lapillus bug: Creature-like Behaving Particles Based on Interactive Mid-Air Acoustic Manipulation

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ABSTRACT

Modern technology development has made the border between life and matter more ambiguous. Studies that find creature-like behavior from inorganic materials are carried out in the field of art and entertainment. On the other hand, it is an important issue to manipulate objects without implanting any actuators directly inside.

In this research, we aim to extract and express creature-like behavior from inanimate objects by usage of external force. By generating a standing wave with focused ultrasound, a phenomenon known as acoustic levitation enables a physical particle to float in mid-air. The particle is trapped in the ultrasonic focal point and follows its position. We have developed a system so that users can interact with the floating particle that looks and behaves as though it is a small hovering bug. We have received many reactions and opinions from attendees at exhibitions. In this paper, we describe the system overview, concept, design, implementation, and feedback from the exhibitions.

Author Keywords

Focused Ultrasound; Phased Array; Acoustic Levitation; Interaction; Actuation; Creature-like Expressions

ACM Classification Keywords

H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION

When considering the interaction between computers and humans, the limitation of screens has always existed. A common interaction method is to use interfaces outside the screen, to manipulate information inside the screen; however, there are an increasing number of approaches that aim to remove this limitation [1, 2]. Generally, information inside screens tends to be dynamic, but objects existing in the real world are static. Approaches such as projection mapping, that enables inanimate matter to appear as though it is dynamic, are now popular. On the other hand, it is an important issue to provide information and feedback directly to users regarding the manipulation of objects [3, 4].

When we consider manipulating objects, there are two types of general approaches. One approach is to implant mechanical actuators directly into the object (direct actuation). In this method, it may be easy to manipulate and control the object, but we sometimes find it difficult to implant the actuators because of their size and shape. There are also limitations in moving the objects, due to physical connections, wires, and substrates. Another approach is to use external forces to affect the object (indirect actuation). In this approach, actuators are not implanted in the object itself; therefore, the object retains its original features. This approach enables us to manipulate simple objects that do not have any complex components.

Using the indirect actuation process, the author previously created a system that manipulates objects by utilizing the features with interaction [5]. However, the object remained stuck on the ground because of the unavoidable force, gravity. In this paper, we propose a method of manipulating objects in mid-air by indirect actuation. Additionally, we aim to develop methods for interaction with the levitated objects.

Specifically, we used an ultrasonic phased array and a phenomenon known as acoustic levitation to manipulate the

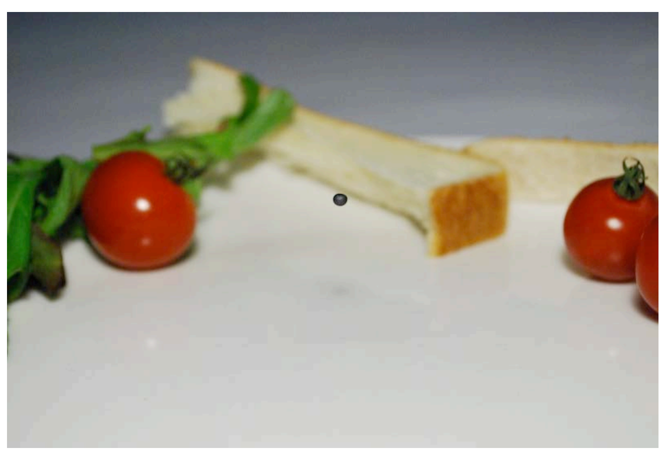

Figure 1. lapillus bug

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particle in mid-air. We have focused on a unique feature that the particle trembles in mid-air and exhibits creature-like behavior, similar to a fruit fly. In the following sections, we describe the technology and implementation of our system, and an interactive installation named "lapillus bug" (Figure 1), which has a particle flying about, behaving like a type of bug, and interacting with humans.

