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Avoiding Collisions when Interacting with Levitating Particle Displays

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Abstract

Levitating particle displays are an emerging technology where content is composed of physical pixels. Unlike digital displays, manipulating the content is not straightforward because physical constraints affect the placement and movement of each particle: dragging a particle may cause it to collide with others along its movement path. We describe initial work into four new interaction techniques that allow users to avoid collisions when directly manipulating display content. Techniques such as these are required for interactive levitating displays to be practical when scaled up to large sizes.

Author Keywords

Acoustic Levitation; Levitating Particle Display; Ultrasound.

CCS Concepts

•**Human-centered computing** → *Gestural input; Haptic devices; Displays and imagers;*

Introduction

Levitating particle displays [6] are a novel technology where content is composed of physical "pixels" held in the air. Several methods can be used to levitate display elements; the most common is acoustic levitation using focused ultrasound from one, or more, arrays of emitters, allowing multiple pixels to be precisely positioned and controlled
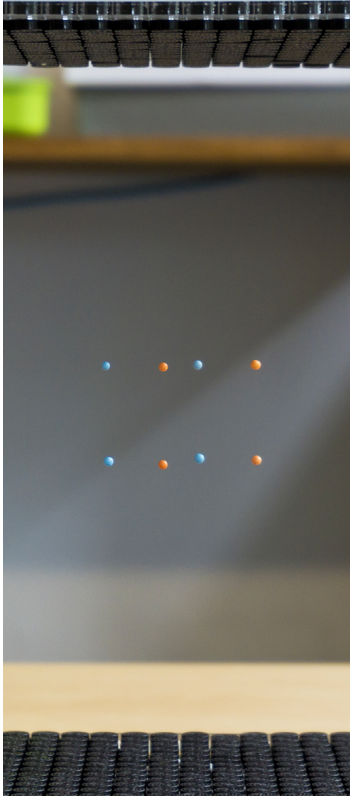
Figure 1: A levitating cube consisting of eight polystyrene beads ($\varnothing 2$ mm), oriented at $45°$ to the viewer. The blue beads and orange beads form the far and near sides, respectively. Please see [4] for a video that more clearly conveys this 3D representation. The ultrasound emitters are visible above and below the cube.

independently [14] (Figure 1). Polystyrene beads ($\varnothing 1$ mm to 3 mm) are typically used as the pixels to create point cloud representations of data [6, 15]. Whilst simple in appearance, these beads can be moved rapidly with synchronised lasers to create opaque animated graphics [8, 10], or used as the anchors for lightweight materials [13], allowing this technology to be used for complex and opaque in-air graphics and animations.

In an acoustic levitation device, the physical display particles are held in place by *traps*, areas of low sound pressure surrounded by high pressure [12]. The most common type of trap uses *standing waves*: sound waves travelling in opposite directions from emitters above and below create a static wave-like interference pattern, with alternating regions of high and low pressure. Suitable objects can be "trapped" in the low pressure areas, where the forces acting upon them are stable. By manipulating the phase of the sound waves, the traps can be moved with a high degree of precision. Most levitating particle displays use small polystyrene beads, whose diameter is less than half of the wavelength (e.g., [2, 5, 6, 7, 10, 13, 14], Figure 3), although other particle materials can be used too (e.g., liquids [16]).

Recent work has demonstrated simple interactions with these displays. Freeman *et al.* [7] described techniques for selecting a levitating particle, as a first step towards more complex interactions. Users targeted a particle by pointing an extended finger at it in mid-air. Since the levitating particles are the only elements in the display, a subtle shaking movement was used to give feedback about which particle was currently being targeted. Bachynskyi *et al.* [2] investigated particle movement, using finger movements in air to directly translate the particle.

Those works investigated basic interaction techniques in very simple display scenarios. Freeman's selection

technique was demonstrated with a maximum of two particles [7], whilst Bachynskyi's movement technique was only used with a single particle [2]. For practical use, levitating displays will have many particles that impose physical constraints affecting how users interact with the display content. For example, it will be necessary for particles to avoid colliding with each other because, if they get too close, they will be caught within a single trap.

In this paper, we discuss the physical constraints that affect acoustically levitated objects and begin to investigate novel techniques for avoiding collisions. Whilst our focus is on acoustic levitation, these techniques are relevant to other physical displays where avoiding collisions is necessary (e.g., those based on drones or actuated tangibles).

