# LeviPrint: Contactless Fabrication using Full Acoustic Trappingof Elongated Parts.


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## ABSTRACT

*LeviPrint* is a system for assembling objects in a contactless manner using acoustic levitation. We explore a set of optimum acoustic fields that enables full trapping in position and orientation of elongated objects such as sticks. We then evaluate the capabilities of different ultrasonic levitators to dynamically manipulate these elongated objects. The combination of novel optimization algorithms and levitators enable the manipulation of sticks, beads and droplets to fabricate complex objects. A system prototype composed of a robot arm and a levitator is tested for different fabrication processes. We highlight the reduction of cross-contamination and the capability of building on top of objects from different angles as well as inside closed spaces. We hope that this technique inspires novel fabrication techniques and that reaches fields such as microfabrication of electromechanical components or even in-vivo additive manufacturing.



## CCS CONCEPTS

• **Hardware** → *Emerging architectures*; • **Applied computing** → *Computer-aided design*.

## KEYWORDS

acoustic levitation, additive manufacturing, contactless manipulation, robot arm, end-effector

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## 1 INTRODUCTION

Fabrication in the form of assembly or additive manufacturing has evolved considerably due to its combination with computer systems, novel actuators and end-effectors. Additive manufacturing has been booming since the last decade, it will not only be used to fabricate objects by the Maker community but also in the aeronautical, automobile, and medical sector for prosthetic as well as tissue engineering. Manufacturing is usually complemented with assembly, which is the placement of the parts that compose the final object, a common example is the pick&place of electronic components on a printed circuit board (PCB).

Across ordinary assembly and manufacturing techniques, a common characteristic is that the parts or materials that are manipulated or dispensed are in direct contact with the machine. Consequently, special equipment is required to manipulate small or fragile components, and the handling of liquids, powders or hot materials is challenging. Furthermore, contact-based processes inherently lead to cross-contamination, so when dangerous materials or bio-materials are employed, it is necessary to have multiple manipulators or sterilise them between the changes of materials.

We propose to use acoustic manipulation as a contactless way of distributing materials in additive manufacturing as well as placing and orientating parts in assembly processes. Thereby, it is possible to manipulate small and fragile parts as well as liquids or powders, bringing more versatility to the processes. There is less cross-contamination since the manipulator does not touch the parts or material. Moreover, it enables manufacturing scenarios not achievable with traditional 3D printing, such as threading through cavities or adding to the manufactured item on any direction.

Levitation and manipulation of small particles and droplets have been achieved before but never combined in a full prototype for contactless fabrication. Furthermore, there is no existing work on how to trap in position and orientation elongated objects, this would open new possibilities in contactless manufacturing since beams, sticks or girders are vital for the rapid fabrication of robust and lightweight structures.

In this article, we introduce *LeviPrint* a method to generate acoustic fields that fully trap small particles, droplets and, more importantly, manipulate and reorient elongated bodies such as sticks. Also we present a fully working system to fabricate 3D structures using contactless manipulation. The novel contributions are:

- *A method to optimally trap a stick*. We analyze different acoustic fields in terms of their capability to trap in position and orientation an elongated object.
- *Levitators capabilities*. A study of the capabilities for dynamic orientation of elongated objects inside different acoustic levitators.
- *A Contactless Fabrication System*. An integration of an acoustic levitator, mechanical translator and droplet injector to realize a working prototype.

In section 2, we analyze the existing research regarding the capabilities and uses of acoustic levitation for fabrication. Section 3 summarizes the main models employed to simulate the acoustic field generated by phased arrays and the forces that they exert on objects. In section 4, we evaluate different methods to generate acoustic fields to fully trap a stick. Section 5 presents the dynamic manipulation capabilities of various levitators using the selected method. In section 6, we combine the insights from the previous sections to build a prototype that enables contactless fabrication mixing liquids, particles and sticks. In the next section (7), we showcase some of the structures build with the system. Finally, in section 8, we discuss limitations and future work.

## 2 RELATED WORK

In this section, we review the manipulation capabilities of ultrasound and its uses in fabrication. We note that acoustic levitation still lacks the capability of moving and orienting thin elongated objects larger than the wavelength of sound. Also, integrated prototypes that combine the required processes for fabrication (injection, manipulation and fusing mechanism) have not been developed.

### 2.1 Fabrication: Assembly and Additive Manufacturing

Assembly can be defined as the process of picking the parts that compose an object and placing them with the correct orientation and position. This process can be observed at multiple scales; a crane will position the girders for a building [Shapiro and Shapiro 1988], robot arms will position components of a car [Marvel et al. 2018] and pick&place machines will pick electronic components and place them on a PCB [Baby et al. 2017].

Additive manufacturing is defined as adding material layer by layer into a final object. This is opposed to carving or milling, in which parts from a block of material are removed to create the final object. Multiple innovations have been added to additive manufacturing to enable multiple colors, the use of less support structure, better layer distribution or non-planar 3d-printing [Dai et al. 2018; Etienne et al. 2019; Hornus et al. 2020; Song et al. 2019]. However, these techniques rely on direct contact between the dispenser (e.g., nozzle) and the objects that are being built. We reckon that acoustic manipulation could be employed to create a contactless system.

### 2.2 Acoustic Manipulation

Acoustic Manipulation has the potential to become a fundamental tool in contactless processing [Foresti et al. 2013], given: the wide range of particles that can be manipulated for a given operating frequency (from the micrometre to the centimeter scale), materials (plastic, metal or liquids), relative-high strength (larger ratio of input power to radiation force) when compared with optical trapping, and non-damaging effects on the trapped samples [Marzo et al. 2017].

Particles inside an acoustic field are subjected to radiation forces [Bruus 2012; Gor'kov 1962; Karlsen and Bruus 2015], it is possible to design the fields so that these forces converge from all directions into a point in which the particles get trapped [Brandt 2001]. In the most basic configuration, an emitter opposed to a reflector creates a standing wave and particles are trapped at its nodes [Whymark 1975]. More complex arrangements allow for dynamic control of the trapped particles.

The acoustic field can be dynamically modified by adjusting the phase or amplitude of the emitters, this allows to move particles in 3D using 4 opposed arrays [Ochiai et al. 2014], this was simplified to two-opposed arrays [Omirou et al. 2015] and later to a single array by using acoustic tractor beams [Marzo et al. 2015]. However, acoustic tractor beams have trapping forces which are 8 times weaker than regular standing waves [Marzo 2020], limiting its applications. With the introduction of holographic methods, it was possible to acoustically levitate multiple particles independently [Marzo and Drinkwater 2019; Plasencia et al. 2020].