RELATED WORK

Actuating Objects

There are studies that make it possible to move objects without implanting actuators directly inside them. Actuated Workbench [6] and Madgets [7] are typical examples of this approach. They use an array of electromagnets to move the object on a flat surface. ZeroN [8] uses magnetic levitation to manipulate a single object in mid-air. By placing objects in mid-air, resistance such as friction, which occurs for objects set on a surface, does not occur. These studies use specially modified objects that have magnets implanted, and do not make use of the intrinsic material properties.

Ultra-Tangibles [9] is a system that enables contactless manipulation of objects using ultrasound. This approach does not require any special manufacturing for the object. However, the workspace is limited by the surrounding ultrasonic devices and object manipulation is limited to two dimensions.

Acoustic Levitation

There is another method for manipulating objects in mid-air that uses a phenomenon known as acoustic levitation. Acoustic levitation is a procedure by which objects are trapped in the nodes of standing waves produced by ultrasound (Figure 2). Researchers have accomplished levitation and manipulation of particles [10, 11]. Kozuka et al. [11] placed two ultrasonic transducers 18 mm to 26 mm away from each other. The sound waves interfered with each other, and by controlling the phase difference, the levitated object was manipulated in one dimension, vertically. Foresti et al. [12] described a method for manipulating levitated particles horizontally by transferring them over multiple piezoelectric transducers. Xie et al. [13] demonstrated a method for levitating small animals. Using a single transducer and a reflector, living animals, such as ladybirds, were levitated in the nodes of the standing wave. The procedures mentioned above are all achieved in small areas, where a human would have difficulty inserting hands and interacting with the levitated objects.

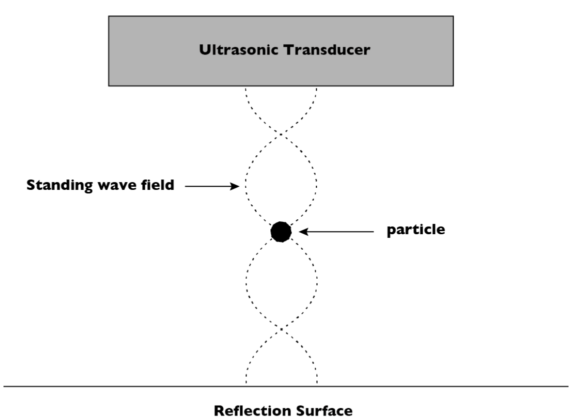

Figure 2. Basic Principle of Acoustic Levitation

In this research, we use travelling waves produced from ultrasonic transducers and reflected waves to generate standing waves to levitate objects (Figure 2). A portable ultrasonic phased array system is used, in which ultrasonic transducers are arranged. This device was originally developed to provide non-contact tactile sensations or interactions [14]. Focusing ultrasound carries strong ultrasound in the distance and thus enables the levitation of objects in a large area where humans can interact intuitively. Ochiai et al. [15] also uses focused ultrasound. Four ultrasound devices, which are surrounding the workspace, manipulate particles three-dimensionally. In our system, the ultrasound device is hung from the ceiling, facing downwards; therefore, users can gain access from all sides. Moreover, the system does not require multiple ultrasound devices arranged face-to-face, but uses reflection from the floor. Therefore, we can use this system in everyday situations, such as tabletops with reflections from the table or plates.

Inorganic Matter and Creature Imitation

In this research, we attempt to create an installation that focuses on the "creature-like" behavior that occurs when objects undergo indirect actuation. The relationship between life and matter is believed to be very close [16]. Studies that found and expressed creature-like behavior from inorganic materials were carried out in the field of art and entertainment. For example, "New creatures" [17] is a video in which stop-motion animation is used to apply creature-like movements to inanimate objects from our daily lives. Studies attempting to demonstrate such behavior in the real world have been also carried out. Meter Crawler [18] is a robotic snail with implanted motors. Species Series [19] is a robot that was made by implanting actuators inside garbage. However, this present study uses real world materials without implanting or attaching anything.

