A volumetric display for visual, tactile and audio presentation using acoustic trapping

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Science-fiction movies portray volumetric systems that provide not only visual but also tactile and audible three-dimensional (3D) content. Displays based on swept-volume surfaces1–3, holography3, optophoretics4, plasmonics5 or lenticular lenslets6 can create 3D visual content without the need for glasses or additional instrumentation. However, they are slow, have limited persistence-of-vision capabilities and, most importantly, rely on operating principles that cannot produce tactile and auditory content as well. Here we present the multimodal acoustic trap display (MATD): a levitating volumetric display that can simultaneously deliver visual, auditory and tactile content, using acoustophoresis as the single operating principle. Our system traps a particle acoustically and illuminates it with red, green and blue light to control its colour as it quickly scans the display volume. Using time-multiplexing with a secondary trap, amplitude modulation and phase minimization, the MATD delivers simultaneous auditory and tactile content. The system demonstrates particle speeds of up to 8.75 metres per second and 3.75 metres per second in the vertical and horizontal directions, respectively, offering particle manipulation capabilities superior to those of other optical or acoustic approaches demonstrated until now. In addition, our technique offers opportunities for non-contact, high-speed manipulation of matter, with applications in computational fabrication7 and biomedicine8.

Operating principles of the MATD

To create visual content, we levitate a 1-mm-radius, white, expanded polystyrene (EPS) particle as a good approximation to a Lambertian surface. Such a particle allows the use of predictive models of acoustic trapping forces, as well as a simple analytical model to describe the perceived colour under controlled illumination (see Methods, ‘illumination control’). The hardware-embedded computation of the twin trap (see Methods, ‘Embedded computation of twin levitation traps and focusing points’) provides controlled and fast levitation of our scanning particle and is synchronized with a diffuse illumination
module (RGB light-emitting diodes, LEDs). This allows the creation of a POV display with accurate control of the perceived colour (gamma-corrected with $\gamma = 2.2$) that can deliver 2D or 3D vector contents by POV (Fig. 1b, c, e) or fully rasterized contents (Fig. 1d; exposure time, 20 s), even under conventional indoor illumination conditions (see Supplementary Video 4).

Our tests (see Methods, ‘Linear speed tests’ and ‘Acceleration, sharp corners and minimum radius of curvature’) revealed high scanning speeds and accelerations, much higher than those of optical or acoustic setups demonstrated until now. The most critical display parameters are summarized in Table 1 according to the various modes of operation of the MATD: single particle with no amplitude modulation (visual content only), single particle with minimum amplitude (in the worst-case scenario, displaying visual and audio content) and time-multiplexed dual trap with minimum amplitude (in the worst-case scenario, delivering all visual, audio and tactile content). The trapping forces and achievable speeds and accelerations vary with the direction of motion of the particle (that is, they are highest in the vertical direction). Table 1 provides the maximum displacement parameters along the horizontal direction (in the worst-case scenario, with weaker trapping forces) as conservative reference values that allow content reproduction independently of the particle direction.

The parameters in Table 1 are used to compute and plan paths to create POV content visible to the naked eye. Human eyes can integrate different light stimuli under a single percept (that is, a single shape or geometry) during short periods of time (0.1 s is usually accepted as a conservative estimation, even in bright environments23), and thus our particle needs to scan the content in less than this time (0.1 s).

Our parameters allow us to determine feasible paths (particle speed, acceleration and curvature within the limits identified), which can be revealed in less than 0.1 s by exploiting only a fraction of the display’s capabilities. The example letter in Fig. 1b (traced at 12.5 Hz, 1 × 2 cm²) requires particle speeds of up to 0.8 m s⁻¹, whereas the face and 3D torus knot in Fig. 1c (10 Hz, 1.8 cm diameter) and Fig. 1e (10 Hz, 2 cm side) require speeds of 1.3 m s⁻¹. Our volumetric contents showed no substantial flicker and good colour reproduction (Fig. 2a), independently of the viewer’s location (Fig. 3a, b). Figure 2a shows examples of colour tests performed with vector images (numbers, as in a seven-segment display) and good colour saturation. Brighter images can be obtained by adding extra illumination modules or more powerful LEDs (details in Methods, ‘Illumination control’).

Figure 2b shows the ability of the MATD to create additive and grayscale colours, and Figs. 1d, 2c, 3c show examples of raster colour content in two and three dimensions, similar to those created by Smalley et al., using particle speeds of up to 0.6, 0.2 and 0.9 m s⁻¹, respectively. The effects of the particle scattering properties (that is, the perceived colour around the particle), the particle speed (that is, the illuminance affected by the path length) and the human response (that is, nonlinear luminance response) must be considered for accurate colour reproduction (see Methods, ‘Illumination control’).

Mid-air tactile feedback at controlled locations (for example, the user’s hand) is created by using a secondary focusing trap and custom multiplexing policy (position, but not amplitude, multiplexing with

Table 1 | Main parameters of the MATD

|                         | Visual only | Visual and audio | Visual, audio and tactile |
|-------------------------|-------------|------------------|--------------------------|
| Highest speed recorded, $v_{\text{max}}$ (m s⁻¹) | 3.75        | 3.375            | 2.5                      |
| Highest acceleration recorded, $a_{\text{max}}$ (m s⁻²) | 141         | 122              | 62                       |
| Highest speed for corner features, $v_{\text{corner}}$ (m s⁻¹) | 0.75        | 0.5              | 0.375                    |
| Highest image frame rate until now (Hz) | 12.5        | 10.0             | 10.0                     |
| Colour (bpp)            | 24          | 24               | 24                       |
phase-difference minimization; details in Methods, ‘Operational modes and multiplexing strategies for single and dual traps’). Well differentiated tactile feedback was delivered using only a 25% duty cycle for tactile content. Thus, 75% of the cycles could still be used to position the primary trap, and the tactile content resulted in minimum loss of scanning speed. For our experiments, we chose a modulation frequency of 250 Hz, avoiding the primary range of human auditory perception24 (2 kHz–5 kHz) to minimize parasitic noise, but remaining well within the optimum perceptual threshold of skin Lamellar corpuscles for vibration25. The 10-kHz update rate for tactile stimulation is sufficient for spatio-temporal multiplexing strategies to maximize the fidelity of mid-air tactile content26. Our results (see Methods, ‘Tactile generation and quality’) show accurate positioning and focusing of the tactile points and sound pressure levels greater than 150 dB, well above the threshold of 72 dB required for tactile stimulation27 (illustrated in Supplementary Video 5).

