Levitation Printing: Feasibility Study of a New Food Printing Method with Ultrasound Levitation

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***Abstract*—Contemporary food culture is becoming increasingly personalized and entertainment-oriented. Within this evolution, there is a growing interest in integrating computing with food, placing digital gastronomy at the forefront of this new wave. Existing research in this field has mainly focused on enhancing the sensory experience of food after cooking, such as through visual enhancement with Extended Reality or taste adjustment using electrical stimulation. However, there is also a growing interest in improving the dining experience during cooking using computing. Under this new vision, there is a particular surge in interest in food 3D printing, although current food 3D printers primarily focus on texture, with a narrow color gamut. This study explores the feasibility of a new food 3D printing concept called "Magic Drops," aiming for personalized dining experiences and entertainment in cooking using ultrasound levitation. After defining the requirements and conducting preliminary experiments based on the proposed method, we created a prototype that aligns with the concept. We then verified whether two liquids could be moved and mixed to a designated position using ultrasound levitation. This process was successful, although we observed phenomena of one liquid dropping during movement. Based on these results, we propose improvements for realizing Magic Drops and discuss its potential applications as well.**

***Keywords*—human food interaction, food 3D printing, ultrasound levitation, spherification, molecular gastronomy**

I. Introduction

The progression of culinary arts has been a testament to humanity's relentless pursuit of innovation, blending technological advances with cultural shifts. The journey from basic food preparation techniques to the industrialization-driven standardization of food production marks significant milestones in this evolution. The current trend towards personalized dining experiences signals a further evolution, emphasizing the role of innovation in shaping future food culture.

Digital gastronomy [1] has emerged at the forefront of this evolution, offering novel ways to enhance the dining experience. However, much of the existing research within this domain has primarily focused on augmenting the sensory experiences of food post-cooking, such as through visual enhancements with Extended Reality [2] or taste modulation using electrical stimulation [3, 4]. This has opened up new avenues for culinary experiences but has also highlighted a gap in integrating technology directly into the cooking process itself.

Magic Drops [5] is our proposed concept using ultrasound levitation. This technique combines several liquid drops into a single droplet in mid-air, moves it to a specified position, and allows it to free-fall. In the context of molecular gastronomy, the mixture drops holding sodium alginate solution are allowed to free-fall into a container filled with calcium lactate solution. This process results in the formation of drops encased in a calcium alginate film within the container. These drops are edible, and their color and flavor can be controlled throughout the process.

This paper verifies the feasibility of "Magic Drops," a concept we previously proposed.

The contributions are summarized as follows:

- We established criteria to satisfy a new food printing method, setting the foundation for new culinary fabrication techniques.
- We constructed a device for outputting liquid within the acoustic space of an ultrasound device, enabling the manipulation of food ingredients in novel ways.
- We confirmed that liquids could be mixed in mid-air, demonstrating the potential for creating complex and customized food structures without direct contact.

II. Related Work

A. Related Work

D'Angelo *et al.* [6] conducted a study applying spherification in food printing. They investigated the possibility of depositing colored calcium lactate solutions in three-dimensional shapes into a sodium alginate solution using a desktop extruder. While the results showed the formation of three-dimensional shapes, they encountered a challenge where the gelation process of the calcium solution progressed more quickly on the sides of the tank, hindering the deposition of uniform planar layers.

Maeda *et al.* [7] also explored the use of edible beads in block shapes for food printing. Their approach involved creating objects using edible beads made from a combination of water-soluble food ingredients and gummies. Although this study focused on the creation and potential shaping of the blocks themselves, it did not verify the actual methods of arranging the blocks. Instead, they adopted a method for moving pre-shaped blocks to specific locations.

B. Problem of Related Work

The common Fused Deposition Modeling (FDM) food printing method suffers from a narrow color gamut and requires frequent material changes in the nozzle to achieve color representation. Furthermore, in the research on food printing using spherification [6], the inability to express a

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single flat shape arises because the process involves creating a single large droplet. Another challenge in the block-shaped food printing method [7] is the need for a mechanism to move the block after it has been created.