We previously developed "tamable looper" [5]; a cluster of magnets that moves like a creature and humans can interact with and tame the "creature". However, this present research utilizes more common materials. The objects do not remain attached to surfaces and expressions are created in mid-air.

SYSTEM DESIGN OF THE LAPILLUS BUG

The technology is based on an ultrasonic phased array. This device was originally designed for contactless haptic interaction, stimulated by acoustic radiation pressure at the focal point of the ultrasound array [14]. This ultrasonic phased array can be focused to a single point, by applying appropriate phase delays to the transducers. The particle follows the focal point, since it is trapped inside the standing wave. Therefore, controlling the position of the focal point enables the levitated object to move horizontally. We utilize the principle mentioned above to levitate and manipulate an object in a three-dimensional real space, without any modification to the original material. Furthermore, users can freely manipulate and interact with this floating particle. We associated this small particle with a kind of bug to accomplish the interaction between humans and a “creature”.

Hardware Design

Figure 3 presents the system overview of the lapillus bug. In this system, we hang the ultrasonic phased array device facing downwards, using the surface of the table, or any other solid flat object, as a reflection plate, placed at a distance of 200 to 300 mm.

We levitate the particles by placing them inside the nodes of the standing waves produced by the focused ultrasound. The focal point of the ultrasound is movable, which enables the particle to move two-dimensionally and to exhibit creature-like features. The levitation is started by using fingers or tools, such as tweezers, and placing the particle at a given height. When the particle is released, it is absorbed into the nearest node of the standing wave.

The size of ultrasonic phased array device is: 250 mm (W) × 250 mm (D) × 60 mm (H), with 285 ultrasound transducers arranged in a rectangular area. The array produces ultrasound with a frequency of 40 kHz, and an 8.5 mm wavelength. Therefore, the nodes of the standing waves, where particles can levitate, are produced at 4.25 mm intervals.

We also installed a camera, for image processing to enable interaction, and four small DC fans for device cooling and temperature stability.

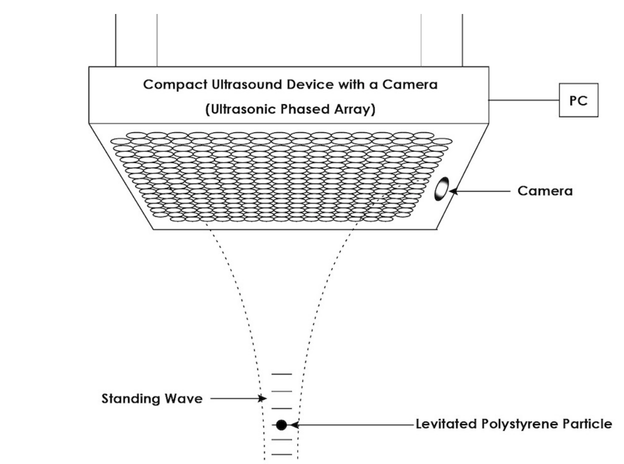

Figure 3. Overview of System

Software Design

The software is based on openframeworks, a framework for C++. The refresh rate of the device is 1 kHz, so we developed the program to run faster than 1000 fps, for maximum performance. However, the frame rate of the image processing is limited by the camera to 30 fps. Therefore, the manipulation of ultrasound and image processing are carried out in separate threads.

The manipulation of the ultrasound focus is based on an algorithm that calculates the appropriate phase differences for the ultrasound output. The levitated particle is trapped and fixed over the focal point and follows the position of that point. The resolution of that position is approximately 0.27 mm, which can be updated every millisecond.

Image processing is used to recognize the users' manipulations. We will describe the details of the interaction in the installation section. The camera captures images of objects or the light spots from laser pointers that are used for users' inputs. For example, when we use a red laser pointer for input manipulation, we recognize the color, brightness, and the size of the feature, to distinguish the laser spots from the levitated particle. The threshold for discrimination depends on the environment, such as lighting and distance from the surface to the device. Therefore, we first determine the location of the camera with respect to the ultrasound position and calibrate the threshold with the color information obtained under the operating environment.

