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JOLED: A Mid-air Display based on Electrostatic Rotation of Levitated Janus Objects

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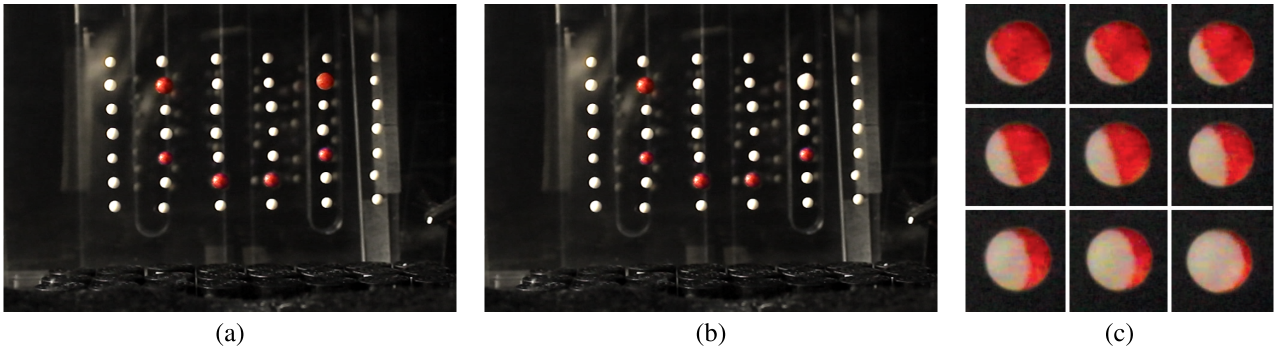
(a) (b) (c)

Figure 1. JOLED is a novel mid-air reflective display. (a) and (b) show a dynamic image of a smiley face winking one eye. (c) shows continuous control of rotation of a Janus voxel.

ABSTRACT

We present JOLED, a mid-air display for interactive physical visualization using Janus objects as physical voxels. The Janus objects have special surfaces that have two or more asymmetric physical properties at different areas. In JOLED, they are levitated in mid-air and controllably rotated to reveal their different physical properties. We made voxels by coating the hemispheres of expanded polystyrene beads with different materials, and applied a thin patch of titanium dioxide to induce electrostatic charge on them. Transparent indium tin oxide electrodes are used around the levitation volume to create a tailored electric field to control the orientation of the voxels. We propose a novel method to control the angular position of individual voxels in a grid using electrostatic rotation and their 3D position using acoustic levitation. We present a display in which voxels can be flipped independently, and two mid-air physical games with a voxel as the playable character that moves in 3D across other physical structures and rotates to reflect its status in the games. We demonstrate a voxel update speed of 37.8 ms/flip, which is video-rate.

ACM Classification Keywords

H.5.2. User Interfaces: Graphical user interfaces, interaction styles, prototyping, screen design, user-centered design

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Author Keywords

Human-computer Interaction; Emerging Interfaces; Three-dimensional Displays; Actuated Surfaces; Shape-changing Displays; Mid-air Displays; Electrostatic Actuation; Acoustic Levitation; Janus Particles

INTRODUCTION

Recently, levitated objects have been used in tangible user interfaces, physical visualization and graphical interfaces applications. Users can see, feel and control information through a large levitated object [16], or experience expression of materials and nondigital information through a cluster of small objects [24, 27, 28]. The manipulation of the 3D position of the levitated objects has already been shown, but a true mid-air physical display has not yet been demonstrated. Such a display will have free floating objects in a large volume which users will be able to reach or walk through, and see, feel and control each object independently. We envision the use of a levitation technique to float the objects and a force field to control each object independently. Also, each object could present multi-modal visual, olfactory etc. sensory experiences independently.

A levitated objects based display could improve user experience (UX) of a tabletop or mobile device significantly. Currently, the space above tabletops and mobile surfaces is mostly used for social interactions and collaboration. Extending the display surface to the space above can improve UX, e.g., the quality of applications involving 3D data and tasks [8]. Using floating objects in this space can additionally provide an interactive interface to visualize digital information. As the levitated objects could be loosely packed providing a partially see-through interface, it could facilitate sharing information and collaboration. Using physical objects for information visualization can support effective and efficient communication, learning, problem solving and decision making [12].

To build a floating objects based display, a levitation system is required which could also control the 3D position of a 3D grid of levitated objects. If the objects are small in size and lightweight, then a large number of them could be levitated to enhance user perception and interaction. For the levitated objects to present different sensory experiences, a preparation technique to impart different properties to the objects and an excitation technique to address individual objects is required. In this paper, we present JOLED: Janus Object Levitated Electro-rotated Display, which is a floating object based mid-air display. An acoustic levitation technique is developed for 3D position control of small light-weight objects. Janus objects, which present different physical properties on different faces are used. A novel electrostatic field based rotation control is developed to address each Janus object independently.

The contributions of the JOLED technology are:

- *A mid-air display using Janus objects*: The voxels in the mid-air display are Janus objects, i.e., they have two or more different faces which are coated with different materials to present different physical properties. For example, they could be differently colored, dark, transparent, diffusive, specular or retro reflective on different faces.
- *An electrostatic charging and rotation control technique*: The voxels are partially coated with dielectric microparticles such that an electric field can be used to electrically charge them by electrostatic charge induction. The electrostatic force generates a torque on the voxel until it gets aligned along the direction of the electric field. This allows the user to control the rotation of the voxels.
- *A reflective see-through display*: The voxels do not emit light or need light from a projector to show information. Transparent indium tin oxide electrodes are used to control the orientation of loosely packed voxels without occluding the field of view.
- *A multi-dimensional bistable display*: The 3D position and horizontal orientation of the levitated voxels are continuously controlled. They can maintain their orientation without power using the stored charge among the electrodes.
- *A customizable display*: A range of light-weight electric insulator materials could be used as JOLED voxels. The voxels are replaceable with different Janus objects with different properties.

JOLED allows users to design the display in many ways, e.g., the levitated voxels can be positioned in user-defined shapes. Acoustically transparent physical structures can be placed inside the levitation volume to make custom designs.

RELATED WORK

ZeroN is a tangible user interface that uses magnetic levitation and control of one object in a predefined volume [16]. The physical voxel is one large permanent magnet which is levitated using solenoids. An optical tracking and display system is used to project images on the levitated object. Users can put the voxel at desired locations and create custom effects such as a planet revolving around its sun.

