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

Ryuji Hirayama, Diego Martinez Plasencia, Nobuyuki Masuda, Sriram Subramanian

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## TABLES:

**Table 1: Main parameters MATD**

| | Visual only | Visual and audio | Visual, audio and tactile |
|---|---|---|---|
| Highest speed recorded ($v_{max}$) | 3.75 m/s | 3.375 m/s | 2.5 m/s |
| Highest acceleration recorded ($a_{max}$) | 141 m/s$^2$ | 122 m/s$^2$ | 62 m/s$^2$ |
| Highest speed for corner features ($v_{corner}$) | 0.75 m/s | 0.5 m/s | 0.375 m/s |
| Highest image framerate until now | 12.5Hz | 10.0Hz | 10.0Hz |
| Colour | 24bpp | 24bpp | 24bpp |

## FIGURES:

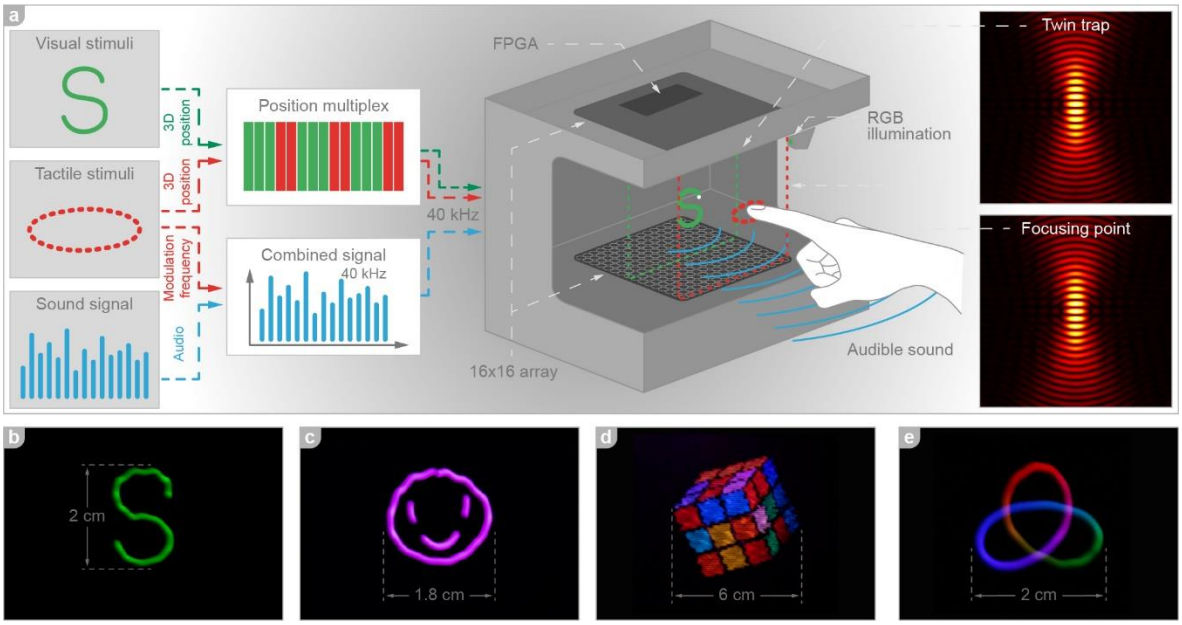



**Figure 1. Main elements in the MATD. (A) A geometrical description of the visual and tactile stimuli, along with sound, are used as input. The system multiplexes the position of levitation and tactile traps. A quick scanning levitated particle and RGB illumination provide visual content (POV method); modulated acoustic pressure provides tactile feedback and amplitude modulation provides audible sound. (B, C) Example POV images (visible by the naked eye) scanned at 12.5Hz and 10Hz (Video SV1). (D) Multicolour 2D raster image (exposure time 20s, peak speed 0.6m/s); (E) Example 3D POV content (3:2 torus knot) scanned at 10Hz (Video SV2).**