In most levitation methods, the particles are smaller than half of the wavelength of the employed sound frequency [Zang et al. 2017]. Near-field levitation allows to levitate larger particles very close to the acoustic emitter [Andrade et al. 2017]. Also, virtual vortices [Marzo et al. 2018a] and other exotic fields [Inoue et al. 2019] can levitate larger-than-wavelength objects, but with limited force and no dynamic capabilities. We do not consider levitation of solid large objects (larger than the wavelength) particularly useful for fabrication since they are not stable, occlude too much the acoustic field, and do not allow for complex designs with fine pieces.

A more interesting manipulation capability for fabrication would be the control of the orientation of elongated objects. We note that many fabricated items use beams, sticks or girders as building primitives for the fast creation of strong and light structures. Ultrasonic arrays are capable of 2D translation and rotation along one axis of toothpicks [Foresti et al. 2013]. Sub-wavelength asymmetric particles can be fully locked [Cox et al. 2018] and controllably rotated when enclosed inside a sphere of emitters [Helander et al. 2020] but not translated. However, there is no existing technique to fully trap an elongated object enabling its reorientation and its repositioning. Consequently, we propose different novel methods (Section 4) to fully trap a stick in 6DoF and we compare them with a traditional tweezers method [Marzo and Drinkwater 2019]. This would allow a contactless system to employ segments as a building primitive.

### 2.3 Acoustic Fabrication

Using levitated particles as graphic representations is an emerging field [Fushimi et al. 2019; Marzo and Drinkwater 2019; Ochiai et al. 2014; Suzuki et al. 2021] but the use of acoustic levitation in fabrication has not been that thoroughly explored. Acoustic Manipulation has been used to pattern cells [Collins et al. 2015], aerosols and small particles [Shapiro et al. 2021] in simple 2D patterns. Melde et al.[K et al. 2016] used a static holographic plate to form more complex 2D patterns of particles that were fused together [K et al. 2018]. In these methods, the fabrication result is a 2D pattern that gets formed as a whole because small particles follow the distribution of the acoustic field. We classify this as 2D printing and not 3D fabrication.

Primitives such as beads, threads, and fabrics have been levitated [Fender et al. 2021; Morales et al. 2019]. However, in all these cases, spherical particles were used as levitated buoys in which acoustically transparent fabric was attached. This limits the materials, shapes, rigidity and in general the possibility of having an additive process.

Automatic injection of droplets inside a levitation system has been shown [Andrade et al. 2018], also a static levitator was attached to a robot arm to translate sub-wavelength particles in a contactless way [Röthlisberger et al. 2021]. However, no system integrates insertion, manipulation and fusing of droplets or sub-wavelength particles; moreover, there is no possibility of working with elongated parts. One patent from Boing (United States) [Harkness and Goldschmid 2018] and another from Neurotechnology Ultrasound (Lithuania) [Putkis 2018] present the idea of a contactless manufacturing systems, yet no full realization is shown, they present the concept.

Optical tweezers have been used to manipulate micrometric spheres to create microstructures [Sinclair et al. 2004]. A prototype was capable of moving spherical particles and stacking them together using biotin [Kirkham et al. 2015]. However, optical tweezers are limited to micrometric sizes. We note that the methods from optics are not trivially adapted to acoustic manipulation because in optics, a focus on the particle is sufficient for trapping whereas in acoustics more complex structured fields are required [Marzo and Drinkwater 2019].

The working methods presented in Section 4 to fully trap and rotate sticks are novel contributions, there is no previous work describing and showing a method to fully trap an elongated object.

## 3 MODELS

In this section, we define the models employed in this work and the common physical definitions that will be used throughout it.

### 3.1 The Emitted Complex Acoustic Field

The piston model is employed [O'Neil 1949] to calculate the complex acoustic field generated by a single emitter that has a radiating part in the shape of a piston vibrating at a single frequency. In the complex pressure, the magnitude represents the amplitude and the angle, the phase. An ultrasonic phased array is formed by multiple emitters operating at the same frequency and varying their amplitude and phase in a controlled way. The total field generated by an array of $n$ emitters is the addition of their emitted fields:

$$P(x) = \sum_{i=1}^{n} \frac{P_0 J_0 (kr \sin \theta_i)}{d_i} e^{i(\varphi_i + k d_i)}, \tag{1}$$

where $P_0$ is the amplitude power of the transducer, defined by its efficiency and driving voltage amplitude. $J_0$ is the Bessel function of order zero. $k = 2\pi/\lambda$ is the wavenumber and $\lambda$ is the wavelength. $r$ is the radius of the piston, $d_i$ is the distance from the emitter $i$ to the point $x$ in space. $\theta_i$ is the angle between the normal of the emitter and the transducer to point $x$ vector.

This models is commonly used and implemented in various frameworks [Marzo et al. 2018b], it is designed to work in open space where there are no large obstacles in the field. In this paper, the trapped particles and structures being built do not affect significantly the acoustic field since they are not fully solid. An analysis of the effect of occlusions on the trapping force can be find in Supplementary Information 1.

### 3.2 Potential, Radiation Forces and Stiffness

The Gor'kov potential approximates the radiation forces exerted on a small sphere that is inside an arbitrary acoustic field. It can be defined in terms of the complex acoustic pressure $p$ and its spatial derivatives $p_x$, $p_y$ and $p_z$. The Gor'kov potential $U$ is given by:

$$U = K_1 \left(|p|^2\right) - K_2 \left(|p_x|^2 + |p_y|^2 + |p_z|^2\right)$$
$$K_1 = \frac{1}{4} V \left(\frac{1}{c_0^2 \rho_0} - \frac{1}{c_p^2 \rho_p}\right) \tag{2}$$
$$K_2 = \frac{3}{4} V \left(\frac{\rho_0 - \rho_p}{\omega^2 \rho_0 \left(\rho_0 + 2\rho_p\right)}\right).$$

The volume of the spherical particle is $V$, $\omega$ is the angular frequency of the emitted waves, and $c$ and $\rho$ are the speed of sound and the density, respectively. Their subindex 0 and $p$ refer to the propagation medium and the particle material.