Pixie Dust is a physical graphical interface that can levitate and control a 2D grid of objects synchronously in a predefined volume [24]. The physical voxels are mostly expanded polystyrene (EPS) beads, which are acoustically levitated using ultrasonic transducers. A projection system is calibrated to the bead positions, and used to create custom physical visualizations. For example, users can put the beads at desired locations manually with background objects such as a toy whale to create custom effects such as a whale's spout.

LeviPath is a physical visualization interface that can levitate and control multiple objects synchronously in a predefined volume [27]. The physical voxels are EPS beads, which are acoustically levitated using ultrasonic transducers. The voxels are moved synchronously in a 3D path to visualize 3D line data or graphic curves. LeviPath and Pixie Dust use two and four modules of phased arrays, i.e., 2D-array of ultrasonic transducers, facing each other to create standing waves and allow users to view from four and two sides, respectively.

Floating Charts is a physical visualization interface that uses two modules of phased arrays in various arrangements. Users can levitate single EPS beads using one-sided modules, and control their heights to create dynamic floating charts [28]. Using a single phased array, the 3D position of a single EPS bead and the horizontal orientation of a single EPS disc are controlled [19]. .

In the above related works, the levitated objects have a single color per voxel. They need an external projector with a camera based calibration system to present more than one visual properties with a voxel. Individual control of orientation of voxels in a 2D grid has not been reported.

Mid-air see-through interfaces have been made using nonsolid diffusers such as fog, smoke or condensed air. A simple 2D mid-air interface uses a laminar screen of fog and an external projector [30]. Depth-fused interfaces use multiple fog screens and projectors [15, 18, 38]. The physical voxels in these displays are the microparticles of fog or smoke. To make a 2.5D fog screen, the fog particles are electrically charged and controllably bent using the electric fields between transparent electrodes [31]. In Poppable display, a soap film acts as the mid-air surface [26]. A projector is used to display images which are deformable using a 2D array of ultrasonic transducers. SensaBubble and Bubble Cosmos use fog-filled bubbles as the physical surface in mid-air [21, 33]. The bubbles are tracked and a projector is used to present graphic content. HoloDust is a mid-air see-through display that uses suspended dust particles in the air as the physical voxels [29]. A particle tracker and scanning projector is used to create graphic content. A mid-air see-through interface using water drops as physical voxels has been built [6]. A multilayered interface is built using three parallel screens of synchronously falling water drops [4]. The water drops are tracked using a camera, and a projector is used to project graphic content. SplashDisplay is a mid-air display that used projectile beads from a tabletop as the physical voxels [20]. A camera and a projector is used to create tangible splash or explosion like effects. All these approaches rely on light projection and require calibration.

Mid-air displays that do not rely on tracking and light projection have been built using focused infrared pulsed laser [32, 13, 25]. The physical voxels are the plasma in air that are created by the high-power laser. The voxels emit light, and make up a monochromatic display. These mid-air interfaces are standalone devices that do not allow integration with other physical structures to make user-defined designs.

Janus objects

Janus objects have two or more distinct asymmetric physical or chemical properties on their surface at different areas. Janus particles are commonly used in chemistry as they allow two different types of reactions to occur on the same particle. The Janus particles are made by fusing different materials, or their surface is coated with different materials.

The Gyricon electronic paper (e-paper) used bichromal and bipolar Janus microspheres, which were manufactured by fusing two different materials [11]. The black hemisphere was negatively charged and the white hemisphere was positively charged. Each microsphere floated and rotated inside an oil-filled cavity. A voltage was applied to transparent silicone sheets to generate electric fields across the Gyricon microspheres. Depending on the direction of the electric field, the microspheres flipped to show their black or white surface to display information. The Gyricon microspheres reflected ambient light and did not emit light or required external projection. The electrophoretic ink (e-ink) e-paper does not use Janus particles. The e-ink capsules are filled with negatively charged white particles and positively charged black dye in an oily solution. The Cospheric e-paper is a reflective display uses bichromal and bipolar Janus microspheres, which are manufactured by hemispherical coating.

Other mid-air technologies

Without using levitated objects, information can be displayed in mid-air using various stereoscopic, augmented and virtual reality techniques [8]. Floating images of 2D displays can also be created in mid-air using two-way mirror [9] or reflective polarizer [34]. On the other hand, JOLED is proposed to improve user experience using physical objects for visualization of information.

OVERVIEW OF JOLED

JOLED is a novel display technology that proposes floating objects in mid-air as embodiments of digital information. The visual expression presented by an individual or a group of JOLED voxels is conveyed by changing their perceived physical properties in addition to their spatial shape. JOLED proposes use of Janus objects as the voxels, which exhibit two or more asymmetric physical properties on their surface. They can be customized and manufactured with different physical properties using different materials. We used expanded polystyrene beads with different colors on its two hemispheres as the voxels. JOLED could use a levitation system to float the voxels and control their 3D position by modulating the levitation force field to create different shapes in mid-air. We propose an acoustic levitation system to levitate and manipulate the 3D position of the EPS voxels. The main feature of JOLED is the independent and individual rotation control of the voxels to show their different surfaces with different physical properties. We present a voxel rotation control technique using electrostatic field and transparent electrodes.

Users can customize their JOLED system by incorporating various physical structures inside the working volume that do not affect the levitation and the rotation fields. We used acoustic transparent and electric insulator materials in our prototypes to build such structures. JOLED offers unique possibilities for direct digital information presentation in mid-air using its linear and rotation manipulation capabilities, or improve user experience of digital information visualization such as interactive data navigation and exploration when integrated with other systems such as a mid-air haptic display [17].

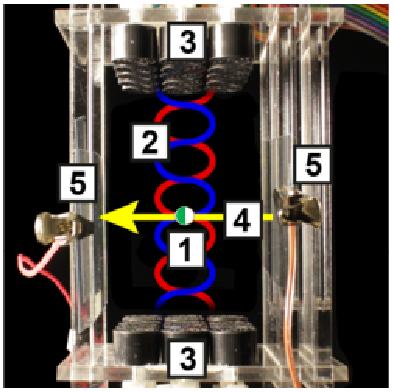


Figure 2. A Janus object (1) is levitated in mid-air using an acoustic standing wave (2) generated between ultrasonic transducers (3). An electric field (4) is created by applying a voltage to the transparent electrodes (5) to rotate the Janus object and change its physical expression.