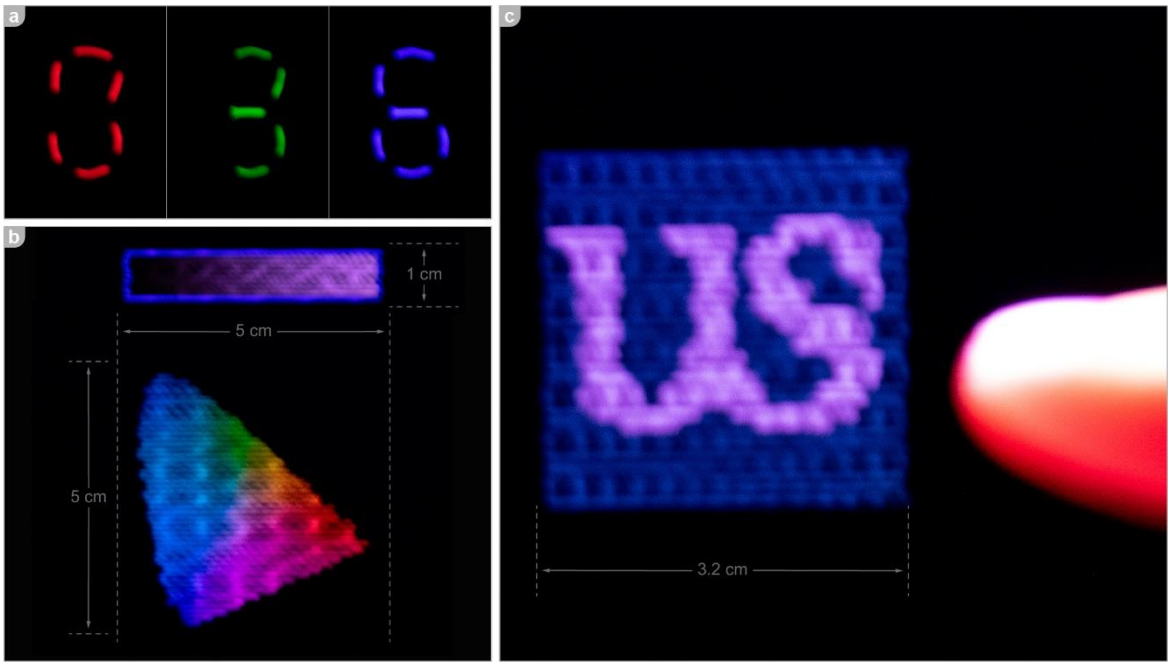



**Figure 2. Colour reproduction of the MATD display. (A) Example POV content (visible by naked eye) with simultaneous sound (see Video SV2), showing highly saturated colours. (B) Additive colour reproduction of the CIE colour space and grayscale (exposure 8s, peak scanning speeds 0.4m/s for CIE and 0.1m/s for grayscale, non POV). (C) Raster image with simultaneous tactile stimuli (exposure 8s, peak scanning speed 0.2m/s, non POV).**