The lower the potential is at a position, the stronger the object will be trapped there. In general, the potential can be visualized as a heightmap and thus minima in the field represent wells where the particles will roll in and get trapped. The radiation force acting on a particle can be obtained from the gradient of the potential:

$$\mathrm{F} = -\nabla U. \tag{3}$$

Another measure of strength of a trapping position is the positional stiffness, which represents how converging the forces are at that position. The Laplacian operator (convergence of the gradient) can be applied to the potential to get a mathematical representation of the stiffness.

$$stiffness = \nabla^2 U = U_{xx} + U_{yy} + U_{zz}, \tag{4}$$

where $U_{aa} = \frac{\partial^2 U}{\partial a^2}$ and $a = x, y, z$ are the Cartesian axes. Large positive values of stiffness represent large converging forces.

### 3.3 Torques and Rotational Stiffness on Elongated Objects

In Supplementary Information 2, we show that the torque and forces acting on a stick can be approximated as the summation of the forces or torques acting on constituent spheres. Potential, forces and stiffness are linear functions of each other, therefore our sphere decomposition approximation can be applied to them. We performed a converging analysis to determine that decomposing the stick into small spheres separated by $\lambda/8$ is sufficient.

When the acoustic field acts on a stick, there is a torque that will affect the orientation. We calculate the torque as the addition of the torques exerted on each constituent sphere. The torque from a sphere is the cross product between the force on that sphere and the vector that joins the sphere to the center of mass of the object:

$$\tau = \mathrm{r} \times \mathrm{F}, \tag{5}$$

where r is the positional vector from the location where the force is applied and F is the force acting on that part of the object. The rotational stiffness can be obtained by differentiating the torque on small rotations of the stick.

## 3.4 Summary

Potential, Force, Positional Stiffness, Torque and Rotational Stiffness will be used throughout the paper to characterize the trapping on an object. These properties were calculated on the simulations but only the most informative ones will be reported. Potential provides a basic measurement, the lower the better, it is not dimensional and gives information both for translation and orientation trapping. Forces should be analyzed along different positions of the objects, since the forces at the trap are 0 and push towards the trap, i.e., they become positive when the objects shifts towards negative positions and vice-versa. Positional stiffness represents the trapping force convergence with a single value, the higher the better, however it does not provide topological information such as the reach of the trap. Torque and rotational stiffness have similar features to force and positional stiffness respectively but acting on orientation instead of position.

# 4 FULLY TRAPPING A STICK

In this section, we derive and analyze algorithms that generate an acoustic field capable of fully trapping a stick inside an acoustic field. The stick has to be trapped in position (3 Dof) and orientation (3 DoF). All methods were evaluated attending to their trapping performance in position and orientation.

We analyzed levitators with different geometries (Fig. 1), they were composed of ultrasonic emitters of 1 cm diameter with the following parameters for Eq. 1: $r = 4.5$ mm and $P_0 = 2.4$, which correspond to a real existing emitter (e.g., model MA40S4S - Murata). The levitators were selected between the most common geometries in the literature for airborne acoustic levitation. Fixed two-opposed inspired by TinyLev [Marzo et al. 2017], two-opposed arrays of 16x16 emitters separated by 23 cm as in [Marzo and Drinkwater 2019; Morales et al. 2019; Suzuki et al. 2021], four orthogonal arrays in a cube formation as in [Ochiai et al. 2014]. We also tried with variations of the cube in the shape of a triangle, cylinder and sphere.

The trapping algorithms will determine the emission phases of the levitators in order to generate a field that traps the stick. The generated fields for the two-opposed levitator can be seen in Fig. 2, similar results were obtained for the other levitators. Similarly, others were designed and evaluated, we just selected the 4 most representative and effective ones. The methods are:

- **Trap at Center:** It is the trivial method of creating a standing wave focused at the center of the stick. It is the default method for trapping sub-wavelength particles. We do not expect it to be effective on a stick but the resulting forces and torques can be used as a baseline for comparison with the other methods.
- **Traps at Sides:** Two trapping nodes are generated at both sides of the stick. A modified Iterative Backpropagation (IBP) [Marzo and Drinkwater 2019] algorithm is employed to maximize amplitude in 2 pairs of focal points above and below the stick, with a phase difference of $\pi$ is forced between the first points of each pair. Thereby, high-amplitude is generated above and below the stick with low-amplitude at the stick. Whilst Marzo and Drinkwater [Marzo and Drinkwater 2019] optimized trapping strength on individual particles, this method traps an elongated body by creating two traps at its sides. The traps were offset 2.5mm towards the stick center, this was the optimum offset in terms of stiffness (see Supplementary Information 3).
- **Minimum Potential:** Employs an optimizer to find the emission phases that minimize the Gork'ov potential along the stick. If we simplify to 2D, this can be seen as digging a potential well with the shape of the object that should be trapped. A quasi-newton optimizer is employed with gradients approximated using finite differences. The parameters were the default ones from Matlab R2019 fminunc function (except, TolFun=0.0025, TolX=eps, MaxIters=30). The result can be interpreted as a strong trap at the center of the stick and two smaller ones at the sides. The target function can be expressed as:

$$SumGorkov(\varphi_1, \ldots, \varphi_N) = \sum_{i=1}^{P} \partial orkovAt\,(pos(i))$$

Where $\varphi_n$ is the emission phase of the $n$ transducer, $P$ is the number of points that form the stick, $pos$ is their position, and $\partial orkovAt$ is the Gork'ov potential at that point (Eq. 2).
- **Minimum Weighted Potential:** Similar to the previous method (Minimum Potential) but the 4 terms appearing in Gork'ov potential (Eq. 2) were weighted using the factors 0.09 for p, 15.01 for px, 8.34 for py and 7.66 for pz. These weights were obtained from the *Traps at Sides* method. The results in Figure 2.c shows that the method tries to fit as many traps as possible along the stick.

The forces and torques acting on a stick under the fields generated by the different methods can be seen in Fig. 3. The stick was 30 mm length, 2 mm width and 1 mm height and placed at the center of the levitator. Similar results were obtained for sticks between 2 wavelengths (1.6 cm) and a a length of 8 cm.

All the forces and torques but the Trap a center are converging since the force is 0 at the neutral position or angle, but become positive if the position or angle gets negative, and vice-versa. The steepness of the curves at the neutral position or angle, characterize the strength of the trap.

The most promising methods are Traps at Sides (TrapsAtSides) and Minimum Potential (MinPot), the rest of the methods were weaker on all of the axes, both in position and rotation. The trap at center (traditional standing wave) does not have the capability to trap along the x-position and the x-torque was marginal. The MinPot algorithm produces fields that are ~10% stronger in force-Y, force-Z and torque-X, however TrapsAtSides is ~25% stronger on force-X, torque-Y, and torque-Z.