Audible sound is created by ultrasound demodulation using upper-sideband amplitude modulation28 of the traps. Our sampling at 40 kHz encodes most of the auditive spectrum (44.1 kHz), and the high-power transducer array produces audible sound even for a relatively small modulation index ($\alpha = 0.2$) while still modulating particle positions and tactile points at the 40-kHz rate. Figure 2a shows three examples of visual content with simultaneous audible content of 60 dB. For simultaneous auditive and tactile stimulation, we combine the 40-kHz multifrequency audio signal with the tactile modulation signal (250 Hz), maintaining the sampling frequency of the individual signals and reducing losses in audio quality (Supplementary Video 1). The MATD supports two modes for audio generation (see Methods, ‘Audio modes supported’). The first mode uses the trapped particle as a scattering medium that implicitly provides spatialized audio29 (that is, sound coming from the content displayed), but in our experience, such directional cues are weak (most of the sound comes from the centre of our working volume). The second mode uses the secondary trap to steer sound towards the user, resulting into a stronger directional component and higher sound levels. However, the use of directional audio currently comes at the expense of delivering simultaneous tactile feedback (simultaneous visual, tactile and directional audio would require multiplexing of three traps—one for each modality).

**Performance of the MATD**

Our instantiation of the MATD presented here was created using low-cost, commercially available components, making it easy to reproduce...
but also introducing limitations. Our tests were performed at a transducer voltage allowing continued usage (12 V peak to peak). Tests at higher voltages (15 V peak to peak, duration ~1h) indicate that increasing the transducer power can result in better performance parameters (for example, maximum horizontal speed of 4 m s\(^{-1}\)) and more complex content. Increased power would also allow operation of the MATD at a 50% duty cycle, further reducing audio artefacts (see Extended Data Fig. 7d). Similarly, transducers operating at higher frequencies (that is, 80 kHz) can also improve audio quality and, combined with a reduced transducer pitch, would improve the spatial resolution of the levitation traps (more accurate paths of the scanning particle).

The MATD demonstrated the possibility to manipulate particles by retaining them in a dynamic equilibrium (rather than a static one, as most other levitation approaches; see Methods, ‘Linear test speeds’), enabling the high accelerations and speeds observed. The use of models that accurately predict the dynamics of the particle (that is, in terms of acoustic forces, drag, gravity and centrifugal forces, but also considering interference from secondary traps and transient effects in the transducer phase updates) would allow better exploitation of the observed maximum speeds and accelerations, enabling larger and more complex visual content. Alternatively, they could enable a more efficient use of the acoustic pressure, providing similar speeds and accelerations to those of the MATD, but allocating a lower duty cycle to the primary trap. This power could then be dedicated to achieving stronger tactile content or supporting a greater number of simultaneous traps (for example, the three traps required for the simultaneous visual, tactile and directional audio scenario).

More advanced illumination approaches (for example, with galvanometers\(^5\) or beam-steering mechanisms\(^6\)) would allow the use of focused light and brighter displays. The use of several illumination modules around the display would provide greater control on the visual properties of the content displayed. For instance, four illumination modules, one at each corner of the MATD, would allow us to illuminate only the outside part of the globe in Fig. 3c. The hidden parts of the globe would be minimally visible, independently of the user location.

Combining a denser illumination array (for example, a ring of light sources) and the predicted light-scattering pattern of our particle, the total scattered field from the particle can be computed as the linear combination of the scattered fields from each light source. This could be used, for instance, to create visual content approximating various material properties (for example, to make content look metallic or matte), simulating different lighting conditions or even delivering different contents in different viewing directions.

The presence of the user’s hands can distort the acoustic field owing to scattering from the hand’s surface. The power and top-down arrangement of our array provide stable operation as the user’s hand approaches from the sides or front (see Supplementary Video 4). Placing the hand below or above the location of the primary trap (occluding one array) is much more likely to produce failures (that is, the scanning particle being dropped). Close proximity of the secondary trap to the primary trap can also distort the trapping of the scanning particle. We successfully reproduced curvature tests at the maximum speed with the tactile point at 2 cm from the circle; this suggests that whereas tactile feedback cannot be reproduced directly on top of the visual content (to avoid scattering from or directly colliding with the scanning particle), tactile feedback can be created in close proximity to the visual content.

Our study demonstrates an approach to creating volumetric POV displays with simultaneous delivery of auditory and tactile feedback and with capabilities that exceed those of alternative optical approaches\(^7\). Polarization-based photorefractive approaches\(^8\) could match the potential for particle manipulation (that is, speeds and accelerations) demonstrated in this study, but they would still be unable to include sound and touch. The demonstrated MATD prototype hence brings us closer to volumetric displays providing a full sensorial reproduction of virtual content. opening a new avenue for multimodal 3D displays, our device and techniques enable positioning and amplitude modulation of acoustic traps at the sound-field frequency rate (that is, 40 kHz), providing also an interesting experimental setup for chemistry or laboratory-on-a-chip applications (for example, multi-particle levitation and mode oscillations demonstrated in Extended Data Fig. 10 and Supplementary Video 6).

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Methods

Experimental setup overview

Experiments were performed using two opposed arrays of $16 \times 16$ transducers, aligned on top of each other and with a separation of 23.4 cm (see Extended Data Fig. 1). We used Murata MA40S4S transducers (40 kHz, 1 cm diameter (about 1.2$\lambda$, wavelength), 12 V peak to peak, delivering about 1.98 Pa at 1 m distance) for the two arrays and high-intensity RGB LEDs (OptoSupply, OSTCWBTHCIS) to illuminate the particle.