TECHNICAL EVALUATION

We have experimented with some elements of our system to evaluate its stability and possibilities. In the following experiments, we located the device 200 mm above the surface, the focal distance was set to 220 mm, we used a 2 mm particle, levitated the particle at a height of approximately 20 mm, and moved the particle at 250 mm/s. Specifically, we examined the appearance of the particle depending on speed, number of particles, generation power, and number of transducers. We examined the stability by recording the average number of times the particle moved back and forth. Details of these movements will be mentioned in the following sections.

The distance between the system and the reflecting surface is adjustable, but it is thought that a larger distance will make the particle unstable, due to the attenuation of the ultrasound with the propagation distances and the diameter of the focal point. According to Hoshi et al. [20], the attenuation of ultrasound travelling through air is small enough to ignore. However, influence of the distance on the diameter of the focal point, w, can be described as Equation (1) [14].

$$w = \frac{2\lambda R}{D} \qquad (1)$$

Here, λ [m] is the wavelength of the ultrasound, R [m] is the focal distance, and D [m] is the length of the side of the square array. We can tell from the equation that w is proportional to R, therefore, when the distance to the device and the reflection surface becomes larger, w increases as well. The energy density at the focal point decreases when this occurs, thus, using this system at a large distance produces instability. Additionally, it was determined experimentally that adjusting the focal distance to 20 mm longer than the distance between the ultrasound system and the reflection surface, resulted in more stable levitation.

The antinode of the standing wave is located on the reflecting surface, as the surface is considered to be a free edge against the acoustic pressure. The wavelength of the ultrasound is 8.5 mm; therefore, the closest node to the surface is at a height of 2.125 mm. In the following measurements, we decided to use the fifth node from the bottom (i.e., at a height of 19.125 mm) to levitate a particle (Figure 4). There is a small difference between the measured height and that prediction from theory. This error may occur because of the differences between the incident wave and the reflection waves.

Moreover, we operated the device for more than 30 minutes before the measurements, since the performance of the device may be affected by its temperature. Additionally, the results may differ depending on the shape of the particle. Therefore, we have to treat the particle with care during experiments.

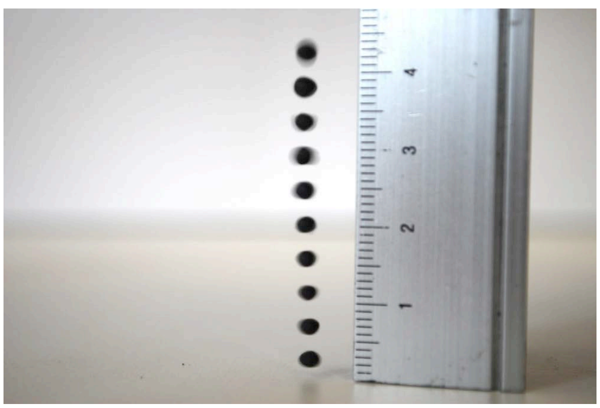

Figure 4. Particles Levitating in the Nodes

Particle Speed

We examined the stability depending on the particle's speed by using the parameters described above.

We counted how many times the particle can move back-and-forth in an area 60 mm wide, by changing the speed with 10 mm/s steps. The maximum number of counts was set to 100, and if the particle fell during the back and forth movement, we reduced the count.

Figure 5 describes the average number of the back-and-forth movements, which we measured five times for each speed. As a result, the particle was stable at speeds up to 310 mm/s, but became unstable at higher speeds. At speeds faster than 350 mm/s, it was difficult even to levitate the particle. Furthermore, when we moved the particle faster than 300 mm/s, the particle deformation, due to pinching, appeared to increase. Therefore, we recommend using this system at speeds lower than 300 mm/s.