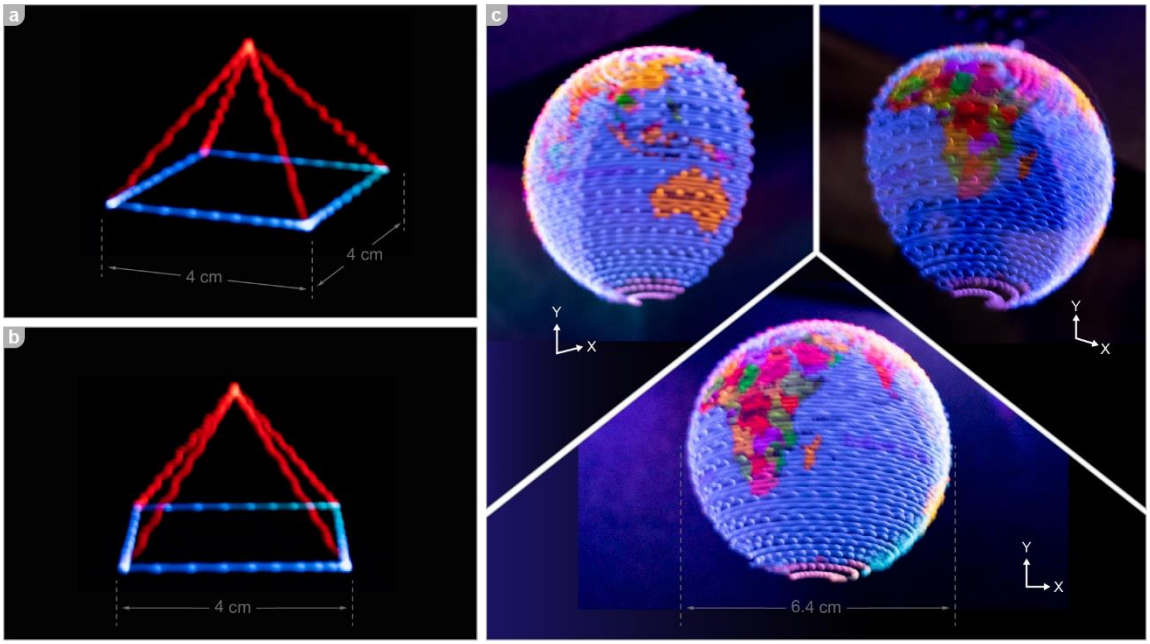
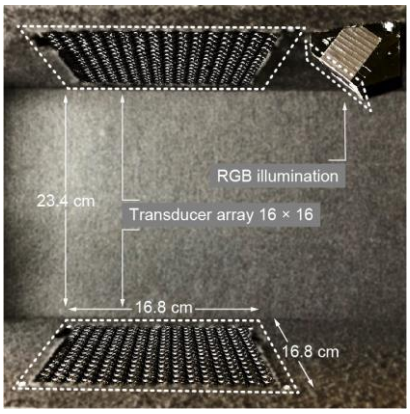
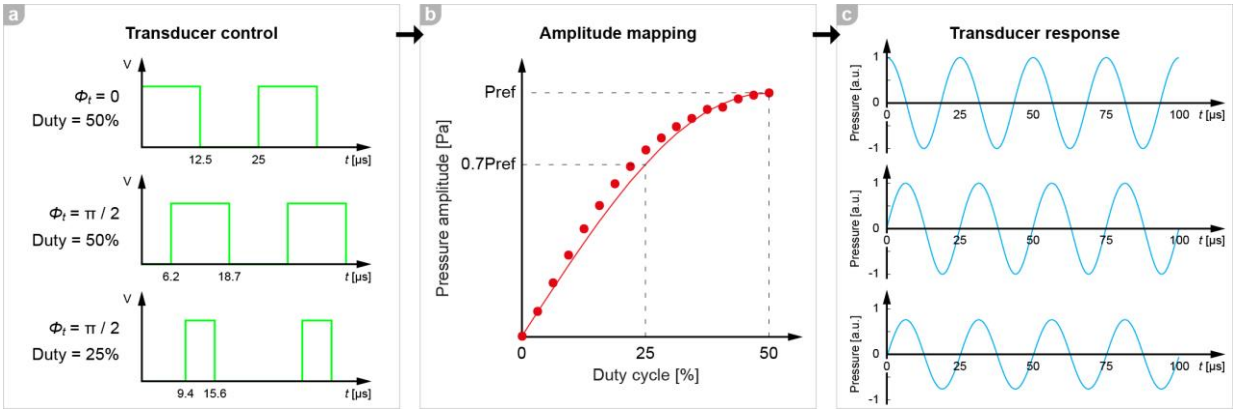



**Figure 3. Rendering of volumetric contents. (A, B) Example pyramid visible from all angles around the display (4cm side, 2s exposure (non POV), scanning speed 0.5m/s). (C) Example 3D raster image with rich colour information (6.4cm diameter, 20s exposure (non POV), peak scanning speed 0.9m/s).**

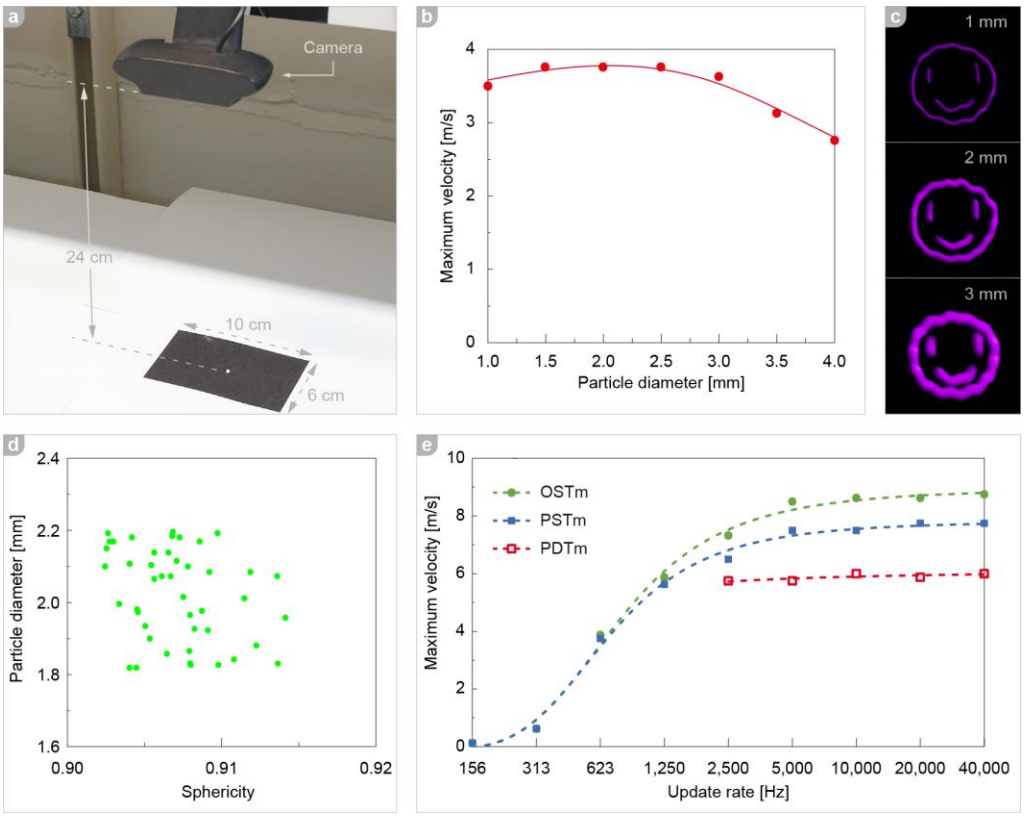
## EXTENDED DATA:



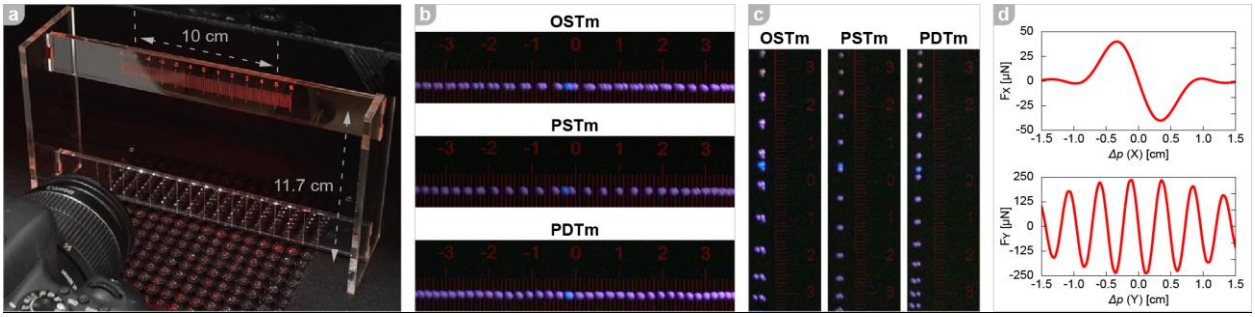

**Extended Data Figure 1: Overview of our MATD prototype.**



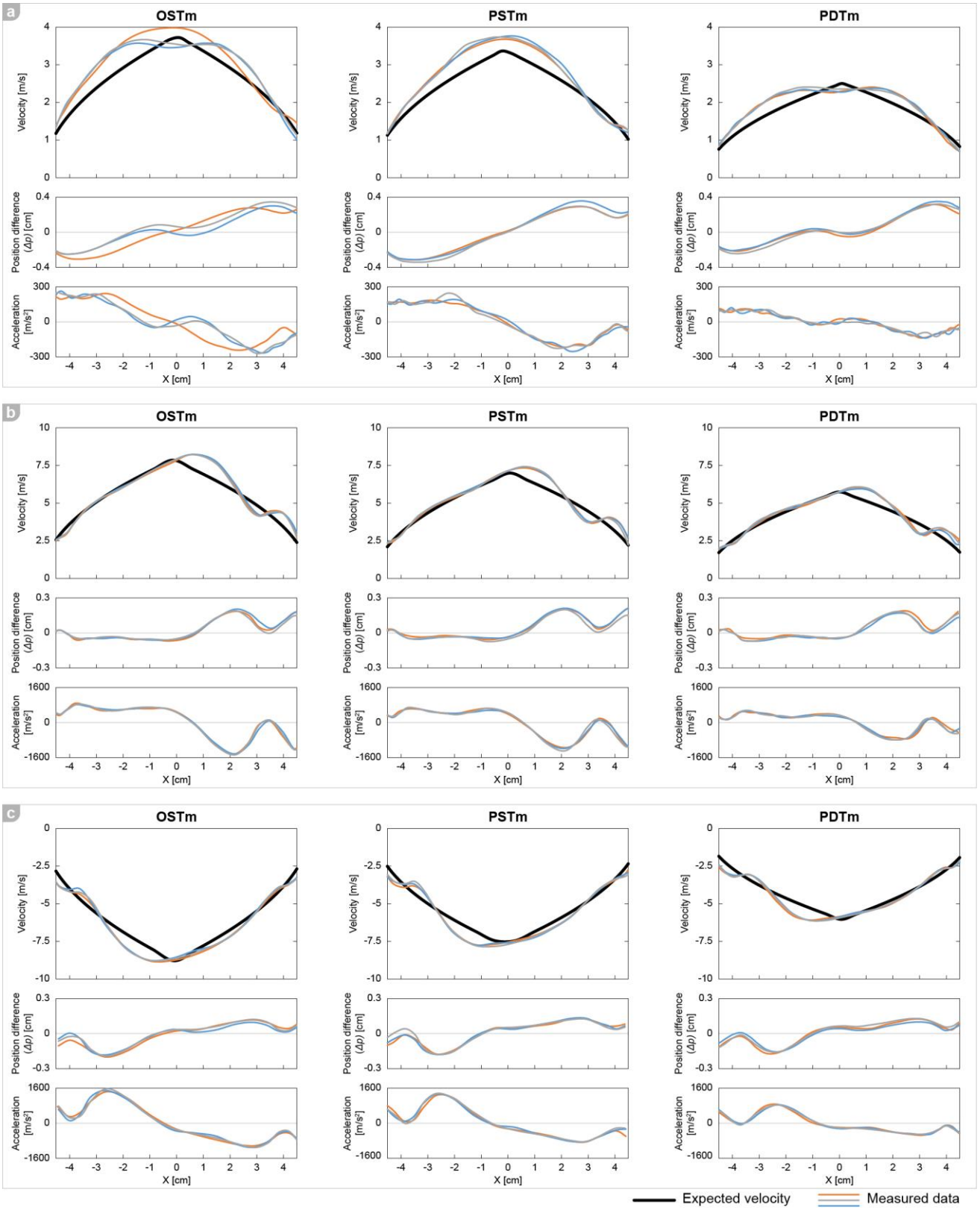

**Extended Data Figure 2: Phase and amplitude control of the transducers used. (A) Square wave input from the FPGA, used to drive the transducer's phase and amplitude, by controlling their phase delays and duty cycles; (B) Non-linear correlation between transducers' pressure and duty cycle as per measurements (dots) and as per our analytical approximation (line); (C) Sinusoidal responses measured from the transducers, when driven by the square waves shown in (A).