Working principle

An implementation of JOLED is shown in Fig-2. The physical voxels are suspended in mid-air using acoustic levitation. Ultrasonic wave transducers are placed at the top and bottom of the working volume to create acoustic standing waves. The antinodes of the standing waves act as acoustic traps where the objects are levitated in mid-air. The spatial distribution of the acoustic traps is controlled by controlling the phase delays of the voltage signals applied to the transducers. By modulating the phase delays of the transducers, the locations of the antinodes are gradually moved in 3D to manipulate the levitated objects. Users can customize the arrangement of the ultrasonic transducers.

The voxel is a millimeter diameter and milligram weight object such as an EPS bead, which is made Janus by the user in a laboratory by coating different materials to its two hemispheres. A thin patch of an electric charging material is put on one hemisphere of the Janus voxel. An electric field is applied to the voxel using two transparent electrodes without occluding the users' view. By modulating the voltage applied to the electrodes, the electric field is controlled which changes the orientation of the Janus voxel and consequently the different physical properties presented to the user.

DESIGN PARAMETERS

Making Janus objects

Designing and manufacturing JOLED voxels is at the heart of its implementation. Each JOLED voxel could present a range of physical properties on one or several of its many facets. For example, one facet could be white, positively charged and specular reflective, and another facet could be black, negatively charged and diffuse reflective. The voxel could be made by fusing different materials, e.g., each quarter segment made from cyan, magenta, yellow and black materials. The voxel could have a coating to show a gradient of a property around its circumference, e.g., a grey scale color gradient around a sphere. We used Janus voxels with two faces. However, each face could present multiple properties at the same time, which could be excited at different times.

The JOLED voxels could be designed and made using mm-size light-weight materials such as EPS, aerogel or polymethyl methacrylate (PMMA or Acrylic). For example, a 4 mm EPS bead is easily handled using inexpensive instruments and thin-coated with different materials on its two halves. Different colors and textures are imparted using different paints and powders. The two halves could have different shapes by compressing or cutting these materials. The surface of these objects could be treated, i.e., roughened or thin-coated with a primer material in order to receive a desired material.

Electrostatic charging of levitated objects

Presenting the different physical properties of the JOLED voxels to the users is a critical challenge. The Janus objects could be modified so that the different physical properties are excited on demand. However, the additional modification should be minimally affecting the physical expression of the voxels. We propose controlled rotation of the Janus objects to show its different facets by modifying them in such a way that does not affect their physical expression.

We present a novel technique that can generate electrostatic charge in the levitated Janus objects. We use the *dielectric polarization* mechanism to charge the levitated objects in mid-air. To achieve this, a small patch of dielectric microparticles is coated on the objects. The coating is very thin such that it does not affect the levitation mechanism due to added mass. It can be coated over by other materials such as paint to preserve the physical property of the Janus object. The position, size, shape and number of the patches is designed to allow a desired degree of rotation.

A range of dielectric microparticles including titanium dioxide (TiO_2) can be used to make the chargeable patch. If the dielectric particles have native surface charge then it gets enhanced in the electric field due to polarization. Dielectric powders with higher surface charge and dielectric constant are more beneficial. Designers must be aware of the chemical hazard of the chemicals and take care in handling them, e.g., the electret materials.

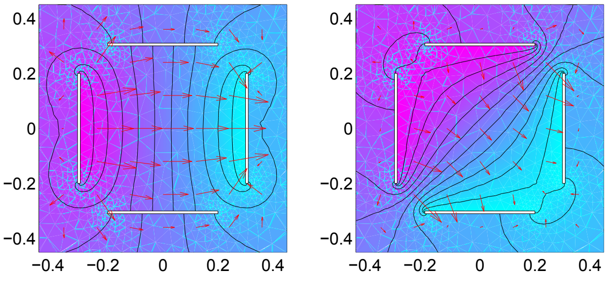
Controlling the rotation of levitated objects

JOLED proposes controlling the angular position of the voxels using an electric field $\vec{E}$ to show its different facets. It operates similar to the Gyricon display, but in mid-air using levitated voxels, where the voxels align themselves along the direction of $\vec{E}$. The Gyricon microspheres were made by hemispherical fusing of two materials with different volumetric electrostatic charge and color. However, we applied a small patch of dielectric material on the surface of the Janus object to induce electrostatic charge in an electric field $\vec{E}$.

We propose using transparent electrodes around the levitation volume to control the rotation of the voxels. The levitated objects need to have electrostatic charge in order to be controlled by an electric field $\vec{E}$. When an $\vec{E}$ is applied across the object, the dielectric patch on the object gets charged by dielectric polarization, and is attracted towards $\vec{E}$. This results in a torque applied to the object. Because the object is levitated in mid-air and is free to rotate, the torque aligns the dielectric patch along the direction of $\vec{E}$. When the object is aligned, the electrostatic force passes through the axis of rotation, resulting in zero torque on the levitated object. When the direction of $\vec{E}$ is reversed or rotated, the dielectric patch reorients itself along $\vec{E}$, which results in flipping or rotating the levitated object.

The electrostatic force on the voxels is smaller than the acoustic trapping force, which ensures they remain levitated. The electrodes around the levitation volume to apply $\vec{E}$ do not to disturb levitation. Also, for physical visualization, use of transparent electrodes such as indium tin oxide electrodes is required not to occlude view. To flip a Janus object to show its two faces, a pair of electrodes on the front and back sides are required. To continuously rotate the object, four electrodes around it are required. To flip the objects, reversal of polarity of the voltage applied to the pair of electrodes is enough. To rotate the object, the voltages applied to the four electrodes need modulation. The design parameters available are the shape, size, position and orientation of the electrodes, the number of electrodes and the voltages applied to different electrodes.