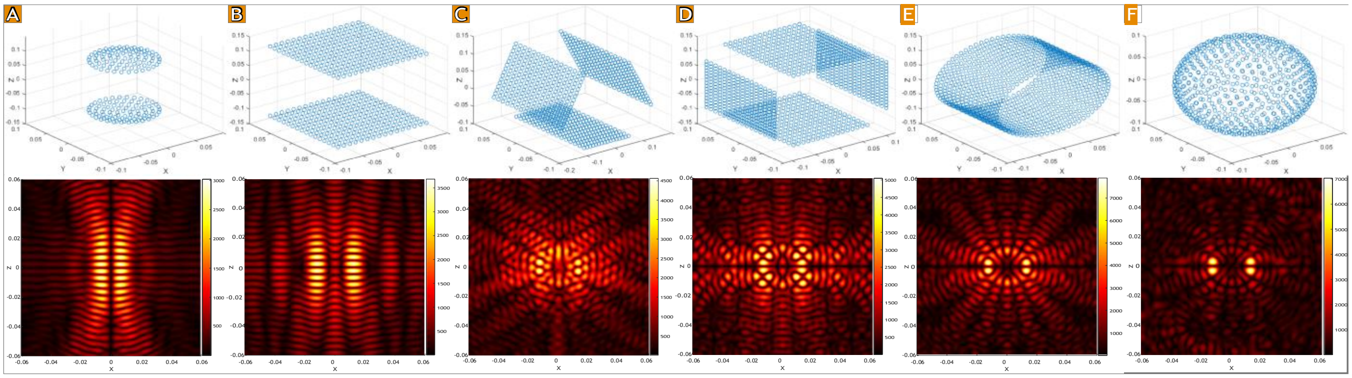

**Figure 1: Different simulated levitator geometries and a vertical slice of the pressure field that they generate when applying the TrapsAtSides method on a thin stick of 30 mm. A) Two-opposed fixed levitator. B) Two-opposed Levitator. C) Triangle levitator. D) Cube. E) Cylinder. F) Sphere.**

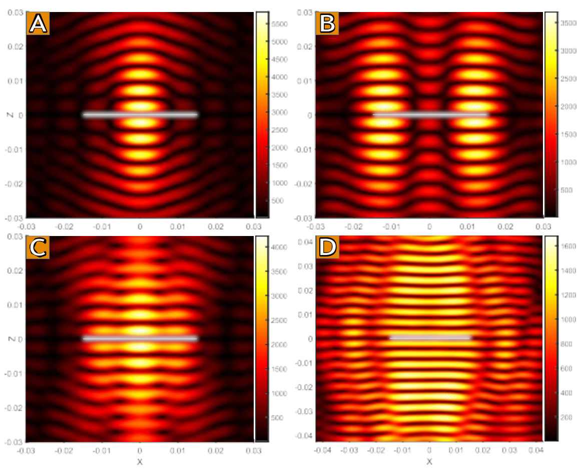

**Figure 2: Amplitude fields around a 30 mm stick for different trapping methods on the Two-opposed levitator. A) Trap at center, B) Traps at sides (2.5mm inward offset) C) Minimum Potential, D) Minimum Weighted Potential.**

TrapsAtSides provides the overall stronger trapping forces and torques. We also note that the fields obtained in TrapsAtSides can be generated by a fixed-levitator without phase control (Fig. 4) and is applicable to sticks of different lengths since the trapping positions are relative to the ends of the stick. Furthermore, it is based on an iterative method (IBP) and is computationally faster than the other methods based on traditional optimization.

We note that the problem of fully trapping a stick is multi-variable and required expert knowledge to analyze the results of the different methods: e.g., the forces and torques in Figure 3, potentials in 5, and stiffness in Supplementary Information 4.

## 5 MANIPULATION CAPABILITIES OF THE LEVITATORS

In the previous section, we have selected the TrapsAtSides method for generating fields that trap a stick in position and orientation. In this section we will analyze the capabilities of the levitators presented in Fig. 6 to orientate the sticks by changing their emission phases. For each levitator, a stick of 30 mm length, 2 mm width and 1 mm height was placed at the center. Then, it was rotated along each axis applying the trapping method at each step and calculating the potential on the stick.

The potentials while rotating (Fig. 5) indicate that all arrangements can rotate the stick around the Z-axis. The two-opposed levitator provides a good balance between manipulation capabilities and being open at the sides, it can rotate a stick around the Z-axis and in Y-axis with a limited angle~30 degrees. The cube arrangement provides full rotations around the Z- and Y-axis, being able to orient the sticks as needed in the piece, this is crucial to fabricate vertical structures and shorings, it just lacks the capability to fully rotate the stick around itself. The cylinder was not superior than the cube, it is more complex to fabricate and less uniform on the potentials along the rotations. The triangle arrangement is not a good alternative since it has less working volume than the cube and less manipulation capabilities. The sphere can orientate the stick around any axis with uniform potential but it is cumbersome to use in a fabrication system. Similar conclusions were derived from analyzing the positional and rotational stiffnes (See Supplementary Information 4).

## 6 SYSTEM PROTOTYPES

In this section, we combine the trapping and manipulation capabilities of an acoustic levitator with a mechanical manipulator that complements the levitator. Thereby, the manipulation of the stick is performed by the dynamic levitator in some DoFs whereas other DoFs are covered by the mechanical manipulator. We note that this control strategy can be easily integrated into the kinematic chains of most control software.

In section 5, we obtained the manipulation capabilities of different levitators, we have constructed the 3 most promising levitators 6 to experimentally realize the manipulations. The levitators were built using MA40S4S (Murata) emitters which are 1 cm in diameter and made of plastic, its parameters for Eq. 1 are $r$ = 4.5 mm and $P_0$ = 2.4 for a 15 Voltage peak-to-peak (Vpp) square excitation signal.