A Waveshare CoreEP4C6 FPGA board was used to receive updates from the CPU (3D position, RGB colour, phase and amplitude), using 10 bits to encode each ($X, Y, Z)$ position (0.25 mm resolution), 24 bits for colour (RGB) and 8 bits for the amplitude and phase of the trap, requiring 18 bytes for each update (9 bytes per array of transducers). An FTDI FT245 protocol at 12 Mbps was used for communication, allowing $40 \times 10^3$ updates per second. The following sections provide details on the relevant aspects of our setup, such as operational modes, technical characterization, multiplexing strategies and experimental tests.

Driving parameters

Transducer operation (phase and amplitude control). The transducers were driven using a 12 V peak-to-peak square wave signal at 40 kHz, producing a sinusoidal output owing to their narrowband response. Phase delays were implemented by temporal shifting of the 40-kHz square wave (see Extended Data Fig. 2a), whereas amplitude control was achieved by reducing the duty cycle of the square wave (that is, reducing the duration of the high period, as in the lower row in Extended Data Fig. 2a). The complex amplitude of the transducers did not vary linearly with duty cycle (that is, a control signal with 25% duty cycle did not result in half the amplitude of a control signal using a 50% duty cycle, see Extended Data Fig. 2b). We performed this mapping by using one transducer and a microphone placed 4 cm from it. We used a GW INSTEK AFG-2225 signal generator to drive the transducer (that is, its square wave, varying phases and duty cycle, as per Extended Data Fig. 1). We used Murata MA40S4S transducers, aligned on top of each other and with a separation of 23.4 cm and local phase updates (as in equation (2)).

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\[
A_t = \sqrt{\frac{\sin^2(\text{duty})}{100\pi}}
\]  

(1)

We stored this function as a look-up table in the FPGA (to map the amplitude to the duty cycle) for efficient computation of the updates at the required rate (40 kHz). This resulted in a modulator providing 64 levels of phase (resolution of $\pi/32$ rad) and 33 levels of amplitude resolution.

Embedded computation of twin levitation traps and focusing points.

The computation of the focus points and twin levitation traps is embedded into the FPGA. For a focus point at position $\rho$ and with phase $\phi$, the phase of each transducer ($\phi_t$) was discretized as follows:

\[
\phi_t \left( -\frac{32}{\pi}kd(\rho, p) + \phi \right) \mod 64
\]

(2)

where $k$ represents the wave number for the frequency used ($k = 2\pi/\lambda = 726.4$ rad m$^{-1}$), $p$ represents the position of each transducer and $d$ represents the Euclidean distance function.

The twin traps were computed by combining a high-intensity focus point (as in equation (2)) and a levitation signature. The levitation signature was implemented by adding a phase delay of $\pi$ rad to the transducers in the top array, as used by Marzo et al.$^{14}$, thus producing traps that maximize vertical forces. The transducer positions and discretized phase delays relative to the distance were stored in two look-up tables in the FPGA, simplifying the computation of the focus point and levitation signature.

Illumination control.

We used one illumination module equipped with high-intensity RGB LEDs (OptoSupply, OSTCWBTHCIS), which was placed on the top right corner of our MATD prototype. The LEDs were driven according to the manufacturer’s parameters (current, 150 mA; voltage, 2.5 V (R) and 3.3 V (G/B)), and gave luminous fluxes of 22 lm (red), 35 lm (green) and 12 lm (blue).

The resulting perceived luminance of the particle (for example, a point in our visual content) for an observer around the MATD can be analytically approximated using the definition of the bidirectional reflectance distribution function (BRDF) as shown in equation (3), and it only depends on the angle $\beta$ between the observer, the particle and the light. The white and diffuse surface of our particle enables us to approximate its BRDF as a Lambertian surface. The small diameter of the particle compared to the distance to the light source allows us to assume that the incoming luminance (the amount of perceived radiant energy emitted per unit area and unit time) is almost constant across the illuminated surface of the particle and has a constant incoming direction (that is, the light source approximated as a directional light). Similarly, because of the large distance to the observer (compared to the particle diameter), we can assume that the direction of the rays from the particle to the observer are also parallel.

The perceived luminance is then the summation of the luminances that are scattered towards the direction of the observer from each fraction of the sphere illuminated by the source and that are visible to the observer, as in equation (3). In the equation, $dF_\beta$ represents the differential of the incoming luminance hitting the particle, $dS$ denotes the differential of the luminance towards the observer at each point of the particle surface, $dS$ represents the differential of the surface and $\theta$ and $\varphi$ represent spherical coordinates:

\[
\frac{dL_{\text{obs}}(\alpha, dF_\beta)}{dF_\beta} = \frac{\int_0^{\pi/2} \int_0^{\pi/2} dL(\alpha, \theta, \varphi, dF_\beta) dS}{\int_0^{\pi/2} \int_0^{\pi/2} dS} - \frac{\int_0^{\pi/2} \int_0^{\pi/2} dS}{dF_\beta}
\]

(3)

Finally, the incoming luminance needs to be corrected for the fraction of time that the particle is actually present in each discretized part of the visual content. The nonlinear human response to luminance (for example, Steven’s power law) needs to be considered; we used a gamma-correction method ($\gamma = 2.2$), similar to the one used in cathode-ray tube monitors, to correct for these effects.

Operating configurations of the MATD, multiplexing strategy and local phase updates

Operational modes and multiplexing strategies for single and dual traps.

The hardware can provide individual phase and amplitude updates at 40 kHz and time multiplexing to simultaneously create several levitation traps (Extended Data Fig. 10a). However, our MATD prototype only requires the use of up to two time-multiplexed traps, a primary twin trap and a secondary focus point, according to two main operating configurations:

(i) Single-trap mode. Only the primary twin trap is present (100% duty cycle, $40 \times 10^3$ updates per second) and loaded with an EPS particle of about 1 mm radius. This levitation trap is used to scan the volume, which, synchronized with our illumination modules, provides the visual
component of the display. Audible sound is generated by sampling the intended 40-kHz audio signal (for example, from a file), which is then used to modulate the amplitude of the transducers in our array.