The direction of $\vec{E}$ between two parallel plate electrodes is normal to the electrode surface from the positive electrode towards the negative or ground electrode. The direction of $\vec{E}$ near the edge of the electrodes is curved showing a fringe field. The parallel plate configuration can be used for each levitated object. Using a pair of electrodes, the direction of the electric field is flipped by reversing the voltage applied to them. This way, individual objects are flipped independently in a 2D grid. The shape and size of the electrodes decide whether $\vec{E}$ at the object has a straight or a curved direction. If the electrodes cover the object entirely then the direction of $\vec{E}$ is a straight line. In that case, the electric field strength $E = V/d$, where V is the voltage applied between



(a) (b)

Figure 3. The electric field (red arrow) and potential (black line) distributions are shown. In (a), positive and ground voltages are applied to the left and right electrodes, and the top and bottom electrodes are floating. In (b), positive voltage is applied to the left and top electrodes, and ground voltage is applied to the bottom and right electrodes.

the electrodes and d is the separation between them. The surface charge density at the electrodes, $\sigma = \epsilon E$, where ϵ is the permittivity of air. The induced surface charge density on the object, $\sigma_{ind} = (1 - 1/\epsilon_r)\sigma$, where ϵ_r is the dielectric constant of the dielectric microparticles. The induced electrostatic pressure on the object over the coated area, $p_{ind} = E\sigma_{ind}$. The voltage V applied to the electrodes and the separation d should be such that p_{ind} can overcome the acoustic torsion pressure that prevents the object from rotating. This acoustic pressure is minimal when the acoustic pressure filed is circular symmetric and the object is a sphere. Because the levitated objects could have an arbitrary shape, the acoustic torsion pressure is nonzero, albeit small. V and d are chosen experimentally. An approximate value of V and d can be obtained using above equations. If the shape and size of the electrodes are such that the curved fringe field passes through the object, then these parameters can be chosen experimentally. If the pair of electrodes are not parallel, then $\vec{E}$ lines are not straight and the surface charge density on the electrodes σ_{ind} is not uniform. A solution for $\vec{E}$ can be derived using the analysis for calculating the capacitance of inclined plate capacitors [36, 37].

The direction of $\vec{E}$ between four electrodes, on the other hand, depends on the shape and size of the electrodes, and separation, inclination and voltage applied among them. In literature, the conformal transformation of SchwartzChristoffel (S-C) mapping has been used to develop the analytical solution for $\vec{E}$ in the space between four electrodes. Similar analysis is presented to calculate the impedance and electrophoretic force in micro-fluidic devices [5, 10], and to calculate the capacitance of inclined plate capacitors [37]. We do not present the analytical solution in this paper. Designers can simulate $\vec{E}$ among four electrodes with various shape, size, separation, orientation and voltages using an electrostatic simulation software. Fig-3 shows $\vec{E}$ between four rectangular electrodes using Matlab simulation. The high voltage (magenta) is 1 kV and the low voltage (cyan) is 0 V. In Fig-3 (a), the voltage is applied between the left and right electrodes, and the top and bottom electrodes are floating. In Fig-3 (b), equal high voltages are applied to the left and top electrodes, and ground is connected to the right and bottom electrodes. By switching and modulating the voltage applied to the four electrodes, the $\vec{E}$ is gradually rotated in the space enclosed by the four electrodes. In JOLED application, we allowed the user to control the direction of $\vec{E}$. Designers could use different number and configurations of electrodes to create custom distribution of $\vec{E}$ and effects for a 2D grid of objects, which are controlled synchronously in a group.

Driving electronics

High-voltage (HV) in the ± 1–5 kV DC range is required for rotation control when the electrodes are separated by tens of millimeters. Commercial HV supply with current limiter should be used. Designers could build custom HV supplies using CockcroftWalton multiplier circuit, which generates HV DC output from low-voltage AC or pulsed DC input.

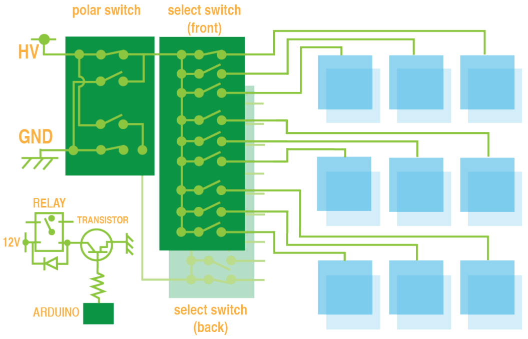


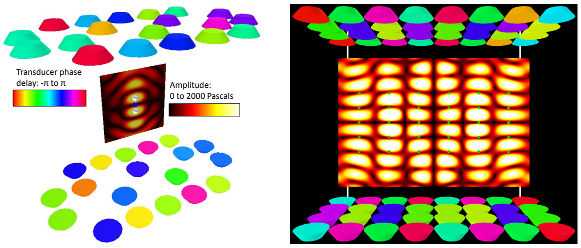
Figure 4. A schematic of a HV switching circuit to drive 3×3 electrodes serially is shown. The back side is connected in parallel to the front side at the polar H-bridge switch.

To switch between the voxels, different topologies such as active matrix, passive matrix and segment driving circuits could be used to select the electrodes. However, active matrix implementation would require HV transistors. Passive matrix high-impedance mode operation could lead to interference between the voxels. Segment driving with one common electrode would require optimization of electrode shape and size to reduce interference. Individual control of voxels requires dedicated electrodes to avoid interference. Fig-4 shows the H-Bridge topology used to build the switching control circuit. It reverses the polarities of the electrode pairs to flip the voxels, as well as provide a floating state so that the electrodes can retain charge for bistable operation.

Controlling the acoustic field

A 2D grid of floating objects is levitated and manipulated in 3D using an acoustic levitation system, which used four ultrasonic phased arrays on the top, bottom, left and right of the levitation volume in [24]. However, visualization experience is improved by using two ultrasonic phased arrays at the top/bottom or left/right by providing more viewing space and angle while manipulating an object in 3D [19, 27, 28]. We have extended this approach and present a new capability to manipulate the 3D position of a 2D grid of levitated objects using two sets of ultrasonic phased arrays. Moreover, this technique is useful with many possible user-defined custom arrangements of ultrasonic transducers.

This approach relies on minimizing the Gorkov potential [35] and its gradient of a spherical object, which results in maximizing the acoustic trapping force on the sphere [19]. The user specifies the arrangement of the transducers and the levitation location by a three-points antinode-node-antinode pattern. The Broyden-Fletcher-Goldfarb-Shanno optimizer [22] provides the phase pattern of the transducers, which creates the levitation point at the specified locations in 3D acoustic field (see Fig-5(a)). The resultant standing wave also levitates objects of various other shapes such as cube and disc. The optimizer runs in real-time allowing users to interactively manipulate the 3D positions of the levitated objects.