III. Purpose

This study proposes a food printing method using ultrasound levitation, based on the concept of "Magic drops," an entertaining computational cooking approach. The purpose of this study is to verify the feasibility of the proposed method.

IV. Approach

A. Spherification

Spherification is a technique from molecular gastronomy that encapsulates liquids in gel-like spheres using a calcium alginate membrane. It involves dissolving sodium alginate, a seaweed-derived polysaccharide, in water, followed by the addition of calcium lactate. The calcium ions from the lactate react with alginate ions to trigger a gelation reaction. This cross-linking forms a gel that wraps the liquid in a sphere, often described by the "egg-box model" due to the structural arrangement of the ions [8].

B. Ultrasound Levitation

Research on ultrasounds, traditionally involving Langevin-type ultrasound transducers, has seen an increase in studies utilizing ultrasound elements since the 2010s. Main objectives include non-contact tactile feedback [9], directional speakers [10], and research on ultrasound levitation. Ultrasound levitation occurs when ultrasounds create a nonlinear effect in air, generating enough pressure difference (acoustic radiation pressure) to levitate small objects in the direction of ultrasound propagation, up to half the wavelength of the output sound source's wavelength at the nodes of standing waves. However, this does not apply in directions perpendicular to the propagation direction [11].

C. Proposal Method

Previous studies [12, 13] have involved dropping materials that solidify upon cooling, such as gels and chocolate, from a nozzle. In contrast, the proposed method uses ultrasound levitation to mix multiple droplets in mid-air and let them fall freely to a specified location, as shown in Fig. 1. In this device, liquids colored with food coloring are mixed in mid-air and allowed to fall. At the free-fall location, the droplets are stacked based on the spherification described in Section IV.A by preparing a tray on which the droplets are placed. The device receives shape, color and taste information from the user and can draw colorful characters, create three-dimensional shapes, etc.

Unlike the methods described in the related work, Magic Drops offers several advantages. By using ultrasound levitation, it eliminates the need for a physical nozzle, thereby overcoming the limitations of narrow color gamut and the requirements for frequent material changes associated with FDM food printing. Additionally, Magic Drops enables the creation of a single flat shape by precisely controlling the mixing and deposition of multiple droplets, addressing the challenge faced in spherification-based food printing. Furthermore, the use of ultrasound levitation allows for the direct placement of the droplets at the desired location, eliminating the need for a separate mechanism to move the blocks, as encountered in block-shaped food printing methods.

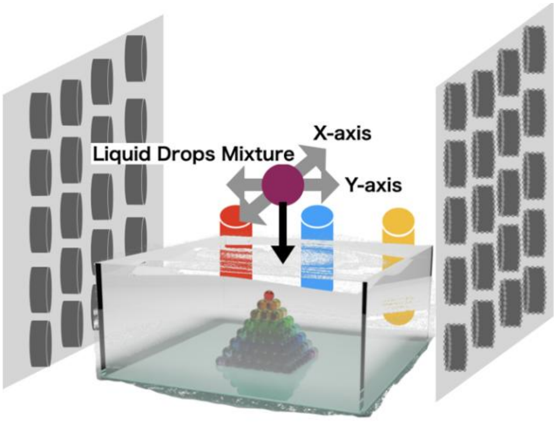

Fig. 1. Proposal image.

V. Prototype Design and Implementation

A. Purpose

The purpose of the prototype is to serve as an initial step in verifying the concept of Magic Drops by testing whether sodium alginate can be mixed at a designated location. Accordingly, Section V. B outlines the requirement definitions to meet this objective, Section V. C describes pre-experimental preparations for device construction, Section V. D discusses the design requirements, section V.E explains the design diagram, and Section V. F covers the implementation.

B. Requirements to Satisfy the Proposed Method

To achieve the method proposed in Section IV.C, we thought it is necessary to satisfy the following requirements.