Levitating Particle Collisions

Levitating particles have a maximum size which scales with the ultrasound wavelength (λ). The maximum size is approximately half of the wavelength (e.g., $\frac{1}{2}\lambda \simeq 4.3$ mm for 40 kHz ultrasound used in most acoustic levitation systems). Particle size does not determine the resolution of the display, however; instead, the resolution is determined by a minimum separation of at least λ between adjacent traps [1]. Separation is necessary to avoid traps merging, in which case, both particles will caught in a single trap, becoming inseparable (as shown in Figure 2).

Avoiding collisions is crucial for the practical use of a levitating particle display. Minimum separation distances can be used as a heuristic to avoid traps merging: λ for horizontal separation (parallel to the ultrasound emitters) and $\frac{1}{2}\lambda$ for vertical separation (perpendicular to the ultrasound emitters) [1]. Naively applying such heuristics to interactive levitating graphics may not be straightforward, however. If a user is actively controlling the position of a
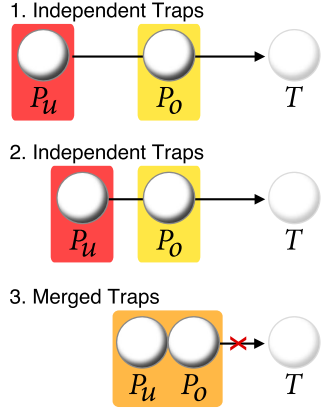
1. Independent Traps

2. Independent Traps

3. Merged Traps

Figure 2: A user-controlled particle P_u will remain in its own trap as it approaches an obstacle particle P_o on its way to target position T, as in (1) and (2). However, if P_u gets too close to P_o, the traps will merge and the particles become inseparable, as in (3), preventing P_u from ever reaching T.
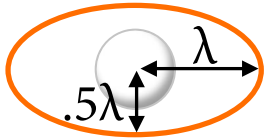

Figure 3: The *collision zone* is the area surrounding a particle where a second trap cannot be established, without a high likelihood of the traps merging. The shape of this zone is not uniform, because minimum separation distances differ with respect to the direction of the standing wave [1].

levitating particle, strictly enforcing separation rules may result in unexpected behaviour; for example, if a particle abruptly stops responding to the user's input or does not move as the user intends.

Collision Avoidance Interaction Techniques

We designed four interaction techniques for avoiding collisions during direct control over a particle's position. Their aim is to enforce minimum separation heuristics and make it clear that the system is resolving a problematic movement trajectory, whilst allowing users to maintain their sense of control over the particle. We describe particle movement using a mid-air finger drag operation (as in [2, 14]), but these techniques are device agnostic (e.g., could also be used with a mouse pointer, joystick, etc). When describing these techniques, we refer to the "*collision zone*" around a levitating particle; this is the region around a particle where collisions are likely to occur (Figure 3).

1. Repel Controlled Particle
Our first collision avoidance technique is based on the principle of *repulsion*: i.e., a force that repels one object from another. For this technique, if a user-controlled particle P_u is moving along a trajectory that intersects the collision zone of an obstacle particle P_o, then P_u is repelled by P_o (see Figure 4). The repelling force associated to P_o will cause P_u to pass around a sphere slightly larger than P_o's collision zone. P_u will move along the surface of this sphere, according to the user's movement, until the zone is passed.

2. Repel Obstacle Particle
Our second technique also applies repelling forces, except this time P_o is repelled by P_u, creating a clear path for P_u to avoid the collision zone (as in Figure 5). Once P_u has passed the collision zone, the repelling force attenuates and P_o will move back to its original position. If there are

multiple obstacles along P_u's current trajectory, each will be repelled as P_u approaches.

3. Divert Controlled Particle
Our third technique avoids a potential collision by diverting P_u on a safe trajectory around P_o (as in Figure 6). Unlike the first repel technique that forces users to resolve the problematic trajectory themselves, this technique finds a safe path for P_u and maps the user's movements onto it. A diversion is calculated between the current position of P_u and the mirrored position on the other side of P_o; subsequent movements by the user are automatically mapped to this new path until the end point is reached. Alternatively, the user can move back again; if they pass the beginning of the diversion path, the diversion is cancelled and the user regains control over P_u's position.