(a) (b)

Figure 5. (a) An optimal levitation point with a user-defined arrangement of transducers is shown. (b) A 2D grid of levitation points with optimal phases of the transducers and the pressure field is shown.

To make a 2D grid, the optimization function is modified to include the three-point pattern specified in at each location on the grid, which should be separated by $\lambda/2$ (see Fig-5(b)), where λ is the wavelength of ultrasound emitted by the transducers. Sequential control points are specified to move the resulting grid up, down, forward or backwards smoothly. The optimization function gives the new phase patterns for the new control points, and the voxels are translated by changing the phase of the transducers gradually. Similarly, to tilt the 2D grid, the three-points patterns are specified tilted. The proposed method also works when a reflector is used for levitation. The reflector is modelled as an acoustic mirror, where the existing transducers are mirrored. However, it only supports 2D movement similar to [7]. Because we use phase modulation instead of amplitude modulation, stronger levitation points are created. The proposed approach could be extended to levitate and control the 3D position of a 3D grid of objects. It could support user-defined arrangement of transducers and 3D pattern of levitation points. Designers could test for different working arrangements. However, the levitation locations must be separated by integer multiple of $\lambda/2$.

Power consumption

An estimate of power consumed by a JOLED system is calculated by considering the electrostatic and acoustic subsystems separately. The power P_{es} consumed to establish the electrostatic field depends on the capacitance C between the electrodes, the maximum applied voltage V and the switching time T, i.e., $P_{es} = CV^2/2T$. For example, $P_{es} = \epsilon AV^2/2dT$ for flipping a voxel using a pair of parallel electrodes with area A and separation d. However, computation of the capacitance, when four electrodes are used to continuously rotate a voxel, is not available in the literature. The analysis in [5, 10, 37] could be followed to calculate the capacitance C and estimate P_{es}.

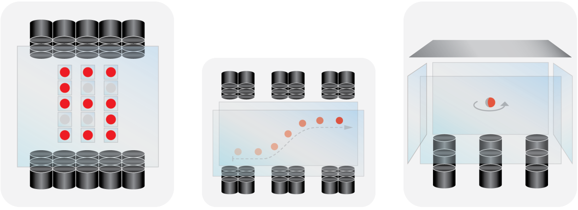

(a) (b) (c)

Figure 6. (a) A bistable display with tightly packed transducers and dedicated electrodes. (b) A 3D game with user-defined configuration of transducers and two electrodes for flipping the voxel. (c) Four electrodes for rotating a voxel, which is levitated using a reflector.

The power P_{ac} consumed to establish the acoustic field depends on the specification of the ultrasonic transducers, i.e., sound pressure L_p (W/m^2) at a distance R (m), directivity α (degrees), input voltage V_{in} (V) and sensitivity (mV/Pa). Assuming that the acoustic power is uniformly transmitted along the directed solid angle, the acoustic power is given by $P_{ac} = 2\pi(1 - cos\alpha/2)R^2 L_p N$, where N is the number of transducers, and they are operated at input voltage V_{in}. If they are operated at a lower voltage, then P_{ac} is reduced proportionally assuming linear transduction.

IMPLEMENTATION

We implemented three prototypes of JOLED: a bistable display, a platform game and a flying car racing game. They are shown in Fig-2, 10 and 11. They have different configurations of the ultrasonic transducers and electrodes, which are described in the applications and shown in Fig-6.

We used 40 kHz ultrasonic transducers (MA40S4S from Murata Electronics, Japan) with diameter of 1 cm, maximum input voltage of 20 V$_{pp}$ continuous rectangular wave, sound pressure level of 120±3 dB (0 dB = 0.02 mPa) measured on the axis at z = 30 cm and directivity of 80° measured at -6 dB points. A custom-made driver board using two L1-128 processors (XMOS, UK) running at 100 MHz was used to drive the transducers and adjust their phases in real-time. A 40 kHz 16 V$_{pp}$ square-wave signal was used to drive the transducers. The driver board generates the signals for 64 transducers at 2 MHz with a phase resolution of $\pi/25$. A computer running a custom software optimized the phases of the transducers for the specified levitation points, and sent them to the driver board through a serial port.

We used EPS beads with 3.5–4 mm diameter and 29.36 g/cm^3 density to make the Janus objects. We applied different colors to the two halves of the EPS beads, and drew arrow marks using permanent marker pen. We used titanium dioxide (TiO$_2$) microparticles (Acros Organics Titanium (IV) oxide, 98%) to charge the beads. The TiO$_2$ powder are white in color, and have density of 4.23 g/cm^3, particle size <44 μm and typical dielectric constant of 85. Polyvinylpyrrolidone (PVP) glue from glue-stick was used to make the dielectric patch on the EPS beads. The coating was very thin such that it did not affect the levitation mechanism due to added mass. The patch was painted over when required.

We used two 1.5 mA and 0.1 mA commercial 10 kV DC power supplies (MJ10P15 from Glassman High Voltage Inc. and DX100R from EMCO High Voltage Corp.) and HV relays (DPF1A-12-13, Sankyo), which have a voltage limit of 13 kV and trigger voltage 12 V and current 1 A [1]. The relays were synchronised using a programmable switching circuit built using an embedded microcontroller (LPC1768, NXP Semiconductors, Netherlands). We could operate the relays at frequency >100 Hz.

EVALUATION

To evaluate the performance of JOLED, we used the prototype shown in Fig-2. It uses two tightly packed 3×5 array of ultrasonic transducers at the top and bottom with a separation of 64.5 mm. The separation between the ITO electrodes at the front and back was 40 mm.

Electrostatic force required to flip EPS spheres

The success rate of flipping 3.5 mm diameter EPS beads at various electrostatic forces was evaluated experimentally using different combinations of voltages (i.e., 3, 6, and 9 kV), separation between the electrodes (i.e., 20, 40, 60, 80, 100 and 120 mm) and width of the electrodes (i.e., 3, 6 and 9 mm). The weight of TiO_2 coating was approximately 100 μg.