A single-sided band-modulation method (modulation index, \(a = 0.2\)) is used, resulting in audible sound of \( \geq 60\) dB (that is, at the level of a conventional human conversation; see Methods, ‘Audio modes supported’). We modulate the amplitude while the particle is levitated to create audible sound at the levitation point. Specifically, we use an upper-sideband modulation (see equation (4)), which avoids harmonic distortion and enables simultaneous levitation and audible sound (see Supplementary Video 1). The modulated signal is computed as:

\[
A_{\text{SSB}} = \sqrt{(1 + ag(t))^2 + (ag(t))^2}
\]

where \(g(t)\) represents the audio signal required to be created at time \(t\) and \(\hat{g}(t)\) represents a Hilbert transform of \(g(t)\). The signal was sampled at 40 kHz and the resulting amplitude \(A_{\text{SSB}}\) (from equation (4)) was sent to the FPGA, together with the remaining parameters required for the current update (that is, position, colour and phase), implicitly retaining the synchronization between the visual (position and colour) and tactile content with the audio.

(II) Dual-trap mode. This mode is used for cases where tactile feedback needs to be delivered (for example, only in the presence of the user’s hand). In this case, the primary trap can be set up as above, but it needs to be multiplexed with a secondary trap, which creates the tactile stimulation. Two main parameters need to be considered for this multiplexing: amplitude multiplexing and position multiplexing.

First, amplitude multiplexing relates to the recreation of tactile textures, which involves a modulation frequency that can be detected by the skin’s Lamellar corpuscles (we used an example modulation frequency of 250 Hz). A naive approach would be to multiplex between the amplitude of the tactile signal (250 Hz) and the auditory signal (multiple frequencies) at the expense of the frequency of each individual signal. We instead combine the tactile and audible signals into a single signal at 40 kHz, thus avoiding amplitude multiplexing (see Methods, ‘Audio generation and quality’).

Second, the location of the levitation and tactile traps also requires multiplexing, which we refer to as ‘position multiplexing’ to reflect the fact that the traps are created at different spatial locations. Unlike amplitude multiplexing, position multiplexing affects only the phases of the transducers, and it cannot be avoided in such dual-trap scenarios. In our MATD system, we allocate 75% of the updates (three contiguous updates or 75 μs; update rate, 30 kHz) to recreate the levitation trap and 25% for the tactile stimulation (one update or 25 μs; update rate, 10 kHz).

These high-frequency changes of location (that is, 10⁶ changes between the tactile and the levitation trap per second) introduce sudden changes in the transducer phases, which might force them to operate at sub-optimal frequencies. To alleviate this problem, the phase of the next update (\(\phi_n\) in equation (2)) is set to the value that minimizes the summation of the absolute phase differences between the phase distribution of the current transducer and that of the previous one.

**Testing of experimental conditions.** The inclusion of the features discussed above (amplitude modulation for sound and multiplexing in the dual-trap mode) has implications for the performance of the system. During our tests, we explored three fixed experimental conditions characterizing the operating performance of the MATD in both optimistic and worst-case scenarios.

(i) Optimistic single-trap mode (OSTM), with only the main trap and fixed maximum amplitude (\(A_{\text{SSB}} = 1\)).

(ii) Pessimistic single-trap mode (PSTM), with only the main trap and minimum amplitude (\(A_{\text{SSB}} = 0.83\), equivalent to using the silent section of an audio file).

(iii) Pessimistic dual-trap mode (PDTM), with both traps (75% duty cycle for the primary trap; 25% for the secondary trap) and minimum amplitude (\(A_{\text{SSB}} = 0.83\)). The secondary (tactile) trap has a fixed location, placed horizontally at the edge of the array and at a height equal to that of the centre of the array.

**Technical characterization: particle control, visual, audio and tactile modalities**

**Preliminary characterization: particle sizes and update rates.** Particle sizes influence the performance of the MATD owing to differences in weight and drag effects. From a selection of highly spherical EPS particles of varying sizes (seven categories, with diameters of 1–4 mm), we initially assessed each particle for sphericity defects and then used a measuring setup to characterize them.

Our setup (see Extended Data Fig. 3a) uses a Logitech HD Pro c920 camera located 24 cm above a 10 × 6 cm² measuring bed. Our software automatically detects the measuring bed and uses homography to correct for perspective distortion. This provided a corrected pixel accuracy of <0.1 mm. We then computed the circularity as the ratio of the area to the perimeter (circularity = 4π(area)/(perimeter)²), accepting only particles with circularity >0.9. Each particle was dropped on the bed five times (to capture different angles of the particle) and was accepted only if the circularity test was successful in all five measurements. Our software also returned the diameter of the particle, which we used to classify the particles in seven binned categories (with diameters from 1 mm to 4 mm, ±0.2 mm tolerance for each category). Twenty particles were collected for each category and used during our tests.

We used these initial sets of particles to choose an optimum particle size for our MATD. Extended Data Fig. 3b shows the preliminary speed tests (experimental procedure, as described in Methods section ‘Linear speed tests’) identifying the maximum horizontal-displacement speed for each category. This initial assessment shows an optimum peak speed for particle diameters between 1.5 and 2.5 mm. Although various sizes could successfully be used to create volumetric representations with the MATD (Extended Data Fig. 3c), we chose the curated set of 2-mm-diameter particles for our remaining experiments. The particle size distribution and sphericity of the set is shown in Extended Data Fig. 3d. The particle density and speed of sound in EPS are approximated as 19 kg m⁻³ and 900 m s⁻¹, respectively.