**



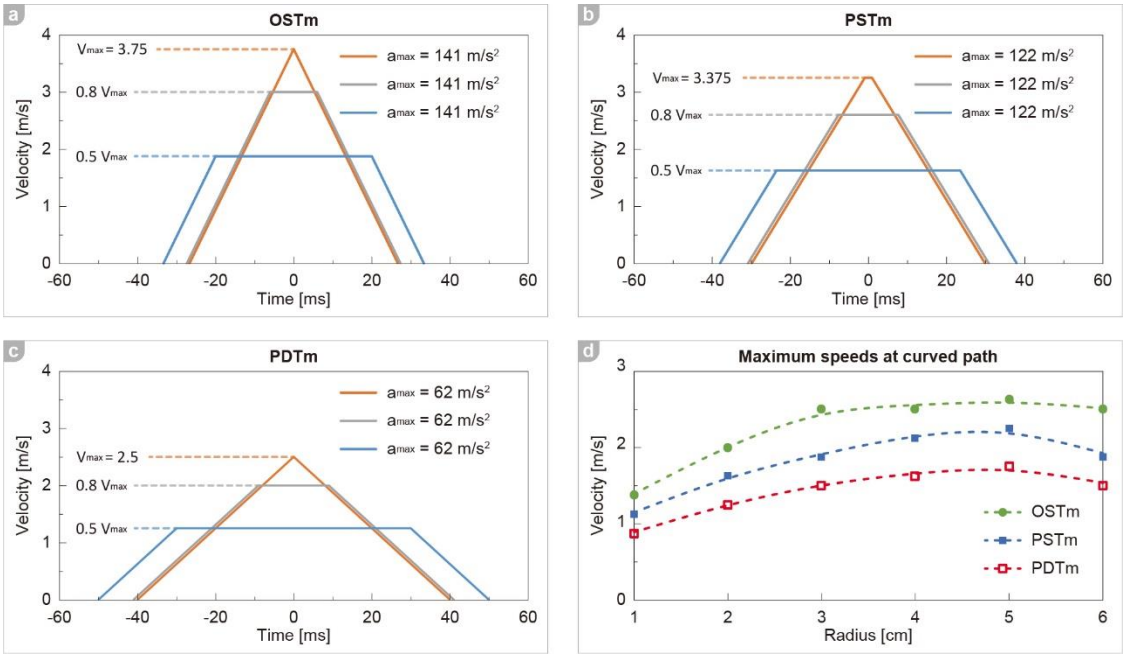

**Extended Data Figure 3: Preliminary characterization of particle sizes and update rates. (A) Camera setup to measure sphericity and diameter of the beads; (B) Maximum linear speeds for different particle sizes; (C) POV representation using different particle diameters; (D) Particle size distribution and sphericity of the 2mm diameter particles used; (E) Maximum linear speeds along the vertical (downward) path for different update rates and for each mode (OSTm, PSTm and PDTm).**