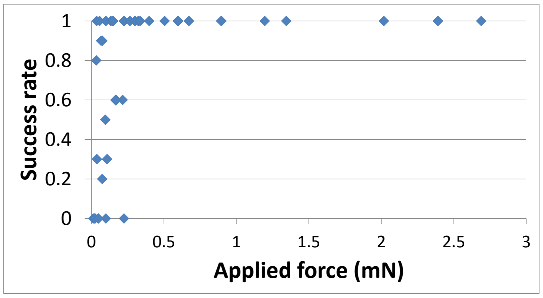


Figure 7. Success rate of flipping a 3.5 mm EPS bead at various electrostatic force values is shown.

The flipping rate at various electrostatic force values are shown in Fig-7. 100% success rate of flipping was achieved above 400 μN force, i.e., 0.7 μN·m maximum torque. The force was calculated using the theory of parallel plate capacitor. This result is useful to calculate the minimum voltage required to flip levitated spherical objects for a given electrode size and separation.

Flipping speed

In addition to measuring the minimum electrostatic force required to flip 3.5 mm EPS beads, we also measured the flipping speed of the beads at various electrostatic force values. The experiment was conducted with voltage fixed at 6 kV, width of the electrodes fixed at 6 mm, and the separation between the electrodes were 20, 40, 60, 80, 100 and 120 mm.

The flipping speeds at various electrostatic force values are shown in Fig-8. The angular acceleration is proportional to the torque generated by the electrostatic force, which is shown in the figure. The maximum flipping speed we consistently achieved was 4.76 deg/ms, i.e., 26.44 flips/sec. The flipping speed indicates the refresh rate of our JOLED implementation, which is video-rate.

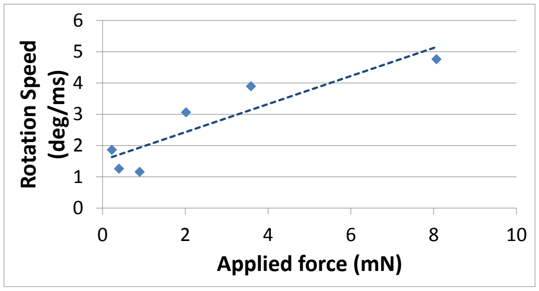


Figure 8. Flipping speed of a 3.5 mm EPS bead at various electrostatic force is shown.

Power consumption

The electrostatic power consumption using a pair of parallel 30 mm × 80 mm rectangular electrodes with d = 64.5 mm, V = 3.5 kV and T = 37.8 ms is P_{es} = 53.3 μW. The acoustic power consumption using 40 kHz transducers MA40S4S from Murata Electronics Ltd. with L_p = 1 W/m^2 at 30 cm, $\alpha = 80^\circ$ and V_{in} =20 V is P_{ac} = 132 mW per transducer. In our prototypes, V_{in} was limited to 16 V, and each transducer required 9 mA current, which gives power consumption of 8.64 W using 60 transducers.

ENABLED APPLICATIONS

We present three applications that cannot be developed using existing technologies, and are uniquely enabled by the JOLED technology. The first application is a mid-air 2D reflective display that uses flipping of levitated voxels to visualize data and text etc. The second application is a mid-air platform game that uses the linear translations of a levitated voxel to jump obstacles along with flipping to show emotion. The third application is a mid-air racing car game that uses the linear manipulation of the levitated voxels to fly around the track and continuous rotation to show moving direction. The later two applications demonstrate the user customization capability of JOLED by integrating external physical structures inside the levitation volume. All the pictures shown in the paper are taken in normal ambient lighting conditions without using any custom illumination. It demonstrates the reflective display capability of the JOLED technology.

Mid-air physical visualization

In Fig-1(a), the levitation area of the first implementation of JOLED is shown. Two 3×8 arrays of ultrasonic transducers with an area of 30 mm × 80 mm were placed facing each other from the top and bottom at a separation of 64.5 mm. A 2D grid of levitated voxels with 6 columns and 7 rows of 3.5 mm diameter EPS beads is shown. The display area is approximately 55 mm × 29 mm. A pair of 50 mm × 120 mm ITO transparent electrodes were placed at the front and back of the display with a separation of 40 mm.

In Fig-1 (a) and (b), we show a dynamic image of an emoticon winking its left eye. A Janus EPS bead with one side red and another white, and a dielectric patch was used as the left eye. TiO_2 powder was glued over a 1 mm^2 area on the white

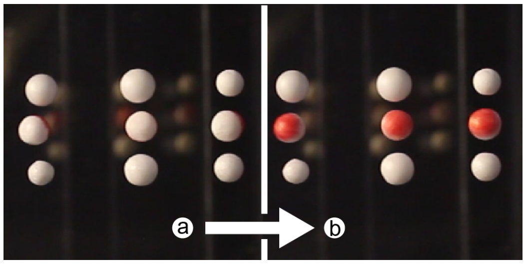


Figure 9. The bistable voxels can flip from the white side (a) to the red side (b).

side. Red colored EPS beads were used to make the right eye and the lips. Rest of the display was made with white EPS beads. A voltage of 3.5 kV DC was switched between the back and front electrodes in order to switch the electric field at the charged voxel. The TiO_2 patch gets charged due to the dielectric polarization effect and a force is exerted by the electric field at the patch location. As a result, a torque is applied on the bead which rotates and aligns it along the direction of the electric field. The torque is zero when the TiO_2 patch is facing the positive electrodes. When the direction of the electric field is switched, a reverse torque is generated and rotates the bead towards the opposite side. By alternating the voltage signal, a winking effect is created.

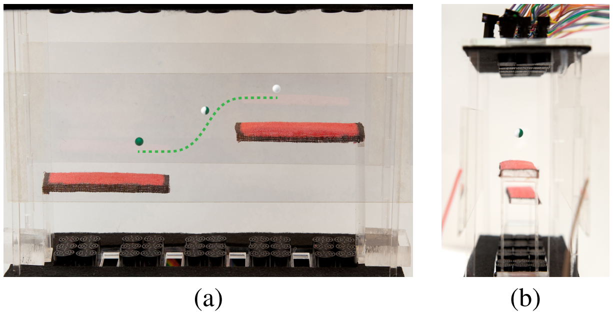
The JOLED implementation in Fig-1 (a) and (b) is a *bistable* display because it has only two global states for the voxels which are retained even after switching off the voltage supply to the electrodes. This happens because the two parallel electrodes act as a parallel plate capacitor. When the voltage signal is switched off without grounding the electrodes leaving them in a floating state, they retain charge and the electric field until the charge is leaked to the surrounding. For this reason, the display keeps its image even after switching off the voltage supply. Note that the levitation system still needs power supply; without it, the ultrasonic transducers stop emitting and the levitated voxels fall down.