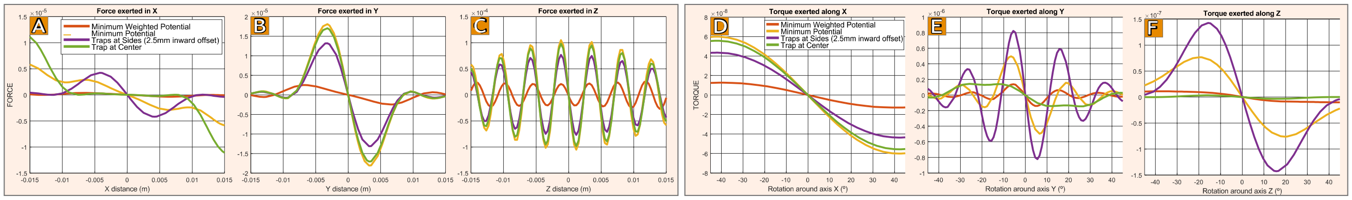


**Figure 3: Forces and torques exerted on a stick by the field generated by different methods: Minimum weighted potential, minimum Potential, Trap at side and Trap at center. A) Forces exerted in the X-Axis. B) Forces exerted in the Y-Axis. C) Forces exerted in the Z-Axis. D) Torque exerted in the X-Axis. E). Torque exerted in the Y-Axis. F) Torque exerted in the Z-Axis.**

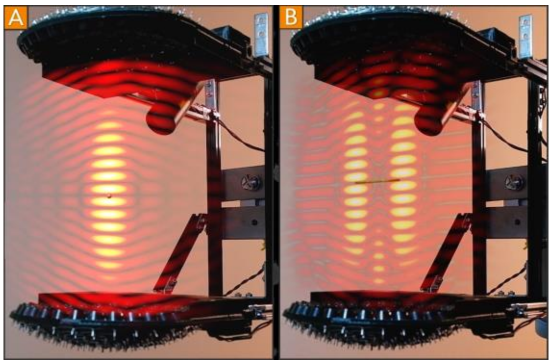

**Figure 4: Pressure fields generated by a fixed-levitator. A) a standing wave creates a trap for holding a single sub-wavelength particle when the emitters are driven with the same signal. B) TrapsAtSides are generated when a halve of the emitters is driven with an inverse polarity signal ($\pi$ phase), this field can fully trap a stick.**

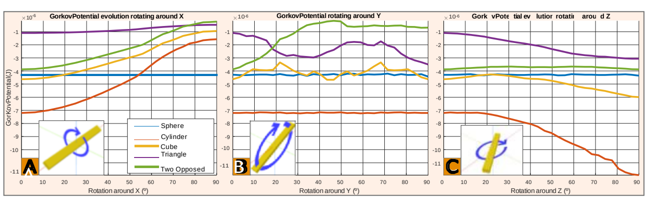


**Figure 5: Gor'kov potential on a stick inside different levitators applying the TrapsAtSides method as it rotates around a A) x-axis, B) y-axis, and C) z-axis. The stick is 30 mm long, 2 mm wide and 1 mm height.**

For larger operating voltages, $P_0$ scales linearly with the Vpp. The bowl design is based on TinyLev [Marzo et al. 2017]. The flat arrays are based on SonicSurface [Morales et al. 2021].

The basic operation of the fabrication prototypes is as follows. An acoustically transparent foundation is placed at the center of the working volume before starting the fabrication process, the foundation is the initial part where other parts or matter will be added. The system starts by trapping with the levitator a droplet of glue dispensed by a syringe pump. Then, the droplet is levitated into the position where the next piece is going to be added. The system picks sticks or particles from an acoustically-transparent

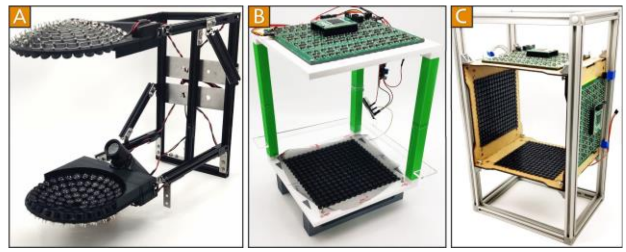

**Figure 6: Constructed levitators. A) a fixed single-axis levitator with bowl geometry. B) two-opposed flat phased-arrays. C) four orthogonal flat arrays in a cube structure.**

repository and positions them in contact with the previously placed glue, UV light is applied to cure the glue. This process is repeated for all the parts.

The main prototype is a fixed two-opposed levitator attached to a 7-DoF robot arm, a secondary prototype made of a a cube levitator mounted on a translation stage was tested, but the first prototype was easier to operate.

## 6.1 Two-opposed Fixed Levitator + Robot Arm

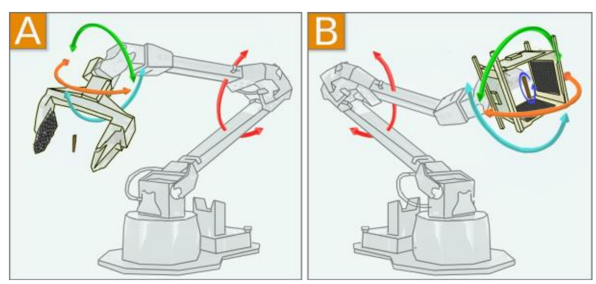

**Figure 7: Examples of levitators attached to a robotic arm to complement or boost their missing manipulation DoFs. A) Fixed single-axis levitator with bowl geometry. B) Four orthogonal flat arrays in a cube structure.**

A 7-DoF robotic arm (UR-3) is attached to a fixed two-opposed levitator (see Fig. 7.C). The fixed levitator is composed of two spherical arrays of 60 emitters each, with 4 concentric rings. It generates a field that traps the stick, using the Traps At Sides method from Section 4, see Fig. 4. A dynamic two-opposed levitator could also be used to add more DoFs to the levitator but for this system it was decided that the levitator would only be in charge of trapping and the robot arm would provide the manipulation DoFs. Alternatively, the fixed single-axis levitator can be held by a human to manually perform the steps involved in LeviPrint: trapping, releasing, translating, orientating and rotation.

### 6.2 Cube Levitator + Mechanical Stage

A cube levitator was attached to a translation stage. The levitator can orientate the stick to have the desired alignment as well as providing limited translation capabilities. The cube was attached to a mechanical translation stage that could provide larger ranges in the translation DoFs.

## 7 FABRICATION RESULTS

We illustrate the capabilities of *LeviPrint* by combining various building primitives such as sticks, beads and droplets to fabricate robust, lightweight and complex structures.