The most straightforward implementation of this technique is to create a sequence of three straight paths around P_o: (i) move away from the collision zone, (ii) move beyond the collision zone, and (iii) return to the continuation of the original trajectory. This simple approach is not ideal because it requires the particle to make three direction changes. Changing direction increases the risk of a particle being ejected when the trap changes direction due to the inertia of the particle. An improved approach is to use Bézier curves to transition to an arc around P_o. Smooth curvature improves the reliability of acoustic levitation by reducing direction change and minimising large shifts in the phase of the sound waves.

4. Particle Swap
Our fourth technique avoids collisions by giving the user direct control of P_o and leaving P_u in P_o's position: i.e., the system "swaps" the particle controlled by the user. This is straightforward because it avoids the need to find a safe path for P_u. However, switching control to a new particle
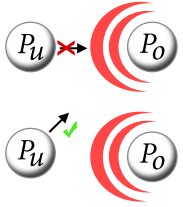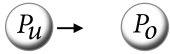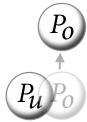
Figure 4: The *Repel Controlled Particle* technique uses a repelling force from P_o to force users to find an alternative path for P_u.

1. Approaching obstacle
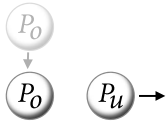
2. Repel obstacle

3. Obstacle returns

Figure 5: The *Repel Obstacle Particle* technique detects when P_u is going to intersect P_o's collision zone (1); a repelling force pushes P_o away from P_u's trajectory (2); the repelling force attenuates as P_u passes to allow P_o to return (3).

raises potential usability issues: is it clear to the user that they no longer have control of P_u?; is it clear that they now *do* control P_o?; how does the user regain control of P_u if they wish to undo the swap?; and how would they return P_o to its original position if control is taken of P_u again? There is a clear trade-off between the simplicity of this technique and the potential design issues it introduces, which require further investigation.

Our initial design addresses these issues by using a pseudo-haptic friction effect, intended to slow down the interaction and make it easier to realise when control is passed to P_o. As P_u approaches the collision zone of P_o, the control:display gain is reduced, creating the impression of friction [11]. Once P_u reaches the boundary of the collision zone, both P_u and P_o are moved in the same direction at the same time; P_u will stop once it reaches the prior position of P_o, with P_o now under user control. The control-display gain returns to normal, with the user's finger movements controlling P_o. The "slow motion" from the friction effect is intended to ease the transition for users.

Avoiding Multiple Collisions

We described our four collision avoidance techniques using a simple scenario with a user-controlled particle P_u and an obstacle particle P_o. Complex shapes (e.g., LeviProps [13] or Floating Charts [15]) are likely to have many particles densely packed into a small area, so our collision avoidance techniques may need to deal with multiple obstacles in succession. We now discuss how each technique deals with multiple particles and highlight the implications for usability that require further investigation.

For both repel interactions, the repelling forces are applied to, and from, all particles in the display. *Repel Controlled Particle* will apply repelling forces from all nearby obstacles

to P_u, forcing P_u to pass around all obstacles. A potential limitation of this technique is that the user may be unable to move P_u "through" the perimeter of a shape, as P_u is repelled from all directions; e.g., a circle with n equally spaced particles on its circumference.

Likewise, *Repel Obstacle Particle* will repel any obstacles along P_u's trajectory, effectively clearing a path for P_u. An important edge case to consider is if an obstacle is repelled towards another nearby obstacle, as this may cause a collision. Our current solution to this is for moving obstacles to repel other obstacles as well, cascading the repellent forces to avoid collisions.

For *Divert Controlled Particle*, it will be necessary to find a diversion avoiding other particles. Our initial implementation first checks if the target position (T in Figure 6) is clear; if not, the target is extended along the trajectory until it lies in a safe position. Then, we simply generate a trajectory around P_o towards T, as described before, and check for potential collisions along the path. If another particle is found, a new trajectory is checked. A limitation of this naive implementation is that it only checks beyond the boundaries of P_o's collision zone; a more nuanced solution is needed to find a safe trajectory around multiple particles, which we will investigate as this work progresses.