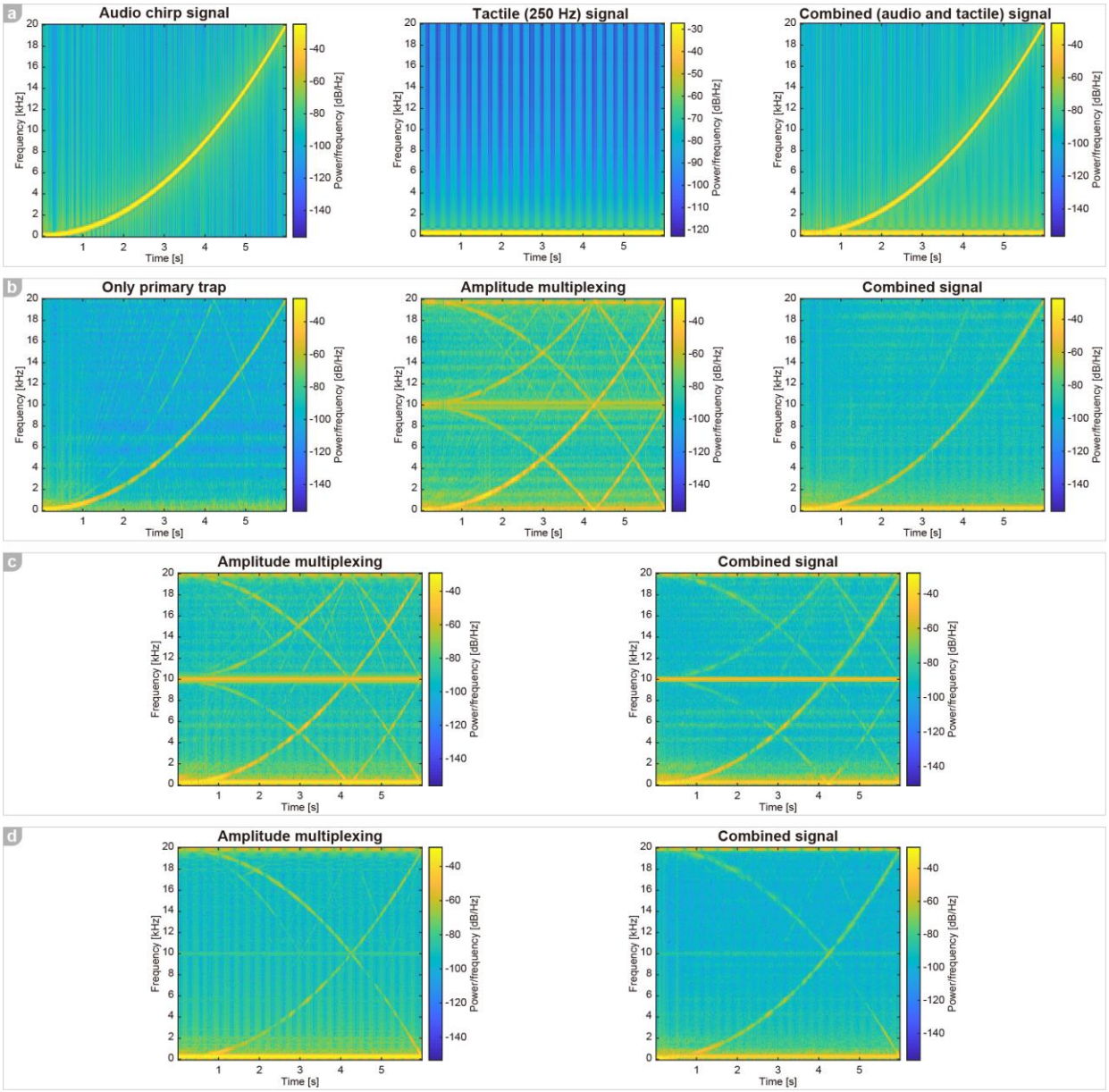

**Extended Data Figure 4: Speed measurement setup. (A) A camera takes a long exposure photograph of the moving bead, which is illuminated by the LED at steps of 1ms; (B, C) The captured images of the horizontal and vertical linear speed test of three different conditions (OSTm, PSTm and PDTm); (D) Approximation of horizontal and vertical radiation forces exerted on a particle located around a levitation trap, as analytically approximated from Gor'kov potential.**