- For the droplets to accumulate in the container, a liquid that turns into gel or solid after falling in mid-air is required.
- A container is needed to accumulate the printed materials.
- A mechanism to control the ejection of the liquid is necessary to create the specified colors.
- A system to control ultrasound levitation is needed to manipulate the droplets.

C. Preliminary Experiments

We conducted preliminary experiments on the materials and components to be used in the device to create a device that meets the requirement definitions set in Section V.B.

1) Verification of accumulability of edible materials

It was confirmed that the created droplets could be layered. As shown in Fig. 2. A, by dropping droplets of red, then blue, and then yellow, layers of about 5mm thickness were formed by the droplets. We verified that the gel of calcium alginate, created by combining sodium alginate and calcium lactate solutions, is suitable as an edible material for this research.

2) Verification of the color gamut of pellets of created by spherification

We conducted a color gamut measurement for droplets created through Spherification. Color identification of the droplets was performed using a chromaticity diagram, based on research by Mr. Hong [14], and the coverage range of the created triangle was evaluated. For this purpose, droplets were created by dropping sodium alginate solution, prepared in the proportions listed in Table 1, into a calcium lactate solution, prepared in the proportions listed in Table 2. The XYZ (Yxy) values for each color were calculated using a Konica Minolta CR-20 colorimeter (light source: D65, measuring diameter: approx. φ8mm, standard light: pulse xenon lamp, observation condition: 10° field of view). These values were plotted on the CIE1964 chromaticity diagram. Measurements for each color were conducted in the same environment.

Fig. 2(b) shows the plotted chromaticity diagram rom the measurements, revealing that it covers 4.63% of the total area, thereby confirming that it possesses a sufficiently wide color gamut to withstand the concept.

Table 1. Quantities of sodium alginate solution used for verification

Content	Quantity
Sodium Alginate[g]	1
Water[ml]	100
Each Food Coloring [g] (Cyan: Food Blue No. 4, Magenta: Food Red No. 102, Yellow: Food Yellow No. 4)	1

Table 2. Quantities of calcium lactate solution used for verification

Content	Quantity
Calcium Lactate[g]	1
Water[ml]	100

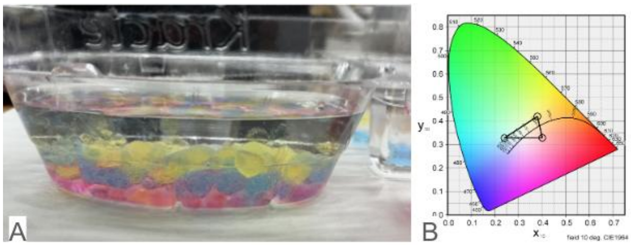

Fig. 2. A: The accumulation process of droplets formed by spherification B: evaluation of colors on the CIE 1964 chromaticity diagram.

3) Selection of the ultrasound device

The following three criteria were used to select the ultrasound device for use.

- It has the capability to move objects in three dimensions.
- Allows changing the focus position via a GUI.
- Can be freely modified.

Meeting the above criteria, OpenMPD [15], which is available under the MIT license, was selected as the ultrasound device. It was confirmed that it is possible to levitate two polyethylene pellets using ultrasound. Thus, we verified that the chosen ultrasound device is suitable for use in this research. It was also discovered that attempting to levitate water results in atomization.

4) Selection of liquid output method

After selecting the ultrasound device and edible materials in Sections V.C.1 and V.C.3, consideration was given to which direction from the ultrasound device's focal point it would be best to output the edible material.

Initially, methods of outputting edible materials through tubes or syringes were considered. After considering the precision of output control and the ease of handling the materials, we decided to use the method of outputting from a syringe.

Thus, syringes of 10ml (needle diameter 0.5 mm), 2.5 ml (needle diameter 0.6 mm), and 5.0ml (needle diameter 0.7 mm) were purchased to verify the most suitable syringe for outputting the sodium alginate solution. Given the viscosity of the sodium alginate solution, we found that a narrow needle diameter would quickly become clogged. As a result, we selected the syringe with the largest needle diameter, 5.0 ml (needle diameter 0.7 mm).

