LeviFab: Stabilization and Manipulation of Digitally Fabricated Objects for Superconductive Levitation

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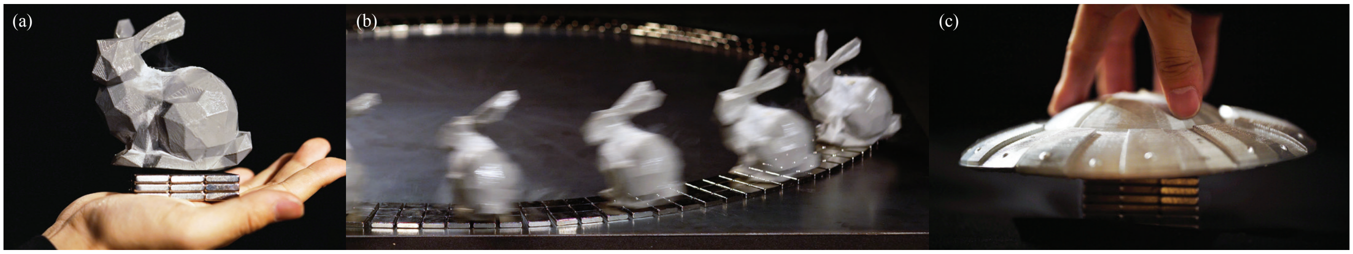

Figure 1: (a) Fabricated bunny model floating on a hand, (b) strobescopic of sliding bunny on a rail, and (c) fabricated UFO model.

CCS CONCEPTS

•Applied computing →Physics;

KEYWORDS

Levitation, Superconductivity, Digital fabrication

ACM Reference format:
Yoichi Ochiai, Tatsuya Minagawa, Takayuki Hoshi, Daitetsu Sato, Satoshi Hashizume, Kazuki Takazawa, Amy Koike, Ippei Suzuki, Atsushi Shinoda, and Kazuyoshi Kubokawa. 2017. LeviFab: Stabilization and Manipulation of Digitally Fabricated Objects for Superconductive Levitation. In *Proceedings of SIGGRAPH '17 Posters, Los Angeles, CA, USA, July 30 - August 03, 2017,* 2 pages.
DOI: 10.1145/3102163.3102233

1 INTRODUCTION

Aerial manipulation of material objects is fascinating and is used in many performance situations. Many scientific demonstrations and magic shows employ these levitations. Acoustic, magnetic, electric, and superconductive levitation are used in many situations. Adding controllability and increasing the design space of these levitation methods are often studied for use in entertainment applications in graphics and HCI communities. In this study, we focus on superconductive levitation (Figure 1) because it has not been well explored for entertainment applications.

Superconductive levitation requires special elements. It requires low temperature for superconductive materials and to satisfy this condition, liquid nitrogen is often used. These superconductive levitation requirements impose various difficulties. Moreover, the demonstration of superconductive levitation shows levitation itself as “contents”. Thus, its levitated structure, manipulate path, and interactions have not been well considered for entertainment applications. We are strongly motivated to redesign the demonstration of superconductive levitation in a more fascinating way by computational fabrication and manipulation methods.

Computational design methods of superconductive levitation have wide applications in not only entertainment but also other HCI context. Now superconductive levitation is limited levitation time because of the temperature limit of superconductive material however, 10 min levitation is enough to use in many HCI usages such as showing the demo of 3D manipulation, discussion with levitated physical icons, and discuss with 3D actuated characters.

We need to solve several problems in both fabrication and manipulation to achieve the 3D printed object levitation and manipulation by ways of superconductive levitation. First, we have to consider the structure the 3D printed object with low temperature

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SIGGRAPH '17 Posters, Los Angeles, CA, USA

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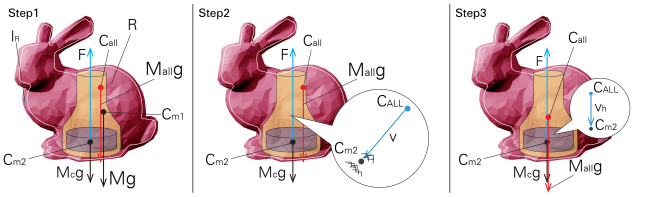

Figure 2: Procedure of inner structure calculation.

3D printed material. Second, we have to design and consider the structure of a 3D printed object to balance its body in midair by including a low temperature unit in the fabricated object. Third, we have to solve the manipulation path of the levitated material to consider its weight and acceleration. Finally, we have to solve the manipulation methods by applying active electromagnet arrays. For these problems, we use computational simulation methods of heat transmutation and magnetic field estimation that float the superconductive material.