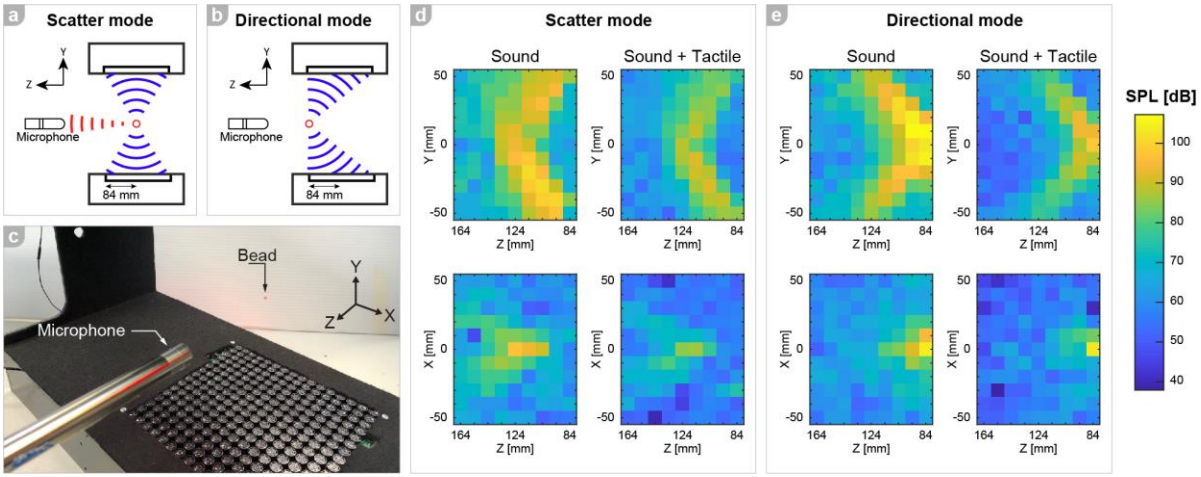

**Extended Data Figure 5: Plots of the speed, distances between the acoustic trap and levitated particle (*Δp*) and accelerations, as measured during our speed tests along the horizontal (A), upward (B) and downward (C).**