### 7.1 Basic Joints

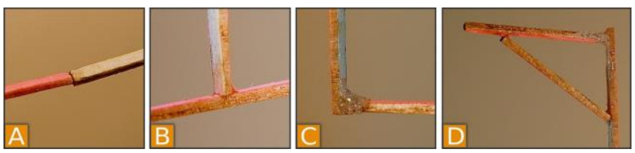


**Figure 8: Types of joints between sticks. A) Butt joint: Two sticks are connected end to end forming a longer segment. B) L-joint: Two sticks are connected end to end at 90 degrees, the angle can be adjusted, more glue should be used since the contact surface is small. C) T-joint. D) Mitered joint: An L-joint reinforced with a third stick connecting the L at 45 degrees.**

Joining sticks together is the main novel capability of *LeviPrint*. For doing so, a droplet of glue is levitated into the main object at the place where the next stick will be placed. The stick is then levitate to come in contact with the glue. UV light is applied to cure the glue. The types of joints can be seen in Fig. 8. We note that also beads can be used to connect sticks.

### 7.2 Fabricating with Particles

Instead of using sticks, only particles (a.k.a beads) are joined together using glue between them. The use of sub-wavelength spherical particles as the building parts enables more flexible designs in terms of shapes since they can be connected from anywhere. However, the process is longer since more parts are needed for the same length when compared to sticks, also the final result is denser and not necessarily stronger (Fig. 9.A).

### 7.3 Fabricating with UV Resin

UV-resin droplets can be used for manufacturing objects with free-form shapes. Droplets are repeatedly moved into its target position and cured until the final objects is formed. The droplets have a dish shape because of the pressure of the standing wave, the droplet can be oriented so that it is aligned with the building direction. We have manufactured a loop of 1cm diameter (see Fig. 9.B).

### 7.4 Complex Objects

The methods presented in the previous subsections can be combined to build more complex objects. We built a cube using orthogonally placed sticks via L joints, we also built a bridge connecting two separated metallic meshes, using different joints to provide a stronger structure (see Figs. 9.C and 9.E).

### 7.5 Adding on Top of Other Objects

Sticks, particles and droplets can be levitated on top of existing solid objects if they are approach from certain angles. The solid object cannot be directly located between the levitated part and the arrays since it would block a significant amount of the field. However, the solid object can be located in front of the levitated part without significantly disrupting the field. We showcase the addition of parts into a spherical object in Fig. 9.F.

### 7.6 Building Inside a Container

Fabric, meshes and sponges are acoustically translucent to the ultrasound field. Therefore, *LeviPrint* can fabricate inside containers made of these material, from the outside. In Fig. 9.D, we fabricate a boat inside a metallic mesh bottle. The sticks and glue are introduced inside the bottle through a small aperture at the side. In airborne Leviprint, the materials of the container are limited but if *LeviPrint* would be adapted to operate in aqueous media, it could assemble microscopic objects in cell-culture media and perhaps even inside living beings (See 9.D).

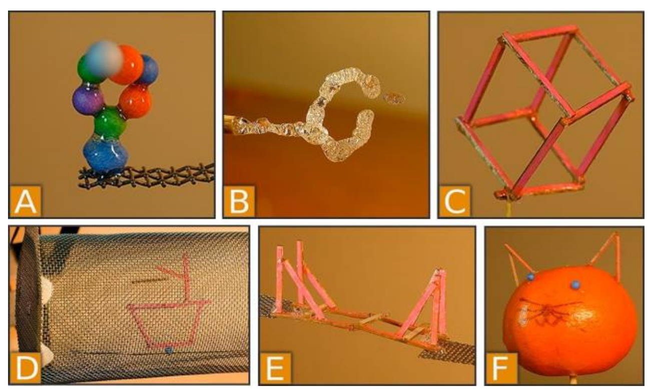


**Figure 9: Fabricated items. A) Particles joined together to build a loop. B) Glue droplets being levitated to its final position to be cured for building a loop. C) Twelve orthogonally placed sticks via L-joints to build a cube. D) A stick being levitated inside a container towards its final position. E) Fifteen sticks joined via butt joints, L joints and miter butt joints to form a bridge. F) Adding multiple primitives at different angles into a solid spherical object.**

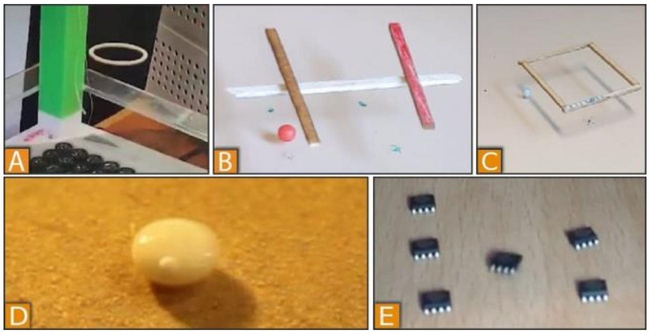


**Figure 10: Another primitives that have been successfully levitated using stick. A) A circle was hold in mid-air using the two-opposed levitator. B) An airplane created by three sticks, using an array on top of a reflective surface. C) a levitated square. D) droplet of milk on a hydrophobic surface. E) electronic components Soic8 levitating over a table.**

## 8 DISCUSSION

The individual steps involved in the results were conducted by a robot arm and an automatized software. The robot arm is programmed to perform the required movements to grab and place each primitive. However, for practicality reasons, on some occasions there was human intervention. We highlight that all the actions that were carried out manually could also have been performed by the programmed robotic arm, droplet dispenser and UV lamp.

Apart from sticks, we tested other primitives such as circles, squares, triangles and crosses. For these primitives, TrapsAtSides was not directly applicable and we employed the MinPot method. These primitives were levitated but we did not explore them since they can be composed with the basic primitives (see Fig.10. A-C).

The levitators presented here were based on various arrays facing each other. However, the developed methods are also applicable when a single array is placed on top of an acoustically reflective surface. The DoFs are limited to 1 DoF rotation and 2D translations at a plane located a a quarter wavelength above the surface. Printed circuit boards or functionalized substrates can be used as surfaces (see Fig.10.D and E).

Given that the fabricated structures are made of thin segments such as sticks, beads or cured glue, the fabricated object does not cause a significant disruption on the acoustic field since its "fill rate" is quite low (i.e., it is like a wireframe object). However, if complete solid objects were manufactured, we foresee two strategies that should be followed. First, the order in which the parts are added should be planned so that they approach the object from an operative angle that does not block significantly the ultrasound emitted from the arrays. As future work, it would also be possible to consider reflections caused by the object.

The emitters were driven at 70% of their maximum power so denser materials could be employed if a non-prototype system with extra cooling and electronics to handle more voltage was designed. The prototypes operated in air at 40 kHz, thus the wavelength $\lambda$=8.6mm determines the scale of the objects that can be manipulated, long sticks give flexibility in this regard. We reckon that decreasing the frequency to work with larger objects is not a feasible research direction; however, operating in water-based media at Mhz range would enable to control micrometric bio-structures on cell-friendly cultures and even in-vivo.