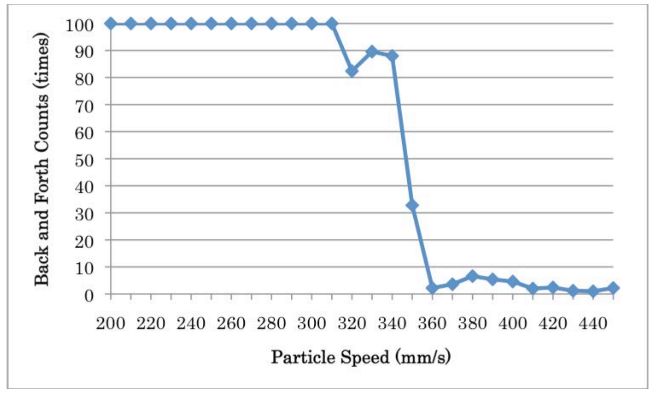

Figure 5. Speed and Stability

Particle Size and Material

In this system, there is a wider range of materials available than for approaches using magnetic actuators. We used 1 mm, 2 mm, and 3 mm diameter polystyrene particles and carried out measurements under the same conditions as discussed in the "Particle Speed" section. However, we did not observe any noticeable difference.

Materials such as sand grains, cotton, and water drops were also levitated. In addition, objects that have specific shapes, e.g., capacitors and microchips, were also levitated.

As mentioned earlier in the technical evaluation section, shapes of objects affect the stability of levitation. The movement and stability is also affected by parameters such as size, mass and so on. A detailed examination of these effects will be carried out in the future.

Multiple Particles Levitated and Manipulated Simultaneously

Not only one but multiple particles can be levitated, simultaneously, with individual manipulation. Since the ultrasonic phased array only produces a single focal point at a time, we need to rapidly switch the focal point between two locations. We attempted to levitate three particles, simultaneously, by switching three focal points at 333 Hz. This was possible but difficult to obtain sufficient stability. However, two particles were successfully levitated by switching two focal points at 500 Hz (Figure 6).

According to the theory of acoustic levitation, particles are trapped in the nodes and multiple nodes exist in the standing wave. Therefore, multiple particles can levitate vertically along the standing wave. We attempted to put particles in the nodes, sequentially from the bottom. As a result, Figure 7 shows that 26 particles were levitated. However, the stability of the particles levitating at the high positions was low. The upper part of the line of particles had a warp. If the number of particles were limited to twelve from the bottom, the objects were successfully moved at up to 100 mm/s. In this way, we can see that multiple particles are able to be manipulated, with a trade-off between the number of particles and stability.