Finally, we explored the effects of the update rate of the MATD on the achievable particle speeds. Specifically, we performed speed tests (procedure as in Methods section ‘Linear speed tests’) along the vertical direction, identifying the maximum particle speeds for a range of MATD update rates between 156 Hz and 40 kHz. Our results are summarized in Extended Data Fig. 3e, illustrating the benefits of the high update rate of the MATD (higher update rates allow higher particle speeds) and that PDTM could not be supported at rates below 2.5 kHz (that is, when operated at 2.5 kHz, the 3:1 time multiplexing rate from our PDTM required 400 μs every 1,600 μs to create the tactile point—during which time the levitated particle would fall).

**Linear speed tests.** The trapping forces depend on the direction owing to the type of levitation trap that we use. Our trap maximizes vertical trapping forces, whereas forces along the horizontal plane are weaker, which affects the accelerations and speeds that can be imparted on the particle in each direction. This section describes our exploration of the speeds that can be achieved with the MATD. Particularly, we used our chosen particles (about 2 mm diameter) and performed tests to characterize the maximum displacement speeds for each of our three experimental conditions (OSTM, PSTM and PDTM) for particles moving along three directions: along the vertical axis \(Y\) (both in the upward and downward directions) and the horizontal axis \(X\). Given our MATD setup, axes \(X\) and \(Z\) are equivalent (for example, 90° rotation). The speed results along \(Z\) are similar to those along \(X\) and are not reported here.

Linear paths of 10 cm were used for these tests, with the particles starting at 5 cm to the left and stopping at 5 cm to the right of the centre of the MATD (for the vertical tests, 5 cm above or below the centre).
Particles started at rest and were constantly accelerated to reach the maximum speed at the centre of the array. They were then constantly decelerated until brought back to rest at a position 10 cm away from the starting position (for example, see Supplementary Video 3). We used a static camera (CANON, EOS 750D) placed 12 cm in front of the MATD (see Extended Data Fig. 4a) and removed all light. We used a long-exposure shot to record our trials and used our RGB illumination system to illuminate (that is, colour-code) the evolution of the particle along its path at steps of 1 ms (for example, see Extended Data Fig. 4b, c).

When exploring the potential maximum linear speeds \(v_{\text{max}}\) we followed a bisection method (initial boundaries \(v_1 = 0, v_2 = 16 \text{ m s}^{-1}\)). We performed 10 tests at each velocity, and considered a test to be successful (and tested the higher semi-interval) only if 9/10 repetitions were successful. We stopped after three consecutive failed tests, and we report only the highest successful speed observed. The same test procedure (bisection search; 9/10 success rate required; stopping criteria: three consecutive failures) was used in all subsequent experiments described in this section (that is, acceleration, radius of curvature, and corner speeds).

Extended Data Fig. 5 summarizes the resulting \(v_{\text{max}}\) values obtained for each condition (OSTM, PSTM and PDTM) for particles travelling along the horizontal (Extended Data Fig. 5a) and in the vertical (Extended Data Fig. 5b, c) directions. In the top panels of Extended Data Fig. 5a–c, the solid black lines represent the speed of the levitation trap, and the coloured lines show examples of actual particle velocities, as captured during the tests. As expected, the maximum displacement speeds are influenced by the mode of operation used. Whereas the decrease in maximum speed is small when audio is included (OSTM versus PSTM), the effect is much larger when tactile effects are introduced because the acoustic power is split between two traps (that is, time multiplexing for the PDTM mode). Also, the linear speeds are much higher along the vertical axis (particularly when going downwards, owing to the effect of gravity) when compared to horizontal displacements. This is because our setup, with top and bottom arrays, and the twin traps create trapping forces around the levitation trap that are much stronger along the vertical direction (see Extended Data Fig. 4d), allowing higher accelerations.

The paths observed in Extended Data Fig. 5 show the expected correlations between particle velocities (top), particle-to-trap distances (middle) and accelerations (bottom). Points of zero \(\Delta p\) (that is, no net force being applied to the particle) correspond to the maximum/minimum points in each velocity plot (that is, derivative equal to zero), and the sign of \(\Delta p\) is aligned with the monotonicity of velocity plots, increasing when \(\Delta p\) is negative and decreasing otherwise. Similar correlations can be observed between the \(\Delta p\) (middle) and acceleration plots (bottom). Accelerations remain positive when \(\Delta p\) is negative and vice versa (that is, the trap acts as a restorative force, following the distribution in Extended Data Fig. 4d), and the prominent features in both plots match well (for example, the maximum, minimum and the intersection points of the plots with the horizontal axes).

As shown in the middle panels of Extended Data Fig. 5a–c, it is worth noting that the particle almost always remained within a few millimetres of the place where the actual levitation trap was placed (\(\Delta p\)), being subjected to high acceleration rates. This observation is important to understand the behaviour of the MATD in comparison to other levitators.

A particle placed exactly at the centre of the levitation trap (\(\Delta p = 0\)) receives a zero net force contribution, making it stable at that position but also providing no acceleration. This is ideal for levitators designed for precise (but slow) particle manipulation. Also, such levitators usually operate at much lower update rates (that is, hundreds of hertz), so when the position of the trap is moved the particle has enough time to transition to the new trap location. As the particle approaches the centre of the trap, the acceleration received decreases. If the duration of each update is long enough, the particle goes past the centre of the trap and starts receiving negative forces (decelerating), becoming engaged in an oscillatory motion until it stabilizes (nearly) at the centre of the trap. Therefore, modulators with a low update rate can result in uneven accelerations of the particle or make it difficult for the particle to retain its momentum (to accumulate speed) between updates.

The particles manipulated by the MATD do not reach such a static equilibrium after each update. Instead, they need to remain at a distance from the centre of the levitation trap (\(\Delta p\)) so as to receive the force and hence be accelerated. This behaviour can be understood in terms of the derivative of the Gor’kov potential at the points around the trap. Extended Data Fig. 4d shows how such forces evolve for points around a trap, as analytically derived by considering our trap (twin trap), particle (radius, about 1 mm; density, about 19 kg m\(^{-3}\); speed of sound in EPS, 900 m s\(^{-1}\)), setup (top and bottom arrays of 16 × 16 transducers, each modelled using a piston model\(^2\)) and assuming 346 m s\(^{-1}\) and 1.18 kg m\(^{-3}\) as the speed and density of air, respectively.

