, 5 × 1.45 × 3.85 mm. (e) Ketchup and mustard, 3 mm wide. (f) Water, 3 mm wide. (g) Sugar crystal, 1 mm wide.

A scaled-up version of TinyLev (i.e., BigLev) which was 160% larger and used 16 mm transducers can levitate samples of up to 6.5 g/cm$^3$ (Fig. 7.2 of the supplementary material).

### Robustness of the levitator

Tests with the levitator showed that it is easy to use and operates effectively from the time of switch on over sustained periods. Continuous levitation of solutions for more than 2 h is shown in Sec. 11 of the supplementary material, with experiments measuring the evaporation rate of sugary water and jelly. We placed a soldering iron (350 °C) at 5 mm from the sample for 10 min and the sample remained stably trapped; this shows robustness against local temperature changes in the air; also, it was possible to form droplets with an ultrasonic mister pointed towards the levitation area demonstrating tolerance to humidity (Sec. 12 of the supplementary material).

### CONCLUSION

We have presented TinyLev, a single-axis non-resonant acoustic levitator capable of holding samples of interest in mid-air. The difference with previous work is that it is made of an array of multiple small transducers instead of one or two Langevin horns. This reduces sensitivity to temperature, lowers the required voltage levels, and simplifies the manufacture process so that anyone can manufacture it using readily available components. Furthermore, it extends the levitation time enabling experiments that were complicated to execute before. We believe that this work is a democratization of acoustic levitation, a technology with enormous potential for multitude of applications (e.g., biotechnology, chemistry, or spectroscopy) but previously constrained to a few research labs. We hope that TinyLev helps more research labs or schools to have access to acoustic levitation or even make it a standard science experiment demonstration.

### SUPPLEMENTARY MATERIAL

See supplementary material for a document with the model for the pressure and the force, the power consumption of the system, the transducers' analysis, the phase deviation effects on the trapping force, the transducers' packing, the placement of the pieces on the 3D printer, other arrangements that were created, transducers' response to different excitation signals, the driving board circuit, the dropping test for other samples, an evaporation test, and a robustness test for humidity as well as temperature change. A video with instructions of how to assemble and operate the levitator is also attached. Finally, a zip file contains the 3D models (STL files) and the source code for the Arduino.

### ACKNOWLEDGMENTS

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