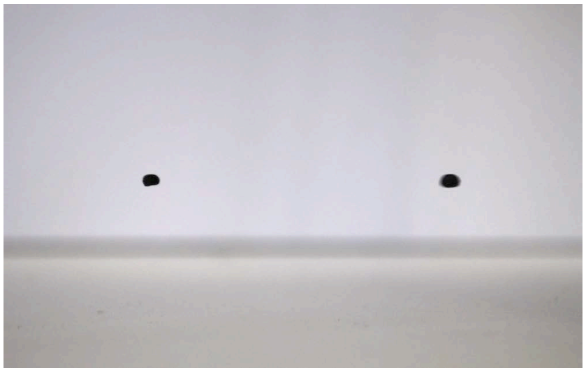

Figure 6. Individual Manipulation of Plural Particles

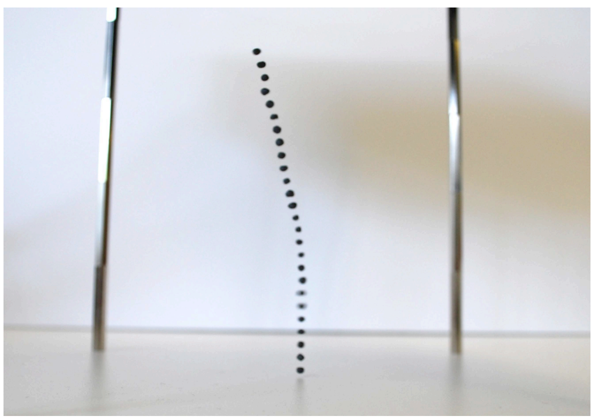

Figure 7. Particles Levitating Over a Single Focal Point

Number of Transducers

There are 285 ultrasonic transducers, arranged in a 17 × 17 array (four transducers were removed from the corners). We can select the number of active transducers: 285, 225, 169, 121, 81, 49, 25, or 9. If the particles can be levitated with fewer transducers, we can consider making the device smaller or manipulating more particles by dividing the array. Therefore, we examined how the particles behave when levitated by fewer transducers (Table 1). The table shows that the system is sufficiently stable with 225 transducers. Using the system with fewer transducers is difficult and it is difficult to even levitate a particle with 49 or less transducers. Therefore, it is not plausible to reduce the size of the current prototype system or divide the array.

Number of Transducers	285	225	169	121	81	49	25	9
Back and Forth Counts	100	100	41	30	0.2	x	x	x

Table 1. Number of Transducers and Stability

Angle between the System and Reflection Surface

The ultrasonic phased array is set parallel to the reflection surface. In order to consider the influence of tilts, possibly occur during setting up the system and to consider further applications, we examined the maximum tilt angle, θ, where the origin is at the center of the lower part of the device (Figure 8). The tilt angle was increased with 1° steps. When we moved the particle along the x-axis, θ was measured to be 9° and 6°, when the particle was moved along the z-axis.

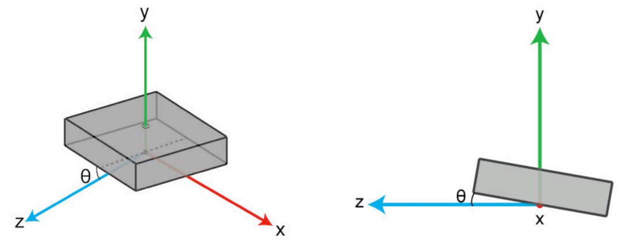

Figure 8. Angle between the System and Surface

Vibration of Particle

In the first section, we mentioned the unique behavior: the particle trembling slightly in mid-air. Particles are trapped as they are attracted to the lower level (trough) of the acoustic potential field [21]. When this occurs, the particle does not remain at the bottom of the trough. The restoring force towards the bottom of the potential field produces simple harmonic motion. This motion is considered to be the cause of the trembling phenomenon. However, the trembling movement changes, depending on environmental conditions and particle shapes. Therefore, controlling them intentionally would be difficult.

Besides, it was possible to reduce the size of the trembling motion by decreasing the intensity of the ultrasound. In this system, the intensity could be adjusted by PWM controls [20], represented by integral numbers from 0 to 623. With a 24 V supply, the maximum output had an acoustic pressure of 16 mN. We carried out measurements under the same conditions as discussed in the section, "Particle Speed" and changed the output force with 10% steps, to determine how the particle behaves with varying output intensity (Figure 9). The output force is not proportional to the output intensity, p, but $\sin^2(\pi p/1248)$. As a result, if the output force was larger than 50% of the maximum, no disturbance was observed. However, the particle was unstable and easily dropped with 30% to 40% of the maximum output. It was possible to levitate a particle with 10% to 20% of the maximum output, but it was not possible to move it stably. Decreasing the output intensity will reduce the vibration of the particle; however, it also reduces the stability of the levitation. Therefore, we can conclude there is a trade-off between the stability and the magnitude of the vibration caused by the output intensity. The vibration of the particle that occurred in our system could be controlled from 50% to 100% of the maximum output force.