As shown in the top graph of Extended Data Fig. 4d, restorative forces along the horizontal axis peak at distances of nearly ±3.5 mm from the centre of the trap, closely matching the distances at which our particles were detected during our horizontal speed tests. A similar behaviour can be observed for the vertical tests. In these cases, the peaks of the restorative forces along the vertical direction (see Extended Data Fig. 4d, bottom) are at distances of ±1.5 mm, again matching our observed displacements.

The fact that the trap and the particle do not always remain at those peak distances (that is, ±3.5 mm and ±1.5 mm) seems to indicate that even higher speeds should be achievable for both horizontal and vertical displacements. This, however, would require a more complex control mechanism to determine the location of the levitation trap, accurately predicting the location of the particle at each point in time (considering the acoustic force along with drag, gravity and centrifugal forces) and positioning the trap accordingly (for example, 3.5 mm ahead of the particle for maximum horizontal acceleration). Other factors—such as temporal changes in the complex amplitude (and hence force) related to the simultaneous creation of audible sound, or the multiplexing and interference from the secondary trap—should also be considered for such a model.

**Acceleration, sharp corners and minimum radius of curvature.** The content for the MATD was created through the definition of closed and smooth parametric curves illuminated with varying RGB colours at different points of the path. For content to be visible by the naked eye, such closed curves need to be traversed by the particle in less than 0.1 s (ref.23), which becomes a constraint influencing the particle manipulation required (that is, the speeds and accelerations that need to be imparted at each point along the curve to reveal it within 0.1 s).

Although the maximum displacement speeds \(v_{\text{max}}\) as identified in Methods section ‘Linear speed tests’ are a relevant constraint to plan/design such paths, other parameters (that is, maximum particle acceleration, feasible radius of curvature versus speed, and maximum speed at corner features) are equally relevant and were explored. Again, our characterization followed a conservative philosophy, identifying maximum/minimum values for horizontal displacements (that is, with the weakest trapping forces). The final parameters obtained for our experimental conditions are summarized in Extended Data Fig. 6.

1. **Maximum acceleration per condition.** Some contents do not (or cannot) make use of the maximum speeds, but they would benefit from increased accelerations. The accelerations identified in Methods section ‘Linear speed tests’ could be limited as a result of the high particle speed \(v_{\text{max}}\) used. For instance, drag forces increase with speed and could limit the maximum feasible acceleration in those tests. Similarly, high-speed particle displacements involve more frequent and larger changes to the phase of each transducer, making them operate at frequencies different from 40 kHz and resulting in decreased performance (that is, emitted pressure).
We explored whether higher accelerations were feasible for lower target linear speeds. The experimental procedure followed for this test was similar to that used in the previous speed test, but the maximum target speeds were limited to the 0.5\(v_{\text{connect}}\) to 0.8\(v_{\text{connect}}\) and \(v_{\text{max}}\) values identified for each condition. Our tests (see Extended Data Fig. 6) revealed that the maximum acceleration achievable was not affected (that is, increased) by the target speed used (that is, the accelerations observed for the OSTM, PSTM and PDTM modes matched those identified in Methods section ‘Linear speed tests’), which seems to indicate that the observed upper limit of the acceleration was not related to the particle speed used, but rather to the trapping force exerted by the MATD.

2) Maximum speed at corner features. We tested the maximum speed at which the particle could execute a complete change of direction (\(v_{\max}\)), such as those required to render corners or sharp features (see Supplementary Video 3). The general experimental procedure was again similar to that described in Methods section ‘Linear speed tests’. The design of each trial, however, was modified to test whether the levitated particle could perform a complete change in direction for a given speed. For each speed tested, the particle started again 5 cm to the right of the centre of the array, accelerated linearly at 0.5\(v_{\max}\) until the test speed was reached, and performed a complete 180° turn when it arrived at 5 cm to the left of the array. The maximum speeds obtained for each condition were 0.75 m s\(^{-1}\) (OSTM), 0.5 m s\(^{-1}\) (PSTM) and 0.375 m s\(^{-1}\) (PDTM), as reported in Table 1.

3) Radius of curvature versus speed. Extended Data Fig. 6d shows the maximum displacement speed that can be achieved for a particle moving along a circular path of different radii (1 to 6 cm). The experimental procedure again followed the method used for the other tests. For each radius and speed tested, the particles started at rest and were accelerated at 0.5\(v_{\max}\) until the test speed was reached, moving along a horizontal circle of the desired radius (see Supplementary Video 3). As expected, our results show a decrease in the maximum linear speed as the radius is reduced (that is, introducing higher centripetal forces). A reduction is also observed for the highest radius tested (12 cm diameter) because such a circle spans across the limits of our operational volume, where it receives less acoustic radiation from the transducers.

**Audio generation and quality.** We explored the quality of the audio generated by the MATD, as well as the artefacts introduced due to multiplexing in the dual-trap mode. The audio signal used in all these tests was a chirp signal with frequency increasing quadratically from 100 Hz to 20 kHz (spectrogram shown in Extended Data Fig. 7a, left).

To characterize the performance of our single-trap mode, we trapped one particle and used our chirp audio signal to modulate the amplitude of our transducers (as shown in Methods section ‘Transducer operation (phase and amplitude control)’ and Extended Data Fig. 2). We recorded the sound generated with an Audio-T echnica PRO35 microphone (the spectrogram of the recorded sound is shown in Extended Data Fig. 7b, left), revealing accurate representation of the input signal with some degradation due to harmonics.

To explore the effects of amplitude and position multiplexing (see Methods, ‘Operational modes and multiplexing strategies for single and dual traps’), we repeated the experiment above for two simultaneous (time-multiplexed) traps and two input audio signals. We used the same chirp signal for a channel and a 250-Hz sinusoidal signal (spectrogram shown in Extended Data Fig. 7a, centre) to recreate the tactile texture. This represents the case in which a primary trap is used to trap a particle (visual and auditory feedback) while the secondary trap is used to create tactile feedback on the user’s skin.