There may be situations where a naive implementation of *Particle Swap* will not work. For example, if P_u is moving towards P_o, there may be another particle P_x beside P_o that prevents it from moving from its current position to become the user controlled particle (as in Figure 8). One solution is cascade changes along the trajectory: i.e., move P_o to P_x's position and move P_x out of its trap to become the user-controlled particle. Our implementation of *Particle Swap* inspects the current trajectory of P_u when a collision is imminent; if multiple particles in succession are found, the
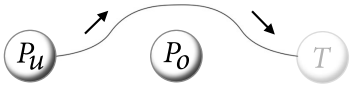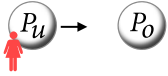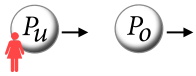
Figure 6: The ***Divert Controlled Particle*** technique forces P_u to take a smooth trajectory around P_o's collision zone, returning to user control after reaching the target position T on the other side of P_o.

1. Approaching obstacle

2. Move both particles

3. Swap user control

Figure 7: The ***Particle Swap*** technique detects when P_u approaches P_o's collision zone (1); moves P_o along P_u's trajectory (2); and leaves P_u in its place and gives the user control of P_o (3).
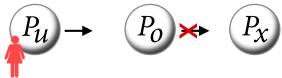

Figure 8: There may be situations where ***Particle Swap*** cannot swap control to P_o because of another nearby particle.

second step shown in Figure 7 is applied to all particles, with the furthest particle becoming controlled by the user.

The formative steps of this research have identified edge cases where avoiding one collision may result in another. We have taken first steps towards addressing these edge cases by refining the designs of our interaction techniques. These exceptional cases have implications for usability, exacerbated by the lack of additional visual feedback that can be given from a levitating particle display. Research is needed to investigate these situations, to explore how our techniques perform and see if users understand what is happening. There may be cases where more feedback is needed, in which case we need to consider how the particles themselves can be used to present feedback (e.g., using subtle movement [7] or projection [10, 13]).

Progress and Planned Experiment

We have implemented these collision avoidance techniques and informally evaluated them with pilot studies. In implementing them, we have identified usability issues and refined our designs to mitigate them, as described earlier.

An emerging theme from early tests was that user intentions did not always match gesture actions: e.g., a user intends to move a particle to the left of its current position, but also unintentionally modifies its height and depth (i.e., y- and z-coordinates). These incidental movements are an inherent issue when in-air gestures are used for 3D position control, because users' conceptual models of hand movement are simpler than what the sensor data reveals. Incidental movements are especially important in an acoustic levitation system where particles are placed in each axis with millimeter precision. We addressed this issue by applying an Exponential Moving Average filter to each axis of finger movement; this means particle

movement more accurately matches user intention.

Our collision avoidance techniques represent a variety of design alternatives, for example: user-chosen paths *Vs.* computer-chosen paths, shifting P_u *Vs.* shifting P_o, and avoiding obstacles *Vs.* taking control of obstacles. The next step in this research is to experimentally evaluate our techniques to give insight into the design choices and understand user performance and preference with these techniques. Since levitating particle displays are a radically new type of display, our participants will not have experienced any interactions like these before, so our experiment will also provide additional insight into whether they can be usable and practical for complex fine-grained interactions.

Our planned experiment task involves the user taking control of a levitating particle and moving it to a target position on the opposite side of an obstacle particle. The experimental conditions comprise our four collision avoidance techniques and a baseline of a naively-imposed minimum separation heuristic (as described earlier). The target position will be a platform on the other side of the obstacle. Experimental measures include success rate (a collision results in task failure); task time for the movement operation; and usability survey metrics (including NASA TLX [9] and SUS [3]).

Conclusion

Levitating particle displays show content composed of physical pixels, precisely held in air by ultrasound. Particles can be used to create point cloud graphics [6, 14, 15], or as control points for laser-cut lightweight materials [13]. Interaction techniques have been developed to allow users to select [7] and re-position [2] the particles, but these have only considered the simplest of use cases (e.g., movement

in the absence of other particles [2, 14]). In practice, levitating displays will consist of many particles (e.g., Figure 1). When a particle is moved near another, there is the risk of collision and the particles become inseparable.

We designed and implemented four novel interaction techniques for avoiding collisions whilst directly controlling the position of a levitating particle. These extend Bachynskyi's LeviCursor technique [2], changing the behaviour of the user-controlled particle, obstacle particle, or both, to avoid collisions. These novel techniques represent combinations of design choices that may affect the usability of interacting with levitating objects. The next step in this research is to empirically investigate our collision avoidance techniques. This will give insight into how users can directly manipulate physical objects through in-air gestures, without them colliding. This will also help us better understand how particle behaviour can support complex interaction techniques in the absence of additional visual feedback, since the particles themselves are the only visible elements in the display.

Acknowledgements

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