LeviPrint: Contactless Additive Manufacturing using Acoustic Levitation with Position and Orientation Control of Elongated Parts

Íñigo Fermín Ezcurdia Aguirre
UpnaLab
Public University of Navarre
Pamplona, Spain
inigofermin.ezcurdia@unavarra.es
https://orcid.org/0000-0003-4268-6760

Rafael Morales González
Ultraleap Ltd.
Bristol BS2 0EL, UK
rafael.morales@ultraleap.com

Asier Marzo Pérez
UpnaLab
Public University of Navarre
Pamplona, Spain
asier.marzo@unavarra.es
https://orcid.org/0000-0001-6433-1528

***Abstract*—LeviPrint assembles small objects in a contactless way using ultrasonic phased-arrays and optimization algorithms. We explore a set of methods that enables 6 Degrees-of-Freedom (DoF) control of elongated bodies. We then evaluate different ultrasonic arrangements to optimize the manipulation of these bodies. The combination of arrangements and optimization algorithms allow us to levitate, orientate and assemble complex objects. These techniques and arrangements can be leveraged for the microfabrication of electromechanical components and in-vivo additive manufacturing. We highlight the reduction of cross-contamination and the capability to manufacture inside closed containers from the outside.**

***Keywords*—acoustic hologram algorithm, 3D acoustic printer, acoustic levitation, acoustic tweezers, additive manufacturing.**

I. Introduction

Acoustic levitation can hold, translate and rotate small objects of different materials without direct contact [5]. Multiple levitating primitives such as beads, threads, and fabrics have been used for assembling complex objects and articulated animated structures [2, 8, 9]. Rotation of sub-wavelength sized non-spherical particles has been achieved using an asymmetric acoustic field created with a phase-controlled transducer array[4]. Furthermore, phased-controlled arrays have been used to reach 3 DoF manipulation (2 translational DoF + 1 rotational DoF) of elongated bodies, like toothpicks [3]. However, 6 DoF manipulation of large elongated bodies (above-wavelength) has never been achieved. Here, we study different trapping techniques and phased-controlled arrays that enable full 6 DoF manipulation of large elongated bodies. Our method allows the translation and rotation of large items in any direction and any axes. In this poster, we propose the use of these techniques to attach beads and large items together as part of an additive manufacturing framework for building complex objects. This approach surpass current limitations of traditional additive manufacturing by reducing cross-contamination or manufacturing inside closed containers from the outside.

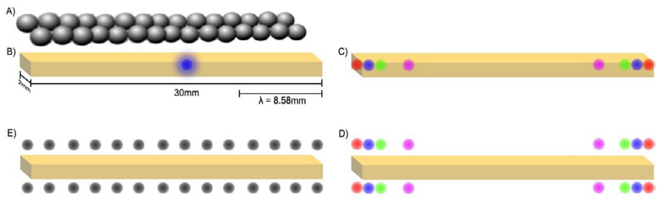

Figure 1. A) Stick approximated as a set of beads. B) Focal point at center of the stick. C) Focal points at sides. Different offsets used: Red=0mm; Blue=1mm; Green=2mm; Pink=5mm; D) Pairs of focal points at sides. Different offsets used: Red=0mm; Blue=1mm; Green=2mm; Pink=5mm; E) Twin wrapper method at 4 PPW (Pairs Per Wavelength).

II. Trapping methods

Arrays of transducers allow accurate generation of ultrasound fields that exert radiation forces on the levitation of particles. Algorithms for multi-point levitation calculate the phase delay for driving the array of transducers and creating a desire pressure field [6] capable of holding and manipulate midair elements. In this piece of work we propose and evaluate 12 different trapping methods for levitating and manipulating elongated bodies (See Fig. 1):

1) **Iterative Back Propagation (IBP) Methods:** These methods [6] generate multiple focal points.