The maximum weight for sticks is that of 8 cm length of balsa wood (16 mg). The system can recover from external perturbations like shaking of the robot arm or weak wind since Acoustic levitation has converging forces and torques [Marzo et al. 2015]. The typical positioning accuracy is around 0.2 mm for levitating system operating at 40 kHz in air [Marzo et al. 2015], but moving into smaller wavelengths would increase this accuracy to the micrometres range [K et al. 2018]. Translation speeds vary from 1 cm/s [Marzo et al. 2015] to 8 m/s [Hirayama et al. 2019] for lighter particles, in our system the sticks were translated at up to 4 cm/s. We note that these limits are system-specific, systems operating at higher voltage, with less separation or working in water-based solutions instead of air would trap more weight, move faster or provide more accuracy.

## 9 CONCLUSION

*LeviPrint* is a technique for fabricating objects in a contactless way using acoustic levitation on primitives such as beads, sticks and droplets. We have presented an optimum acoustic field to trap elongated parts. Afterwards, we analyzed the capabilities of different levitators to allow dynamic manipulation of the stick by changing the emission phases. We designed a levitator integrated with a robotic arm to enable contactless fabrication of complex objects. We hope that the presented methods help other researchers to use acoustic contactless fabrication in other fields such as bioengineering or micro-fabricated machines, and in general that it broadens our concept of additive manufacturing.

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## REFERENCES

Marco AB Andrade, Thales SA Camargo, and Asier Marzo. 2018. Automatic contactless injection, transportation, merging, and ejection of droplets with a multifocal point acoustic levitator. *Review of Scientific Instruments* 89, 12 (2018), 125105.

Marco AB Andrade, Fábio TA Okina, Anne L Bernassau, and Julio C Adamowski. 2017. Acoustic levitation of an object larger than the acoustic wavelength. *The Journal of the Acoustical Society of America* 141, 6 (2017), 4148–4154.

Ashly Baby, Chinnu Augustine, Chinnu Thampi, Maria George, Abhilash AP, and Philip C Jose. 2017. Pick and place robotic arm implementation using Arduino. *IOSR Journal of Electrical and Electronics Engineering* 12, 2 (2017).

E H Brandt. 2001. Suspended by sound. *Nature* 413, 6855 (2001), 474–475. https://doi.org/10.1038/35097192

Henrik Bruus. 2012. Acoustofluidics 7: The acoustic radiation force on small particles. *Lab Chip* 12 (2012), 1014–1021. Issue 6. https://doi.org/10.1039/C2LC21068A

David J Collins, Belinda Morahan, Jose Garcia-Bustos, Christian Doerig, Magdalena Plebanski, and Adrian Neild. 2015. Two-dimensional single-cell patterning with one cell per well driven by surface acoustic waves. *Nature communications* 6, 1 (2015), 1–11.

L. Cox, A. Croxford, B. W. Drinkwater, and A. Marzo. 2018. Acoustic Lock: Position and orientation trapping of non-spherical sub-wavelength particles in mid-air using a single-axis acoustic levitator. *Applied Physics Letters* 113, 5 (2018), 054101. https://doi.org/10.1063/1.5042518 arXiv:https://doi.org/10.1063/1.5042518

Chengkai Dai, Charlie CL Wang, Chenming Wu, Sylvain Lefebvre, Guoxin Fang, and Yong-Jin Liu. 2018. Support-free volume printing by multi-axis motion. *ACM Transactions on Graphics (TOG)* 37, 4 (2018), 1–14.

Jimmy Etienne, Nicolas Ray, Daniele Panozzo, Samuel Hornus, Charlie CL Wang, Jonàs Martínez, Sara McMains, Marc Alexa, Brian Wyvill, and Sylvain Lefebvre. 2019. CurviSlicer: Slightly curved slicing for 3-axis printers. *ACM Transactions on Graphics (TOG)* 38, 4 (2019), 1–11.

Andreas Rene Fender, Diego Martinez Plasencia, and Sriram Subramanian. 2021. ArticuLev: An Integrated Self-Assembly Pipeline for Articulated Multi-Bead Levitation Primitives. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. 1–12.

Daniele Foresti, Majid Nabavi, Aldo Klingauf, and Dimos Poulikakos. 2013. Acoustophoretic contactless transport and handling of matter in air. *Proceedings of the National Academy of Sciences* 110, 31 (2013), 12549–12554.

Tatsuki Fushimi, Asier Marzo, Bruce W Drinkwater, and Thomas L Hill. 2019. Acoustophoretic volumetric displays using a fast-moving levitated particle. *Applied Physics Letters* 115, 6 (2019), 064101.

Lev P. Gor'kov. 1962. On the forces acting on a small particle in an acoustical field in an ideal fluid.

William A Harkness and Josh H Goldschmid. 2018. Free-form spatial 3-D printing using part levitation. US Patent 9,908,288.

Petteri Helander, Tuomas Puranen, Antti Meriläinen, Göran Maconi, Antti Penttilä, M Gritsevich, Ivan Kassamakov, Ari Salmi, Karri Muinonen, and Edward Haeggström. 2020. Omnidirectional microscopy by ultrasonic sample control. *Applied Physics Letters* 116, 19 (2020), 194101.

Ryuji Hirayama, Diego Martinez Plasencia, Nobuyuki Masuda, and Sriram Subramanian. 2019. A volumetric display for visual, tactile and audio presentation using acoustic trapping. *Nature* 575, 7782 (2019), 320–323. https://doi.org/10.1038/s41586-019-1739-5

Samuel Hornus, Tim Kuipers, Olivier Devillers, Monique Teillaud, Jonàs Martínez, Marc Glisse, Sylvain Lazard, and Sylvain Lefebvre. 2020. Variable-width contouring for Additive Manufacturing. *ACM Transactions on Graphics (TOG)* 39, 4 (2020), 131–1.

Seki Inoue, Shinichi Mogami, Tomohiro Ichiyama, Akihito Noda, Yasutoshi Makino, and Hiroyuki Shinoda. 2019. Acoustical boundary hologram for macroscopic rigid-body levitation. *The Journal of the Acoustical Society of America* 145, 1 (2019), 328–337.

Melde K, Mark AG, Qiu T, and Fischer P. 2016. Holograms for acoustics. *Nature*, 518–22.