In Fig-9 (a) and (b), we show flipping of multiple voxels. In this case, the three EPS beads in the middle row are Janus with red and white sides, and modified using the charging technique. When the electric field is switched between the front and back electrodes, the three voxels rotate by 180° in sync. Fig-9 (c) shows that users can make custom visualization effects by customizing the voxels such as their location, size, colour and multiplicity. For instance, the winking effect could be recreated using a Janus voxel at the top right.

Mid-air 3D physical games

JOLED can be used to build novel customizable interactive physical 3D interfaces. We present two such implementations to demonstrate this capability.

A time-lapse image of a platform game with a character jumping in mid-air from the upper right platform to the lower left platform is shown in Fig-10 (a). The game character is represented by a Janus EPS bead which is half green and half white. The TiO_2 dielectric patch is placed on the white side. The bead is levitated by placing ultrasonic transducers above and below the platforms. We used a different configuration of 60 ultrasonic transducers, i.e., 5 groups of 2×3 transducers with 10 mm gap between the groups placed facing each other from the top and bottom. The proposed acoustic field control algorithm was used to update the phases with a moving antinode-node-antinode pattern. The view area was 130 mm× 115 mm. A pair of 50 mm × 150 mm size ITO transparent electrodes were placed at the back and front of the platforms with a separation of 40 mm. An acoustically transparent fabric (felt) was mounted on top of laser-cut optically transparent acrylic stands to make the platforms. In spite of the loosely packed ultrasonic transducers, the levitated voxel could be manipulated in the entire 3D space including above and below the felt platforms. The bead was flipped to show the green or white face by switching the polarity of 3.5 kV DC voltage applied between the electrodes.



(a) (b)

Figure 10. Mid-air 3D platform game: a) A game character represented by a Janus voxel successfully jumps from the upper right platform to the lower left platform in mid-air. The successful jump changed the mood from blank to colorful. b) Side view of the mid-air 3D interface.

The aim of the game was to successfully jump from the upper-right platform to the lower-left platform. If the jump was successful, then the blank (white) character became colorful (green) showing a change in mood. If the jump was not successful then the mood did not change. Users controlled the lateral movement using the left and right arrows, and the jump using the space bar on a keyboard. Six users played the game (2 females and 4 males; age 23–37). They seemed visibly excited and gave us positive feedback about this new physical game.

Figure 11. Mid-air 3D racing game: A flying car like character going under a bridge following a curved path is shown from top. The orientation of bead is controlled continuously to show the heading direction.

A time-lapse image of a flying car over a racing track (topview) is shown in Fig-11. The car character is represented by a Janus EPS bead which has a 1 mm^2 TiO_2 dielectric patch on one side. An arrow painted on top is showing the heading direction of the car. The bead is levitated by placing ultrasonic transducers below it and a transparent acrylic sheet 64.5 mm above them which acts as an acoustic reflector. We used a configuration of 60 transducers, 10 rows and 6 columns, with 10 mm gap between each of the transducers, and the proposed acoustic field control algorithm to generate the phase patterns to move the EPS bead. The working area was 120 mm × 200 mm. Two pairs of 50 mm × 100 mm and 50 mm × 180 mm ITO transparent electrodes were placed on the sides of the levitation volume. An acoustically transparent fabric (polyester) and laser-cut acrylic fixtures were used to make the race track. The track had raised areas to represent roads crossing at different heights, and the car could fly above and below the roads. The users rotated the car clockwise or counterclockwise using up or down arrows, and moved the car forward or backwards using left or right arrows on a keyboard. The spatial movement was achieved using acoustic levitation, and the orientation was controlled using the two pairs of electrodes. The voltage was modulated between 0 – 5.5 kV DC and the polarity was switched depending on the track position.

The JOLED implementations for mid-air game used a single voxel. The acoustic levitation algorithm could be modified to levitate multiple voxels. Transparent electrodes could be placed inside the levitation volume to make custom designs such as placing them on the platforms in the obstacle-jump game or beside the tracks in the racing-car game.

DISCUSSION

Safety

Exposure to high level of ultrasound can negatively affect the human auditory system, e.g., leading to temporary threshold shift (TTS), i.e., temporary reduction or loss of hearing which recovers within a relatively short time post-exposure. Maximum permissible levels for airborne ultrasound in the industry is 145 dB SPL at 40 kHz [14], and regular exposure above this limit could lead to noise-induced permanent hearing loss. Designers must take care to avoid over exposure to ultrasound. They could use a calibrated ultrasound microphone to measure the sound level, or use an acoustic simulator to compute the sound level. The maximum sound level in our prototypes using 60 transducers with $V_{in} = 16$ V and focused at 10 cm is 141.6 dB SPL, i.e. <145 dB SPL.

EEEL safety rules [23] for HV recommend operation below 3 mA DC when the voltage exceeds 1 kV DC. The stored energy should not exceed 10 mJ. Designers should use commercial HV supplies that have a current limiter. They must carefully evaluate the stored energy between the electrodes in large or compact JOLED systems that could potentially exceed 10 mJ. The current in our HV supply was limited to 1.5 mA (< 3 mA DC). The stored energy with 30×80 mm^2 electrodes at 64.5 mm separation and 3.5 kV voltage was 2.2 μJ ($\ll$ 10 mJ). JOLED uses transparent electrodes, which are polyethylene terephthalate (PET) sheets coated with nanometer thin layer of indium tin oxide (ITO). The users are exposed to the PET sheet which is an electrical insulator, and the conductive ITO layer faces away from the users.