Next, we considered the orientation of the syringe relative to the ultrasound device. The options for the direction of the syringe's needle were facing downwards, upwards, or sideways. Upon testing the output of the sodium alginate solution in the direction of the ultrasound device's focal point, we found that orienting the needle downwards was the most stable method for detaching the liquid from the syringe and achieving levitation in mid-air.

Following this process, we decided to install the 5.0 ml (needle diameter 0.7 mm) syringe facing downwards.

D. Design Requirements

Based on the requirements definitions and selections made during the preliminary experiments as mentioned in Section V.B, the overall configuration diagram of prototype is shown in Fig. 3. Before operating the ultrasound device, information on color and pellet coordinates is obtained from the file entered on the PC side, and this information is converted into data for moving the focus of the ultrasound device and ejecting droplets from the syringe. Subsequently, during the actual printing process, the process of ejecting droplets from the syringe and then levitating and mixing them with the ultrasound device is repeated. The requirements for designing the prototype system to create it are described below.

1) Conditions for the model file input

The model file input must include not only the geometric structural information of the model to be printed but also its material color information.

2) Placement condition of the liquid output section

The liquid output section should be installed within the movable range of the ultrasound levitation.

3) Conditions of liquid output

To quantitatively control the volume of the liquid to be levitated and the stability of the ultrasound levitation, the liquid output will be automated using a microcontroller or similar device.

4) Placement condition of the droplet accumulation section

The droplet accumulation section should be installed within the movable range of the ultrasound levitation.

5) Placement condition of the ultrasound device

The ultrasound device should be fixed on rails with screws or similar, allowing for adjustment of the distance between ultrasound devices due to minute spacing between ultrasound devices.

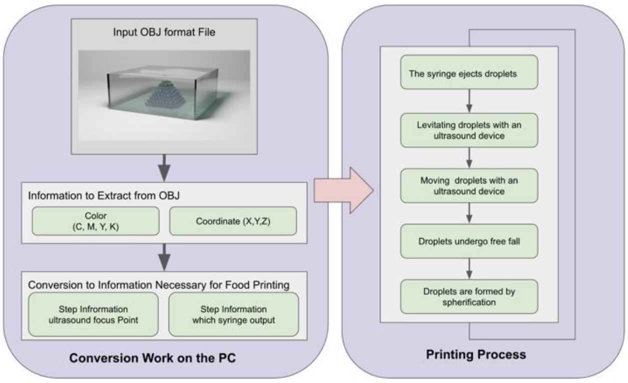

Fig. 3. Overall design configuration diagram.

E. Design Diagram

Based on the design requirements specified in Section V.D, a detailed design was conducted. The specifics are described in the subsections below.

1) Design of the model file input

Our prototype needs to use files that support both the color and geometric structural information of the model. Therefore, the input model files should be OBJ files instead of STL files.

2) Design of the ultrasound device

We designed the ultrasound device to be fixed with an aluminum frame to meet the requirements defined in Section V.D.1.

3) Design of the liquid output section

Utilizing the Syringe Pump by Linus Meienberg, which is available under the CC BY 4.0 DEED license on Thingiverse (https://www.thingiverse.com/thing:2797132), it was installed in a manner that allows the syringe to be pushed downwards. The Syringe Pump is designed to convert the rotation of the stepping motor into a gear that moves the installed syringe up and down.

Furthermore, we found that the sodium alginate solution output at the focus of the ultrasound from the syringe does not detach due to the surface tension between the needle and the sodium alginate solution. Therefore, modifications were made to move the Syringe Pump itself up and down using a servo motor.

The mentioned stepping motor and servo motor are connected via an Arduino Uno R3, and they were designed to operate by switching the toggle switch.

4) Design of the droplet layering section

Considering the need to fit enough sodium alginate solution, the visibility of the layered droplets' colors, and the requirement to fit between ultrasound devices, a white container measuring within 100[mm] in length, 100[mm] in width, and 40[mm] in height was prepared.