- **At center:** One focal point is created at the center of the stick. The stick is levitated but not reoriented.
- **At sides:** Two focal points are created at the sides of the stick. Alternatives were tested offsetting the focal points 1mm, 2mm, 2.5mm and 5mm towards the center of the stick.
- **Pairs at sides:** Previously named *'at sides'* focal points are split into pairs. Alternatives were tested offsetting the focal points 1mm, 2mm, 2.5mm and 5mm towards the center of the stick.
- **Twin wrapper:** Previously named *'pairs at sides'* focal points are extruded along the stick with different distributions. 1, 2, 4 and 6 PPW (Pairs Per Wavelength).

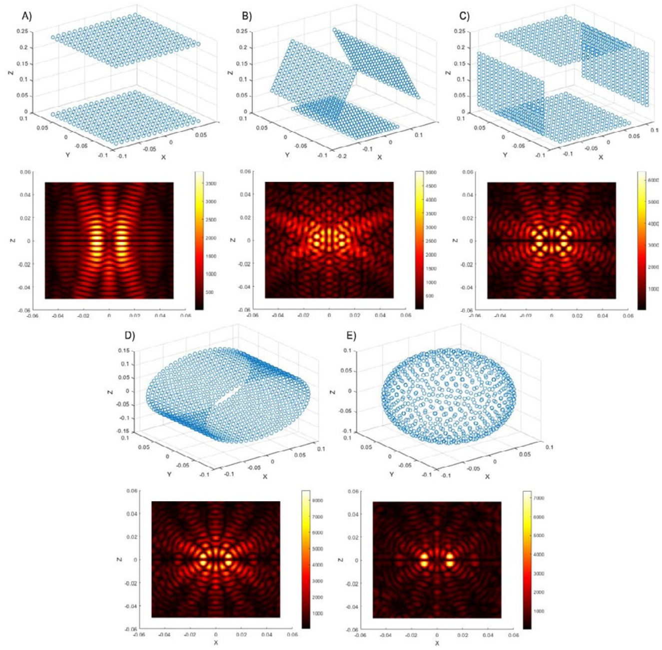

Figure 2. Transducers' arrangements simulated and a vertical slice of the pressure field that they create when applying IBP pairs at sides method. A) Two-opposed. B) Triangle. C) Cube. D) Cylinder. E) Sphere.

III. Transducers' arrangements

The quantity and distribution of the transducers plays a vital role in the manipulation capabilities of the final device. We have simulated and analyzed the behaviour of 5 different arrangements: 1) Two-opposed (512 transducers); 2) Triangle shaped (768 transducers); 3) Cube (1024 transducers); 4) Cylinder (1024 transducers); E) Sphere (642 transducers); See Fig. 2.

After benchmarking simulations of the setups, the two-opposed arrangement and the cube arrangement both were finally built to conduct experimental research with them. SonicSurface's Open Hardware Phased Arrays[7] were employed to build these devices. The cylinder and sphere arrangements were discarded, despite the good results shown in the simulations, because of the reduced working volume they offer towards additive manufacturing and their high complexity.

IV. Simulations and Conclusions

Forces, torques, Gor'kov potentials, positional stiffness and rotational stiffness were measured for a 30mm x 2mm stick placed in the center of the working volume when rotating it along each of its axes using the different IBP methods.

Positional Stiffness measures how converging are the forces in position, it is equivalent to the Laplacian of the potential. Rotational Stiffness measures how converging are the torques. The Gor'kov [1] potential for acoustic radiation pressure on a sphere is an approximation of the forces exerted on the sphere. The acoustic radiation forces push the particle towards the Gor'kov minimum potential.