Extended Data Fig. 7b shows the results of mixing both audio and tactile signals either by amplitude multiplexing (time-multiplexing the amplitude of each signal at 20 kHz) or by combining them into a single 40-kHz signal (signals added in the frequency domain, as in Extended Data Fig. 7a, right). Our tests show improvements in the reconstructed audio in the second case (Extended Data Fig. 7b, right), discouraging the use of naive amplitude multiplexing (Extended Data Fig. 7b, centre).

The use of position multiplexing (that is, focusing the acoustic power at the location of the levitation trap for 75 μs, and then refocusing it at the location of the tactile trap for 25 μs) cannot be avoided if simultaneous tactile and audio-visual content is to be delivered. Position multiplexing introduces frequency aliasing at the 10-kHz multiplexing rate (as well as harmonic frequencies) as a result of acoustic pressure being focalized at different locations. Our tests show that our multiplexing approach (using position multiplexing with a combined 40-kHz signal; see Extended Data Fig. 7c, right) reduces audible artefacts when compared to the use of both amplitude and position multiplexing (Extended Data Fig. 7c, left), particularly for harmonics, and that our approach minimizes artefacts in the human primary auditory range (that is, 2–5 kHz).

This study also illustrates the need for high update rates for an MATD modulator (that is, beyond enabling higher particle speeds, as shown in Extended Data Fig. 3e). Our multiplexing schedule involves a multiplexing rate of 10 kHz, creating aliasing effects also at harmonic frequencies (that is, 20 kHz). A modulator with a lower rate would create artefacts at many more frequencies, spread across the auditory range (for example, a modulator operating at 10 kHz would require a multiplexing rate of 2.5 kHz, introducing artefacts around 2.5 kHz, 5 kHz, 7.5 kHz, and so on). It is also worth noting that the aliasing effects in our prototype (around 10 kHz) are related to the multiplexing schedule used (75% for levitation, 25% for tactile), which in turn is related to the power constraints of our prototype. Increased transducer power, allowing effective levitation at a 50% duty cycle (50% for levitation, 50% for tactile feedback), would avoid most of these artefacts by shifting them around a primary 20 kHz frequency. Extended Data Fig. 7d presents the results of a test performed using our method in such a configuration (50% duty cycle), which showed reduced artefacts and even better quality than in the 75% configuration (Extended Data Fig. 7d, right).

**Audio modes supported.** The MATD supports two different modes for creating audio: a scatter mode (Extended Data Fig. 8a), which provides non-directional sound but is compatible with simultaneous visual and tactile content, and a directional mode (Extended Data Fig. 8b), which uses the secondary trap to steer the sound in the direction of the user but does not allow simultaneous tactile points (that is, only visual content and directional audio).

We measured the audible sound generated by each of the two approaches, using a 2-kHz audible signal as the audible output. Our measuring setup comprised a modified 3D printer (OpenBuilds Sphinx 55), in which the extruder had been removed and replaced by a calibrated microphone (Nordic Environmental Analyser 121; shown in Extended Data Fig. 8c). Our software controlled the position of the microphone with 0.1 mm accuracy by issuing G-code commands over a serial port connection. Displacements of the microphone were followed by 1 s pauses (after the end of the motion) to avoid interference due to vibrations. We also configured the microphone to measure sound only in the one-third octave band of 2 kHz around our intended audible signal (that is, unconstrained measurements would also capture harmonics, resulting in higher but misleading sound pressure results).

Each of these audio modes (scatter and directional) were tested for two cases: one measuring the audible response when only audio is delivered, and another one with both audio and tactile feedback delivered. For the directional mode (which cannot support all three modalities simultaneously) the second case is representative of situations in which the primary trap is used for directional audio generation and the secondary one to create tactile feedback.

Extended Data Fig. 8d, e shows the results of our tests for horizontal and vertical scans around the MATD volume. The results show audible levels of sound at all points around the display (74 ± 12 dB for the non-directional scatter mode and 72 ± 13 dB for the directional mode).
Points of higher intensity can be found around the MATD, which are expected as a result of constructive interference. In the directional case, high pressure levels of 103 dB can be observed around the intended target point, which then continue to propagate forwards along the direction between each transducer array and the focusing point. In all cases, the inclusion of simultaneous tactile and audio information results in only a small reduction of the intensity of audible sound (66 ± 11 dB and 63 ± 12 dB for the non-directional and directional methods, respectively).

Tactile generation and quality. We reused the measuring setup described in Methods section ‘Audio modes supported’ to scan the sound pressure level (SPL, in decibels) generated by our MATD when delivering tactile sensations (see Extended Data Fig. 9a), by replacing the microphone with a calibrated Brüel & Kjær 4138-A-015 microphone connected to a PicoScope 4262 oscilloscope and using the PicoScope SDK to retrieve the measurements. We measured the SPL generated by our system for a single tactile point at the centre of the array under three conditions, always using the multiplexing schedule described for the dual-trap mode.

In the first condition, only the tactile content was delivered (that is, the array created a tactile point during the 25% duty cycle allocated to the secondary trap, and no output was produced by the array during the remaining 75% of the time). For the second and third conditions, we reused the content displayed in the second part of Supplementary Video 2 and Extended Data Fig. 9b, with the scanning particle (primary trap delivering visual content) placed 5 cm to the front and left of the tactile point. The second condition used a 250-Hz signal for side-band modulation, representing the case in which only visual and tactile content are present. The third condition, however, included the combined signal (that is, audio with a 2-kHz signal combined with a 250-Hz signal) to represent the case in which all visual, tactile and audible content is present.