F. Implementation

Based on the design described in Section V.D, we implemented a device as shown in Fig. 4. The following subsections provide detailed explanations.

1) Ultrasound device section

On the PC, the ultrasound device is developed using Unity to send commands to the FPGA attached to the ultrasound device. The program is available on GitHub (https://github.com/RMResearch/OpenMPD).

The model of the chassis is also based on a 2D model provided by Prof. Plasencia's laboratory. This was created by cutting a 5 mm thick transparent acrylic plate using a laser cutter at the Kagoshima University Kotozukuri Centre. We drilled fixing holes to attach it to an aluminum frame to meet the requirement definitions.

2) Liquid output section

In the liquid output section, a syringe containing liquid is pushed out by a stepping motor controlled by a microcomputer. In the droplets stacking section, a container containing a calcium lactate solution is placed within the range where ultrasound levitation can be performed.

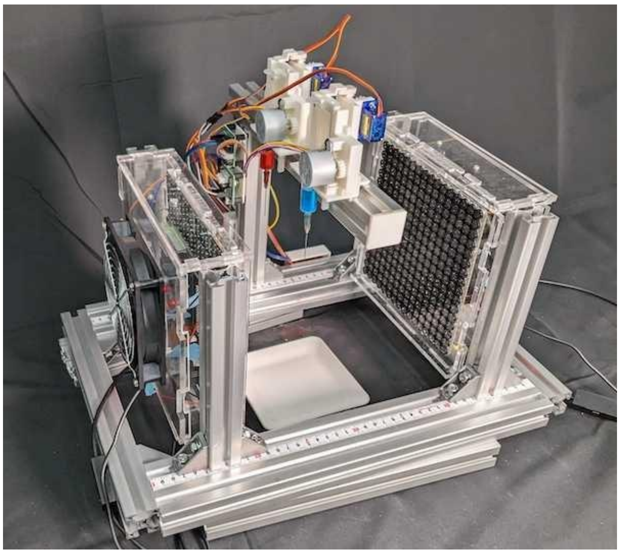

Fig. 4. Overall image of the device.

VI. EXPERIMENT

A. Experiment Purpose

The objective of this experiment is to verify whether it is possible to use ultrasound levitation to levitate droplets of sodium alginate solution (a mixture of cyan and magenta food coloring) in the air and move them to a specific position for mixing.

B. Experiment Method

- Prepare a sodium alginate solution mixed with cyan and magenta food coloring in each syringe.
- Align the point of focus of the ultrasound with the position of the needle tip of each syringe from the ultrasound device.
- Move the point of focus of the ultrasound to the middle position of each syringe.

C. Experiment Results

Fig. 5 shows the sodium alginate aqueous solutions mixed with cyan and magenta food coloring floating in mid-air. The left side shows a successful case where the mixing was achieved at the designated position, with time-lapse images. The right side shows a failed case where the cyan droplet fell during the merging process, also with time-lapse images. In these failed cases, phenomena such as one of the liquids falling or being attracted to the ultrasound device during mixing were observed. In 100 trials, successful mixing occurred five times.

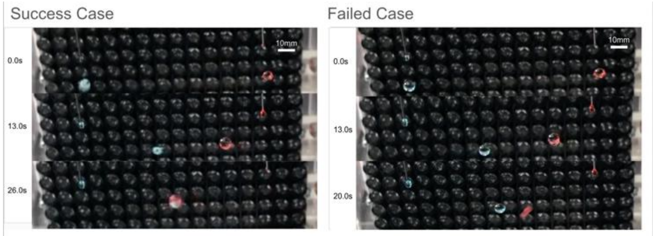

Fig. 5. Successful (left) and failed (right) sodium alginate solutions levitated with ultrasound.

D. Discussion of Experiments

Currently, the success rate of liquid mixing while using ultrasound levitation stands at 5%. We considered factors contributing to the droplets falling during the process from both the sodium alginate solution and the ultrasound levitation device perspectives.