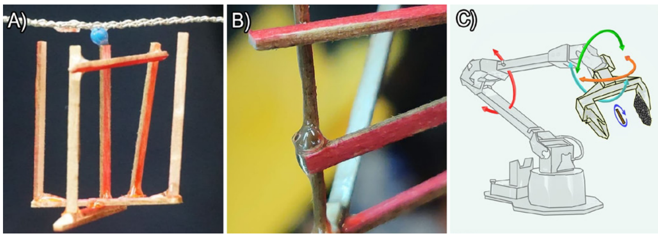

Figure 3. A) Photo of a large structure being built below the foundation. B) Photo of a solidified UV-cured glue droplet bonding two sticks together C) A 1-DoF rotation levitation device attached to a robot arm to perform precise movements and rotations.

As shown in Fig. 4.A), both methods, Twin Wrapper with 4 PPW and IBP at sides with 5mm offset appears to be the two preferred methods to be used for grabbing the stick caused by their low Gor'Kov potentials. Due to the high positional and rotation stiffnesses (Fig. 4 B, C and D), the cube arrangement appears to be a good alternative to the two-opposed arrangement for achieving the 90º rotations, critical for manufacturing vertical pieces and shorings.

V. Additive manufacturing

We illustrate the potential of Leviprint using varying numbers of primitives (sticks and beads), and making use of the different manipulations by our methods. The right combination of them will result in a robust structure that can be manufactured. Our methods will translate and position the primitives into their desired locations. Then, they will be fixed together by using an adhesive element. An acoustically transparent foundation should be placed in the center of the working volume before starting the building process as initial elements will be fixed to it (see Fig. 3.A). Applying spray glue was tested, however, it deliver excessive glue producing issues in the working volume such as stick areas and slow dry. Instead, we propose a new method using small droplets of UV-cured glue. A delivery mechanism (a syringe) delivers the glue which is levitated and placed accurately into the acoustic levitator. This method presents several benefits; it is cleaner, more precised, and easier than spraying glues (see Fig. 3.B). Additionally, these droplets can be used as a construction primitive on their own.

Finally, a robotic arm is proposed to hold a levitated device to speed up the manufacturing process. A custom levitator which generates a specific pressure field will be attached to the robot. (see Fig. 3). We note that the DoF in manipulations can be distributed between the robot and the levitator, e.g. Z-translation as well as rotation is performed by the levitator and the rest of the manipulation by the robot.

These new levitating manufacturing strategies will drastically reduce cross-contamination and they will offer the possibility to manufacture inside closed containers. Moreover, it enables manufacturing techniques not achievable with traditional 3D printing, such as threading through cavities or adding to the manufactured item towards any direction.

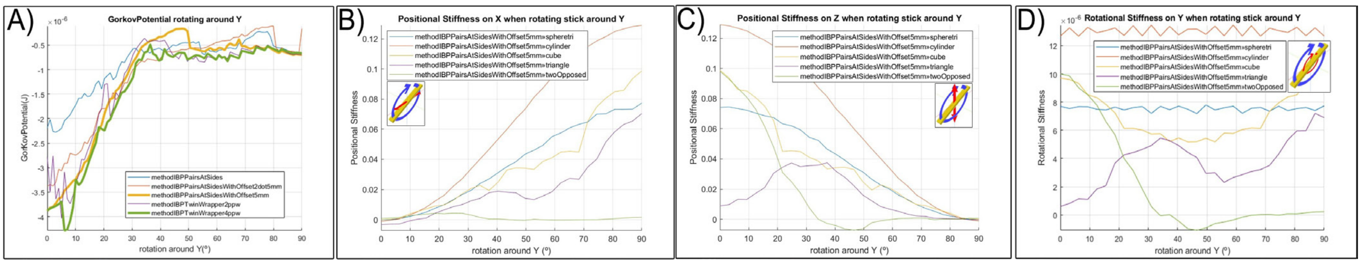

Figure 4. A) Gor'kov potential when rotating the stick along its Y axis. B) Positional Stiffness on the stick on axis X when rotating the stick around Y. C) Positional Stiffness on axis Z when rotating around Y. C) Rotational Stiffness over axis Y when rotating around Y.

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