2 PRINCIPLES

2.1 Superconductive levitation

We use $YBa_2Cu_3O_7$ as superconductive material in this study. It is classified into type II superconductors [Brandt 1989]. The materials in this class exhibit more stable levitation than those in type I superconductors. While the materials of type I superconductors are levitated solely based on the Meissner effect (perfect diamagnetism), those of type II superconductors are levitated based on the combination of the Meissner effect and flux-line pinning effect. Magnetic flux lines penetrate the materials of type II superconductors at the inhomogeneities, and resist the force that makes the penetration position (pinning). Due to the hysteretic property of the pinning effect, the materials can be not only levitated over magnets, but also suspended under them.

The force $\boldsymbol{F}$ on a small superconductor volume V magnetized parallel to a magnetic field $\boldsymbol{H}$ is written as

$$\boldsymbol{F} = \mu_0 M\left(H\right) \nabla H \tag{1}$$

where $M(H)$ is the magnetization curve which has a hysteretic property [Brandt 1989].

Although we intended to consider the Meissner effect and the flux pinning effect separately, we could not find an explicit expressions as far as we surveyed. It seemed that the micro characteristics of flux pinning had been well theoretically explored rather than the macro characteristics. Therefore, we measure the vertical and horizontal forces and use the measured values in designing.

We make rails by arranging a lot of small neodymium magnets or electromagnets. We form an S-N-S formation in the transverse direction of the rail, and a uniform formation in the longitudinal direction. These kinds of rails are usually used in the demonstrations of superconductive levitation [Miryala and Koblischka 2014].

2.2 Stabilization

2.2.1 Theory. The schematic diagram of a model floating in air is shown in Figure 2. $\boldsymbol{C}_{m1}$ is the center of gravity of a given model R, M is the mass of R, $\boldsymbol{C}_{m2}$ is the center of gravity of the superconductor S, M_c is the mass of S. When the magnetic flux H obtained in the previous chapter is applied to the superconductor, the force F for lifting S can be regarded as $\boldsymbol{C}_{m2}$. Here, if we solve the problem so as to balance the moment of R with respect to buoyancy with respect to S and the xy moment with respect to the center of gravity of S, it can be formulated as follows.

$$\boldsymbol{C}_{m1} M_g = \boldsymbol{C}_{m2}(F - M_{cg}) \tag{2}$$

At that time, when M becomes equal to or less than F, the model levitates in the air while still at the specified position. The position is a spatial position having a magnetic force intensity satisfying $F = M_g + M_{cg}$. The shell thickness of R is R and l_i is the thickness of the heat insulating material in R. To adjust M so as to satisfy the above formula, space is created inside by adjusting R. Further, it is decided by temperature transfer simulation to be described later, and its weight is fed back to again determine the position and internal structure of the superconductor. To stabilize R, it is necessary to minimize the distance v between $\boldsymbol{C}_{m1}$ and $\boldsymbol{C}_{m2}$. However, when $\boldsymbol{C}_{m2}$ is moved away from the outer wall of the model, the levitation distance decreases by the same amount. There is a trade-off of this problem.

2.2.2 Calculating Inner Structures. Figure 2 outlines the method. First, as step 1, determine the thickness R of the exterior of the model. Find the volume V and the center of gravity $\boldsymbol{C}_{m1}$ from the given model and the density of filaments used in the 3D printer. The levitation weight per superconductor is 750 g, and the required number of superconductors is decided.

Then, in Step 2, the insulator enclosing the predetermined number of superconductors (H: 11 mm × R: 25 mm) is obtained and the thickness l_i of the insulator is determined. The thickness of this insulator is a parameter for determining the surface temperature later. Where to place the insulator including the superconductor is determined by the position of the center of gravity and the shape of the model underneath. If there is only a structure whose cross-sectional area S is less than the size of the superconductor × the area (the cross-sectional area including the insulator) at a place close to the bottom of the model, it is searched as it is. In the case where there is no structure that fills the cross sectional area only in a place larger than the levitation distance of the superconductor, the model cannot be levitated unless it is expanded.

As Step 3, place this insulator in the model. Find the part that is close to the center of gravity of the model and has a cross sectional area S or more and insert it. Stretch the top of the insulator to penetrate the exterior of the model. After that, find M_{all} and center of gravity $\boldsymbol{C}_{all}$ from the weight of the insulator including the superconductor and the weight of the model.fifiNext, a vector $\boldsymbol{V}$ from $\boldsymbol{C}_{all}$ to $\boldsymbol{C}_{m2}$ is obtained, and voxel carving is performed such that $x = y = 0$ among the $v(x, y, z)$. If there is no need to perform voxel carving, it ends there. Then, the interior is filled with voxels from the bottom of the model so that z of vector $\boldsymbol{V}$ from $\boldsymbol{C}_{all}$ to $\boldsymbol{C}_{m2}$ becomes small. The smaller z, the more stabilized the stabilization.

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