Scalability

The voxels are loosely packed in our implementation (see Fig-9). The display density is 29.2% using 10 mm diameter planar transducers. The theoretical limit of display density is 39.2% using smaller 8.6 mm (λ) diameter planar transducers. A tight packing with display density of 78.5% could be achieved using nonplanar transducers, which are not commonly available. In this case, smaller electrode designs would be required to optimize the tradeoff between electrostatic torque and interference. Such a system could enable the applications described in introduction. To study scalability, we implemented passive matrix addressing in which each voxel is selected by corresponding row and column electrodes at the back and front. Because the JOLED voxels do not exhibit a threshold for electro-rotation, we observed noticeable cross-talk between the voxels shared by the rows or columns. The active matrix addressing is required for scalability, in which the electrodes of each voxel are isolated from the selected row and column using transistors to eliminate cross-talk. However, this approach requires microfabrition using thin-film technology, which currently does not allow HV operation.

Our display prototype can levitate up to 15 EPS beads in 7.5 cm high columns using 120 dB SPL transducers operated at 16 V. Up to 120 beads in 60 cm high columns could be levitated using 8 times more powerful transducers within the safety limit of 145 dB SPL. More columns could be added using more transducers. The vertical separation between the beads is equal to $\lambda/2$. Thus, more beads could be added using higher frequency transducers.

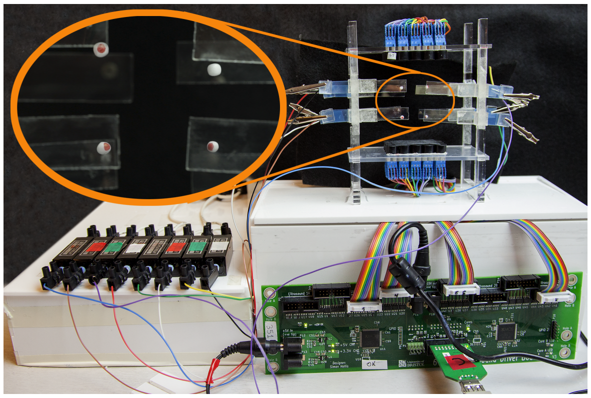


Figure 12. The evaluation prototype with individual control of EPS beads is shown. The exposed electric and acoustic driving circuits belong to their boxes on the left and right.

JOLED could be scaled by allotting dedicated pairs of electrodes to each voxel. In Fig-12, we show individual control of a 2×2 array of voxels. The acoustic levitation system is the same as shown in Fig-2. Each voxel has its own pair of electrodes. They are addressed using the circuit shown in Fig-4. The electrode pairs retain their states even when other voxels are addressed. The voxels are flipped individually as shown by the top-right bead in Fig-12. When a pair of electrodes is switched to flip its local voxel, this motion is not transferred to any other nearby voxel; therefore the scalability of independently addressing voxels is not limited. However, the need for individual connections to the electrodes might impose a limitation to make large JOLED systems with dense array of electrodes. The cross-talk between the pairs of electrodes could be minimized by using smaller electrodes or by increasing the separating between them. To drive a large number of electrodes individually using this method, 3D fabrication could be used to connect to each of the electrodes

The atmospheric absorption and attenuation for 40 kHz ultrasound at 20°C temperature, 1 atmosphere pressure and 45% relative humidity is approximately 1.3 dB/m and 1.25 dB/m [2, 3]. Hence, these phenomenon do not prohibit building large JOLED systems, but they could be considered in the design process.

In our prototypes, the electrodes are placed around the levitation volume, and the acoustic and electric manipulations of the voxels do not interfere with each other. However, rotating individual voxels in a 2D grid requires placing four electrodes around each of them. The breakdown voltage of air is 3 kV/mm, which requires the adjacent electrodes to be separated, e.g., by more than 2 mm for 6 kV DC operating voltage. A transparent insulator such as PET could be used instead as separator for tighter packed operation. Presence of electrodes inside the levitation volume will interfere with the levitation, and will require simultaneous placement of voxels along with the electrodes.

Only one degree of freedom of rotation can be controlled using two pairs of electrodes. However, using three pairs of electrodes around the voxel, three degrees of freedom of rotation could be controlled. Perforations in the electrodes with separation $< \lambda/4$ could allow effective acoustic levitation.

We placed the EPS beads manually. However, because a 2D grid of levitation points can move in 3D, a system could be built to automatically create a 2D grid gradually from bottom up by picking up a row of beads at a time, or from the side by picking up a column of beads at a time. Acoustic levitation using 2D transducer arrays allows rendering volumetric shapes. The Janus objects are individually addressable using dedicated electrodes, which allows parallel manipulation to render a video. Acoustic levitation could allow direct touch interaction using high power transducers.

FUTURE WORK

A promising application of JOLED could be an interactive 2.5D mid-air reflective display using tightly packed Janus voxels, which are translated and rotated independently to show different images by reflecting ambient light. A killer application of JOLED could be a 3D display where the media or characters could change their collective shape, size and appearance using translation and rotation of tightly packed Janus voxels. This would be a disruptive innovation for a range of applications including data visualization, exploration, animation and gaming using mobile, tabletop or standalone devices. However, key innovations in Janus object preparation and their levitation, manipulation and excitation are required.

Janus objects: Users could easily customize the millimeter size ESP beads with different materials, and a range of physical properties could be presented. For example, they could be a combination of dark, or specular, diffusion or retro reflective. The physical properties in future could combine sensory materials such as visual, tactile and olfactory etc. to provide multi-sensory experience. The Janus voxels could exhibit more than two or a gradient of a physical property over its surface or volume to provide a continuous range of physical expression.

Levitation system: Other levitation systems such as magnetic levitation could be developed to float and move suitable JOLED voxels in mid-air. To rotate the voxels, other techniques such as magnetic or acoustic manipulation could be developed. Selected physical expressions could be presented without rotation of the voxels by exciting the voxels using other mechanisms such as UV, visible and infrared lasers when they are coated with suitable materials.

CONCLUSION

Mid-air physical displays can improve user experience via improved perception and interaction. Recent research in tangible user interfaces, visualization and graphics has been motivated toward physicalization of digital information. Previous research relied on projection of digital content on the floating physical objects rather than the objects expressing a variety of digital information effectively by themselves. With the JOLED concept, we present Janus objects that can present different physical properties on its different facets, and allow visualization of digital information with small form factor and low energy consumption. We have shown methods to materialize JOLED displays with a combination of acoustic levitation and electro-rotation. The former is used to hold and translate the voxels in mid-air and the latter to orientate the voxels and display their different facets. Three enabled applications, i.e., a bistable display and two physical games are presented to demonstrate the unique capabilities of JOLED. We have presented the design-space and evaluation methodologies for interested users.

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