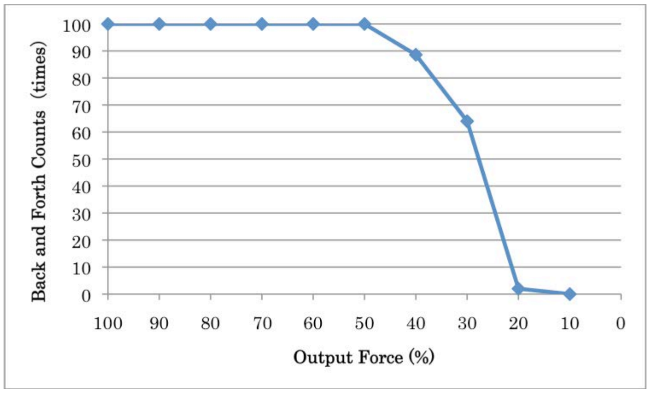

Figure 9. Output Force and Stability

INSTALLATION OF LEVITATING PARTICLES

In this system, we levitate objects and present creature-like features to develop applications in the fields of art and entertainment.

Overview of the Installation

A levitated particle that trembles rapidly may exhibit creature-like behavior, similar to a fruit fly. Therefore, we developed an installation where users observe and interact with an artificial "bug," i.e., an inorganic piece of material behaving as if it is alive. They may also experience an unusual event: taming a wild creature that is generally untamable.

In this installation, a fruit-fly-like black particle floats above a plate with leftovers from breakfast. When there is no input from the user, the particle floats about irregularly. The movement is designed to move in arcs and freely. While it's moving, the speed of the bug changes time to time with acceleration. We designed the speed and acceleration to change under the range based on the particle speed section. The computer-generated behavior may be more examined by referencing principles such as ``12 basic principles of animation'' [22]. However, when an input is provided, the particle moves as intended.

We have prepared two kinds of methods for the users to interact with the particle. One is to move a red tomato placed on the plate (Figure 10) and the other is to project a light spot on the plate with a laser pointer (Figure 11). We developed the interaction method by referencing the instinct of fruit flies that they are attracted and gather to fruits and lightings.

The interaction is implemented by using a web camera placed next to the ultrasonic phased array. By recognizing the size of the red object (a tomato) with the web camera, we enable the particle to float around the tomato. We directed the particle not to stay near the tomato all the time, but to float about randomly and then return to the tomato. With this interactivity, users can take part in the ecology of the "bug".

Figure 10. Interaction Using Tabletop Objects

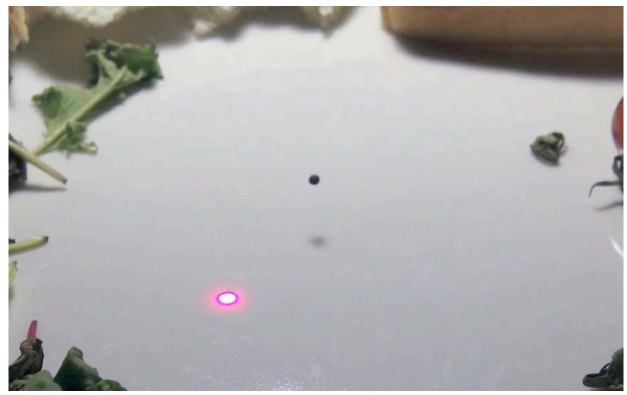

Figure 11. Interaction by a Laser Pointer

Moreover, we make use of the color and brightness information from the image acquired by the web camera. When using a laser pointer, the particle can be directed to continuously follow the laser spot. The focal point holding the particle is moved towards the position illuminated by the laser pointer. The users can play with the "bug" in real time.

Exhibitions and Discussions

Up to now, the authors have demonstrated the system through exhibitions, e.g. ACM SIGGRAPH Asia 2013 Art Gallery (20-23 November, 2013) and the exhibition of the award winning works of The Japan Media Arts Festival (5-16 February, 2014, Figure 12). At these exhibitions, we placed breads, tomatoes and leafy vegetables on a plate. The levitated 2 mm sized black polystyrene particle flies about interacting with laser pointers. We designed the stage with leftovers to enhance the context. A black polystyrene grain is used in order to maintain the stability as mentioned in the technical evaluation section, and to enable attendees to realize it as a flying fruit fly.