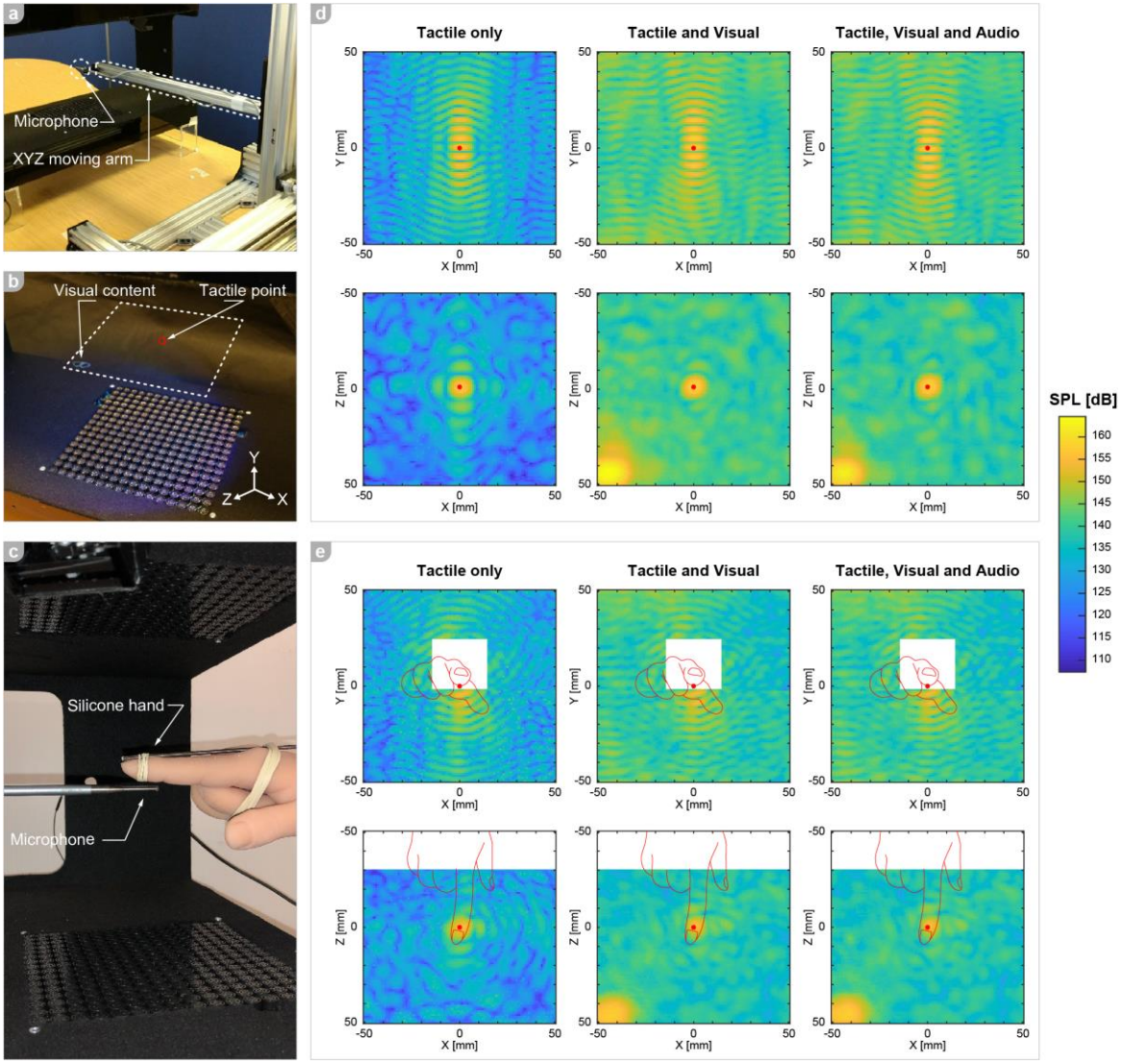

**Extended Data Figure 6: Summary of the particle control performance tests of the MATD for each of the experimental conditions tested. (A-C) Maximum linear speeds and accelerations for each mode (OSTm, PSTm and PDTm). Please note paths denote the speed of the levitation trap, not observed particle trajectories; (D) Maximum linear speeds achieved by particles following circular paths of increasing radii, for each mode (OSTm, PSTm and PDTm).**




**Extended Data Figure 7: Spectral analysis of the audio response in the MATD. (A) Signals used for input: chirp (left), 250Hz (tactile, centre) and signals combined in frequency domain (right); (B) Output from the system when only sound is created (left) and when multiplexed with tactile content using *amplitude* multiplexing (centre) and using 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.**

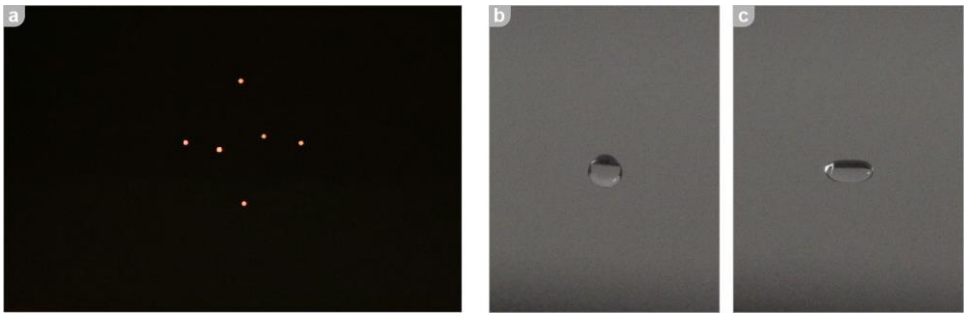



**Extended Data Figure 8: Audio modes supported by the MATD. (A, B) Illustration of the two different modes (*scatter mode* and *directional mode*) and how sound tests were conducted; (C) Audio measurement setup; (D, E) Measured sound pressure level (SPL) distribution of the modes. The SPL distributions were measured in two conditions, sound only and sound + tactile feedback, across horizontal and vertical planes.**




**Extended Data Figure 9: Characterization of tactile feedback. (A) Measuring setup used; (B) Visual content used, together with the tactile point; (C) Measuring setup with a silicone hand (KI-RHAND, from Killer Inc Tattoo); (D) Results of our horizontal and vertical scans of the SPL (dB) for each of our conditions while delivering only tactile feedback, tactile and visual**

**content, and all three modalities (tactile, visual and audio); (E) Results from our vertical and horizontal scans in the presence of a hand, for all three conditions.**




**Extended Data Figure 10: Other applications of the MATD: (A) Simultaneous levitation of 6 EPS particles in a diamond pattern (16.7% duty cycle for each particle, maximum number of particles levitated to date); (B, C) Frequency modulation at 148Hz to produce resonant oscillations (n=2) for a 2mm water droplet, captured from a side.**