To assess the effects that a user’s hand could have (that is, by occluding part of the transducers or via scattering), we measured the field both in the presence and absence of a silicone hand (Extended Data Fig. 9c). When the silicone hand was present, the tactile point was created on the surface of the bottom part of the index finger’s tip. In all three conditions (visual only, visual and tactile, and multimodal), a horizontal and a vertical plane of 10 × 10 cm² were scanned, measuring SPL levels at a resolution of 1 mm. Our results are presented in Extended Data Fig. 9d, e. It must be noted that the presence of the hand prevented measuring across the entirety of the plane (see white regions in Extended Data Fig. 9e), but the areas within ±3 cm around the fingertip could still be reached, covering an area eight times larger than the width of the focusing point (about 7 mm diameter). Also, given the thickness of our scanning microphone (3.5 mm) and irregularities on the surface of the hand, we could not measure exactly the surface of the hand, and the scans presented in Extended Data Fig. 9e are taken on the plane Y = -4 mm.

The results show that the device provided accurate positioning and focusing of the acoustic pressure around the central point (where tactile feedback is present) in all three cases and both in the presence and absence of the hand. The vertical scans show a repeated pattern of lobes, consistent with the interference of the acoustic radiation emitted from the top and bottom arrays. Some differences can be found between the tactile-only condition (first column) and the other two cases, as a result of the effects of the primary trap (visual content). However, the effects around the tactile point are small, the sharpness of the tactile point is maintained, and there is very little variation across all three cases. The maximum pressure levels are found at the centre of the tactile points (157.0 dB, 158.6 dB and 158.5 dB in Extended Data Fig. 9d; 154.7 dB, 155.0 dB and 154.6 dB in Extended Data Fig. 9e) and are always well above the threshold of 78 dB required for perceivable tactile feedback. It must be noted that the presence of a second high-pressure area to the bottom left of the images in the second and third conditions is the result of the primary trap used to deliver the visual content.

Data availability
The data that support the plots within this paper and other findings of this study are available in the main text and the Extended Data Figures. Additional information is available from the corresponding author upon reasonable request.

Code availability
Custom C++ code used for controlling our MATD during our tests is available on GitHub for anyone under a Creative Commons Attribution-Noncommercial-ShareAlike license at https://github.com/RyujiHirayama/MATD.

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Author contributions
D.M.P. and S.S. conceived the idea. R.H. and D.M.P. implemented the system and gathered experimental data demonstrating the idea. Data analysis was led by R.H., with contributions from all authors. D.M.P. led the optimization design with contributions from R.H. and S.S. R.H. optimized the firmware code with contributions from N.M. R.H. wrote the paper, with contributions from all authors.

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Extended Data Fig. 1 | Overview of the MATD prototype. Experiments were performed using two opposed arrays of 16 × 16 transducers, aligned on top of each other and with a separation of 23.4 cm.
Extended Data Fig. 2 | Phase and amplitude control of the transducers used.

a, Square-wave input from the FPGA, used to drive the transducer phase and amplitude by controlling their phase delays and duty cycles. b, Nonlinear correlation between transducer pressure and duty cycle; measurements (dots) and analytical approximation (line). c, Measured sinusoidal responses of transducers driven by the square waves shown in a.
Extended Data Fig. 3 | Preliminary characterization of particle sizes and update rates. 

a, Camera setup used to measure the sphericity and diameter of the particles. 
b, Maximum linear speeds for different particle sizes. In all graphs the markers correspond to experimental values and the lines represent spline curves fitted to the data. 
c, POV representation using different particle diameters. 
d, Particle size distribution and sphericity of the 2-mm-diameter particles used. 
e, Maximum linear speeds along the vertical (downward) path for different update rates and for each mode (OSTM, PSTM and PDTM).
Extended Data Fig. 4 | Speed measurement setup. a, A camera takes a long-exposure photograph of the moving particle, which is illuminated by the LED at steps of 1 ms. b, c, Images captured during the horizontal and vertical linear speed tests at three different conditions (OSTM, PSTM and PDTM). d, Approximation of horizontal and vertical radiation forces exerted on a particle located around a levitation trap, as analytically approximated using the Gor’kov potential.
Extended Data Fig. 5 | Speed, distance between the acoustic trap and the levitated particle (\(\Delta p\)) and acceleration. a–c. Data measured during our speed tests along the horizontal (a), upward (b) and downward (c) directions.
Extended Data Fig. 6 | Summary of the particle-control performance tests of the MATD for each of the experimental conditions tested. a–c, Maximum linear speeds and accelerations for each mode (OSTM, PSTM and PDTM). The paths denote the speed of the levitation trap, not observed particle trajectories. d, Maximum linear speeds achieved by particles following circular paths of increasing radii for each mode.
Extended Data Fig. 7 | Spectral analysis of the audio response of the MATD. a, Signals used for input: chirp (left), 250 Hz (tactile, centre) and signals combined in the frequency domain (right). b, Output of the system when only sound is created (left) and when multiplexed with tactile content using amplitude multiplexing (centre) and combined signals (right). c, Effects of position multiplexing on an amplitude-multiplexed signal (left) and our combined signal (right) for a 75%–25% duty cycle. d, Effects of position multiplexing when applied to 50%–50% duty cycle signals.
Extended Data Fig. 8 | Audio modes supported by the MATD. a, b, Illustration of the two different modes (scatter and directional) and the sound tests. c, Audio measurement setup. d, e, Measured SPL distribution of the modes. The SPL distributions were measured under two conditions—sound only and sound plus tactile feedback—across the horizontal and vertical planes.
Extended Data Fig. 9 | Characterization of tactile feedback. 

a, Measurement setup. b, Visual content used, together with the tactile point. c, Measurement setup with a silicone hand (KI-RHAND, from Killer Inc. Tattoo). d, Results of the horizontal and vertical scans of the SPL for each of our conditions while delivering only tactile feedback, tactile and visual content, and all three modalities (tactile, visual and audio). e, Results of vertical and horizontal scans in the presence of a hand for all three conditions.
Extended Data Fig. 10 | Other applications of the MATD. a. Simultaneous levitation of six EPS particles in a diamond pattern (16.7% duty cycle for each particle; maximum number of particles levitated so far). b, c. Frequency modulation at 148 Hz to produce resonant oscillations ($n = 2$) for a 2-mm-diameter water droplet, captured from the side.