- Factors on the Side of Sodium Alginate Solution:

Sodium alginate tends to decrease in viscosity over time. Considering the high failure rate immediately after the sodium alginate solution is prepared, it is possible that a lower viscosity state may be preferable. Most of the colored part of the levitating sodium alginate solution droplets accumulates at the bottom. This suggests that the weight balance of the droplets is disrupted, leading to a loss of stability.

- Factors on the Side of the Ultrasound Device:

From the ultrasound device side, issues could include the speed at which the droplets are moved. Additionally, just before the droplets mix, one of the sound fields must pass over a location that is hard to levitate (equivalent to the belly area), which could be a contributing factor.

Given these factors, we are considering the following improvements:

- Introduction of a Feedback System During Ultrasound Levitation:

Currently, there is no feedback system in place to determine whether levitating droplets are falling during the process. By installing cameras within the device for image processing, real-time adjustments can be made, ensuring the stability of the droplets and the accuracy of their positioning in relation to the ultrasound focal point.

- Exploration of Other Edible Materials:

In this study, we tested a combination of sodium alginate solution and calcium lactate solution. The unique viscosity of sodium alginate allowed us to perform ultrasound levitation with relatively little atomization. However, by testing other edible materials, there is potential to expand the range of expressions available.

VII. Discussion

In the field of digital gastronomy, the focus has primarily been on enhancing the post-cooking dining experience, with limited exploration of new cooking methods. This study discusses a prototype developed based on the concept of "Magic Drops," a new cooking method using ultrasound.

Upon implementing and evaluating the prototype, it was evident that, despite practical challenges, it was possible to provide a unique culinary experience where ingredients are levitated and cooked mid-air. The future goal is to create devices with enhanced practicality to further validate the proposed method's capability to offer unprecedented food experiences. To achieve the practical application of this prototype, several challenges need to be addressed:

- Synchronization between Ultrasound Levitation and Liquid Output:

The operation currently relies on manual toggles for controlling the syringe in the liquid output section. Improvements could be made by automating coordination with the ultrasound device for smoother operation.

- Creation of a GUI Application:

While our current focus has been primarily on testing the output device, there is a clear need to improve the user interface for managing the entire printing process. Developing a GUI application that facilitates the creation of design blueprints, OBJ files, and G-Code files necessary for printing will enhance operability.

- Validating the Vision:

The vision behind this system is to harness ultrasound levitation technology for innovating food printing into new forms. Future efforts will be aimed at validating this vision by offering practical and diverse culinary experiences. This involves experimenting with different ingredient combinations to create complex and visually appealing dishes and conducting detailed analysis on the texture and flavors of food to enhance sensory satisfaction. Through validating this vision, the goal is to expand the possibilities of digital gastronomy and bring innovation to food culture.

Furthermore, the proposed method of food printing could potentially connect with research fields aimed at reproducing the taste and flavors of previously consumed foods, offering the possibility of nostalgic dining experiences anywhere, anytime. Future aspirations include proposing spaces where cooking and dining offer entertainment value, thereby enriching the culinary experience.

VIII. Conclusion

This research explores the application and feasibility of food printing using ultrasound levitation. The proposed computational cooking method merges technology with culinary arts to create unique dining experiences. We demonstrate the feasibility of practical application of ultrasound levitation while discussing the requirements, design, and implementation of our device. Our evaluation includes the characteristics of the materials used and specific considerations needed for successful application.

Furthermore, our proposed food printing method opens up possibilities for reproducing computer-calculated designs, potentially leading to new dining experiences where computation and food are more naturally integrated. In the future, we aim to create spaces where dining and entertainment converge, enhancing the overall culinary experience.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Hiroki Kawahara performed the experimental tests, evaluated the results, wrote this contribution and presented the results on ICCCM 2024 in Kagoshima, Japan; Kaito Yamao was involved in the tests and helped writing this paper; Takayasu Fuchida and Kentaro Oda supervised this project and helped writing this paper; all authors had approved the final version.

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