Melde K, Choi E, Wu Z, Palagi S, and Fischer P Qiu T. 2018. Acoustic Fabrication via the Assembly and Fusion of Particles. *Adv Mater*.

Jonas T. Karlsen and Henrik Bruus. 2015. Forces acting on a small particle in an acoustical field in a thermoviscous fluid. *Phys. Rev. E* 92 (Oct 2015), 043010. Issue 4. https://doi.org/10.1103/PhysRevE.92.043010

Glen R Kirkham, Emily Britchford, Thomas Upton, James Ware, Graham M Gibson, Yannick Devaud, Martin Ehrbar, Miles Padgett, Stephanie Allen, Lee D Buttery, et al. 2015. Precision assembly of complex cellular microenvironments using holographic optical tweezers. *Scientific reports* 5, 1 (2015), 1–7.

Jeremy A Marvel, Roger Bostelman, and Joe Falco. 2018. Multi-robot assembly strategies and metrics. *ACM Computing Surveys (CSUR)* 51, 1 (2018), 1–32.

Asier Marzo. 2020. Standing Waves for Acoustic Levitation. In *Acoustic Levitation*. Springer, 11–26.

Asier Marzo, Adrian Barnes, and Bruce W. Drinkwater. 2017. TinyLev: A multi-emitter single-axis acoustic levitator. *Review of Scientific Instruments* 88, 8 (2017), 085105. https://doi.org/10.1063/1.4989995 arXiv:https://doi.org/10.1063/1.4989995

Asier Marzo, Mihai Caleap, and Bruce W Drinkwater. 2018a. Acoustic virtual vortices with tunable orbital angular momentum for trapping of mie particles. *Physical review letters* 120, 4 (2018), 044301.

Asier Marzo, Tom Corkett, and Bruce W. Drinkwater. 2018b. Ultraino: An Open Phased-Array System for Narrowband Airborne Ultrasound Transmission. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* 65, 1 (2018), 102–111. https://doi.org/10.1109/TUFFC.2017.2769399

Asier Marzo and Bruce W. Drinkwater. 2019. Holographic acoustic tweezers. *Proceedings of the National Academy of Sciences* 116, 1 (2019), 84–89. https://doi.org/10.1073/pnas.1813047115 arXiv:https://www.pnas.org/content/116/1/84.full.pdf

Asier Marzo, Sue Ann Seah, Bruce W Drinkwater, Benjamin Sahoo, and Sriram Subramanian. 2015. Holographic acoustic elements for manipulation of levitated objects. *Nature communications* 6, 1 (2015), 1–7.

Rafael Morales, Iñigo Ezcurdia, Josu Irisarri, Marco A. B. Andrade, and Asier Marzo. 2021. Generating Airborne Ultrasonic Amplitude Patterns Using an Open Hardware Phased Array. *Applied Sciences* 11, 7 (2021). https://doi.org/10.3390/app11072981

Rafael Morales, Asier Marzo, Sriram Subramanian, and Diego Martínez. 2019. LeviProps: Animating levitated optimized fabric structures using holographic acoustic tweezers. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*. 651–661.

Yoichi Ochiai, Takayuki Hoshi, and Jun Rekimoto. 2014. Pixie Dust: Graphics Generated by Levitated and Animated Objects in Computational Acoustic-Potential Field. *ACM Trans. Graph.* 33, 4, Article 85 (jul 2014), 13 pages. https://doi.org/10.1145/2601097.2601118

Themis Omirou, Asier Marzo, Sue Ann Seah, and Sriram Subramanian. 2015. LeviPath: Modular Acoustic Levitation for 3D Path Visualisations. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI '15)*. Association for Computing Machinery, New York, NY, USA, 309–312. https://doi.org/10.1145/2702123.2702333

HoT O'Neil. 1949. Theory of focusing radiators. *The Journal of the Acoustical Society of America* 21, 5 (1949), 516–526.

Diego Martinez Plasencia, Ryuji Hirayama, Roberto Montano-Murillo, and Sriram Subramanian. 2020. GS-PAT: High-Speed Multi-Point Sound-Fields for Phased Arrays of Transducers. *ACM Trans. Graph.* 39, 4, Article 138 (jul 2020), 12 pages. https://doi.org/10.1145/3386569.3392492

Osvaldas Putkis. 2018. Contactless manipulation apparatus, assembly method and 3d printing. US Patent App. 15/765,126.

Marc Röthlisberger, Marcel Schuck, Laurenz Kulmer, and Johann W Kolar. 2021. Contactless Picking of Objects Using an Acoustic Gripper. In *Actuators*, Vol. 10. Multidisciplinary Digital Publishing Institute, 70.

Jenna M. Shapiro, Bruce W. Drinkwater, Adam W. Perriman, and Mike Fraser. 2021. Sonolithography: In-Air Ultrasonic Particulate and Droplet Manipulation for Multiscale Surface Patterning. *Advanced Materials Technologies* 6, 3 (2021), 2000689. https://doi.org/10.1002/admt.202000689 arXiv:https://onlinelibrary.wiley.com/doi/pdf/10.1002/admt.202000689

Lawrence K Shapiro and Howard I Shapiro. 1988. Construction cranes. *Scientific American* 258, 3 (1988), 72–79.

Gavin Sinclair, Pamela Jordan, Johannes Courtial, Miles Padgett, Jon Cooper, and Zsolt John Laczik. 2004. Assembly of 3-dimensional structures using programmable holographic optical tweezers. *Optics Express* 12, 22 (2004), 5475–5480.

Haichuan Song, Jonàs Martínez, Pierre Bedell, Noemie Vennin, and Sylvain Lefebvre. 2019. Colored fused filament fabrication. *ACM Transactions on Graphics (TOG)* 38, 5 (2019), 1–11.

Shun Suzuki, Seki Inoue, Masahiro Fujiwara, Yasutoshi Makino, and Hiroyuki Shinoda. 2021. AUTD3: Scalable Airborne Ultrasound Tactile Display. *IEEE Transactions on Haptics* 14, 4 (2021), 740–749. https://doi.org/10.1109/TOH.2021.3069976

RR Whymark. 1975. Acoustic field positioning for containerless processing. *Ultrasonics* 13, 6 (1975), 251–261.

Duyang Zang, Kejun Lin, Lin Li, Zhen Chen, Xiaoguang Li, and Xingguo Geng. 2017. Acoustic levitation of soap bubbles in air: Beyond the half-wavelength limit of sound. *Applied Physics Letters* 110, 12 (2017), 121602.