In these exhibitions, we explained the abstract of the installation with demonstrations and asked the attendees

Figure 12. Exhibition of lapillus bug

whether they perceived more features than the inorganic polystyrene grain originally possessed. Comments generally mentioned to real creatures as follows: "It looks as if it's alive."; "I thought that there was a real fly."; and "There's something flying." Furthermore, comments specifically mentioned the trembling: "The way how it trembles is nice." and "The vibration is interesting." It was significant that the trembling behavior, which we have focused on in this study, led to this creature-like behavior and gathered the interest of people.

The attendees gathered around the work and some of them observed the bug closely and from different angles. This seemed to be occurred since we used a plate as a reflection surface, and so that there weren't anything disturbing the access. Some attendees noticed the device but some thought that the implementation was included in the plate or in the table. Additionally, some attendees thought that the particle was created by projection. We can consider that the simple device composition did not disturb the direction of the work by not making the existence and the relationship of the device clearly noticeable.

Attendees who experienced the interaction tried to lead the bug towards the leftovers scattered about or moved the laser pointer back and forth rapidly and enjoyed the creature-like behavior. They mentioned: "It's trying hard to follow the light." and "It's cute."; when they saw the delay in the particle following the laser pointer.

However, many attendees were interested in the principle of levitation. Comments such as "Seeing things levitated is just so interesting." were provided. The attendees were also fascinated by the situation in which matter was freed from gravity and was levitated in the real world.

When there was no explanation to the attendee, some of them did not realize the way to interact with the particle and dropped the particle with their hands. This means that we have room to reconsider the interaction method. Moreover, the attendees did not just want to interact by using laser pointers, but they wanted to insert particles into the acoustic standing wave by themselves. In fact, they inserted not only one but multiple particles, pieces of bread, or the skin of the tomato. It is significant that attendees found it an interesting experience levitating objects with their hands and making inorganic matters come alive.

In this installation, we decorated the space with leftovers. At the meantime, it may be difficult to discuss the creature-like behaviors separately, which results from the decoration and from the acoustic levitation. Therefore, we plan to develop different types of our installation to discuss the effect.

CONCLUSION AND FUTURE WORKS

In this work, a particle was levitated by acoustic levitation. The particle could be moved and interacted with in mid-air. We used an ultrasonic phased array for manipulating the particle and a camera for recognizing the users' inputs. The creature-like behavior of the particle when it was levitated and moved was also observed.

Furthermore, we designed an installation named "lapillus bug", in which a user can interact with a "bug", and tame it paying attention to the creature-like features that the levitated particle exhibits. In fact, many attendees at the exhibitions perceived and enjoyed creature-like features associated with the levitated particle.

Our future plan includes the following topics. We will carry out further examination of the limitations and possibilities related to particle size, shape, material, and numbers. It is predicted that we will be able to levitate heavier materials by enhancing the output of the ultrasound. If so, we may levitate objects that have more detailed shapes, such as small puppets, which could be used to create animated stories. Not only one but multiple particles were levitated and we have discussed the possibilities in this paper. We plan to develop further applications utilizing this property. At present, we only levitate solid matter but using other types of materials, such as liquids, may lead to new spatial expressions.

In the system we have developed, the particle remains at a constant height. We will consider enabling vertical manipulation for three-dimensional movement. Additionally, tweezers were used for the initial placement of the particle, but we are now developing a system that starts the levitation by adjusting the focal point for a particle located on the floor or a stand. Through the exhibitions, the attendees performed interactions that we did not intend. This means that there is a room for improvement in the current interaction scenario. We will consider gestures or tangible inputs to interact with the particle.

Proposals for practical applications are also an important issue. For example, there may be applications in fields where contactless manipulation is required, such as handling small electronic parts for micro-machine technologies.

We will refine the worldview of the artwork “lapillus bug” and attempt to make the border between life and matter more ambiguous.

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